Gravitational-wave event validation by Advanced LIGO and Advanced Virgo detectors Procedures and challenges for the upcoming observing runs

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Francesco Di Renzo On behalf of the Virgo Collaboration <u>francesco.direnzo@df.unipi.it</u>

7.2

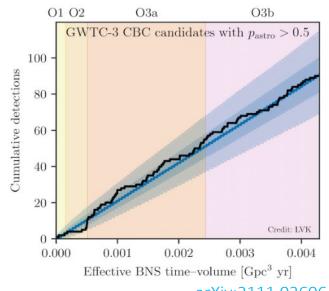


#### Compact binary observations by Advanced LIGO and Advanced Virgo detectors

			24						
01 2015 - 2016	<b>02</b> 2016 - 2017	and the second	de	Est.				03a+b 2019 - 2020	
36 31 23 14	14 77 31 20	11 7.6 50 34	35 24	31 25	15 13	35 27	40 29	68 · 22	25 18
63 36 cw150914 cw151012	21 49 CW151226 CW170104	18 80 GW170608 GW170729	56 cw170809	53 CW170814	≤ 2.8 cw170817	60 GW170818	65 GW170823	105 cw190403_051519	41 GW190408_181902
30 8.3 35 24	48 32 41 32	2 14 107 77	43 28	23 13	36 18	39 28	37 25	66 <b>4</b> 1	95 69
<b>37</b> 56 CW190412 CW190413_052954	76 70 CW190413_134308 CW190421_213856	3.2 175 cw190425 cw190426_1906	69 cw190503_185404	35 GW190512_180714	52 GW190513_205428	65 cw190514_065416	59 cw190517_055101	101 GW190519_153544	156 GW190521
42 33 37 23	69 <b>4</b> 8 <b>5</b> 7 <b>3</b> 6	35 24 54 41	67 38	12 8,4	18 13	37 21	13 7.8	12 6.4	38 29
71 56 cw190521_074359 cw190527_092055	111 87 GW190602_175927 GW190620_030421	56 90 cw190630_185205 cw190701_2033	99 GW190706_222641	19 GW190707_093326	30 GW190708_232457	55 GW190719_215514	20 GW190720_000836	<b>17</b> GW190725_174728	64 GW190727_060333
12 8.1 42 29	37 27 48 32	23 2.6 32 26	24 10	44 36	35 24	44 24	9.3 2.1	8.9 5	21 16
20 67 cw190728_064510 cw190731_140936	62 76 CW190803_022701 CW190805_211137	26 55 CW190814 CW190828_0634	33 GW190828_065509	76 GW190910_112807	57 GW190915_235702	66 GW190916_200658	<b>11</b> GW190917_114630	13 GW190924_021846	<b>35</b> GW190925_232845
40 23 81 24 61 102	12 7.8 12 7.9 19 19	11 7.7 65 47 18 107	34	12 8.3 <b>20</b>	<sup>53</sup> • <sup>24</sup> 76	11 6.7 <b>17</b>	27 19 <b>45</b>	12 8.2 <b>19</b>	25 18 41
GW190926.050336 GW190929.012149 12 7.7 31 12 19 322 GW19126_21338 GW191219_163120	GW190930,133541         GW191033,012549           45         35         49         37           76         82         6W191222,033537         6W191230,180458	CW19105.143521 CW19109.007 9 1.9 36 26 11 61 CW200105.162426 CW200172.1568	59 14 <b>7.2</b>	CW191126.115259 42 33 71 GW200128_022011	GW191127.050227 34 29 60 GW200129.065458	GW791129.134029 10 7.3 <b>17</b> GW200202,154333	CW191204_T10529 38 Z7 63 CW200208_130117	GW191204.171526 51 12 61 GW200208.222617	GW191215 223052 36 27 60 GW200209_085452
24 2.8 51 30 27 78 cw200210.092254 cw200216.220804	38 28 87 61 62 141 cwz00219.094415 cwz00220.061928	39 28 40 33 64 69 GW200220.124850 GW200224.2222	<sup>19</sup> 14 <b>32</b>	38 20 <b>56</b> ⊂₩200302_015811	28 15 42 GW200306_033714	36 14 47 GW200308.173609	34 28 59 GW2003TL115853	13 7.8 20 GW200316_215756	34 14 53 GW200322.091133



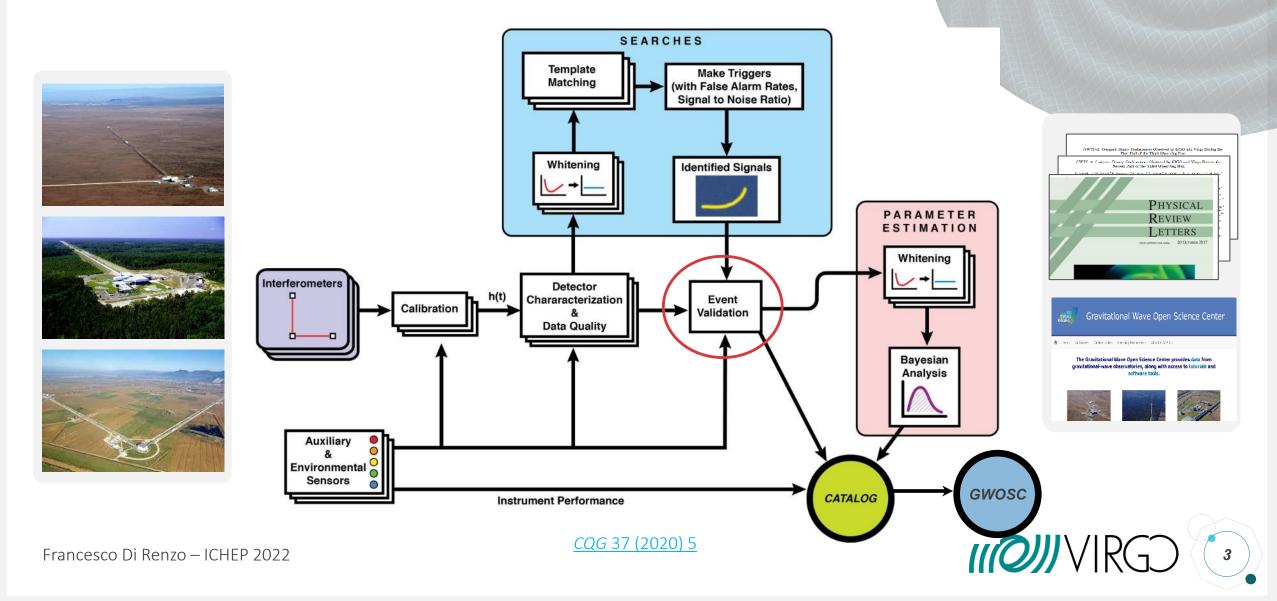
Credit: LIGO/Virgo/KAGRA/C. Knox/H. Middleton



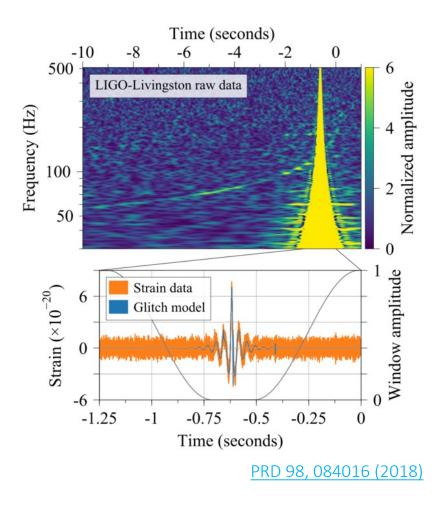
arXiv:2111.03606



#### Data processing overview: from detectors to publications



# The validation of gravitational-wave events



- 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  $\mathcal{O}(10 \text{ min})$  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;

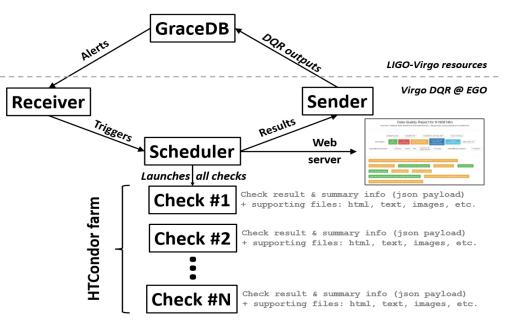
• Final validation (all):

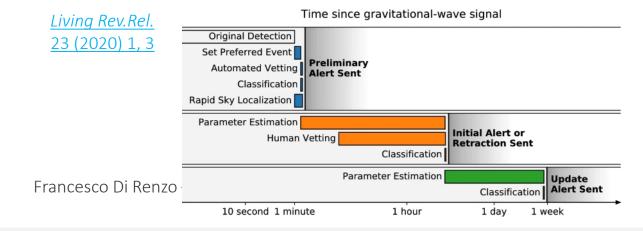
Completed as a final check before publication for all events found by online and/or offline pipelines. The typical timescale is days or even months after the time of the event.



# The Data Quality Report framework

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





- A Data Quality Report (DQR) is a <u>framework developed</u> by LIGO and Virgo consisting in a set of DQ checks;
- It is automatically prompted after each gravitationalwave candidate trigger with false alarm rate (FAR) of 1/day is being generated on <u>GraceDB</u>;
- The results are uploaded back to <u>GraceDB</u> 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

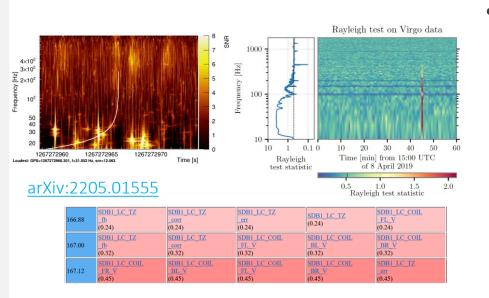
Operation	Time taken [s]				
Operation	Median	Mean	95 <sup>th</sup> percentile		
Data acquired $\rightarrow$ Candidate on GraceDB	52	166	331		
Candidate on GraceDB $\rightarrow$ LVAlert trigger	4	4	11		
$\texttt{LVAlert} trigger \rightarrow Virgo \; \texttt{DQR} \; configured$	331	339	383		
Virgo DQR configured $\rightarrow$ Virgo DQR started	8	10	21		
Operation	Time from start [s]				
Operation	Median	Mean	$95^{th}$ percentile		
Quick key checks	Median 374	Mean 383	95 <sup>th</sup> percentile 619		
			$ \begin{array}{c} 95^{th} \text{ percentile} \\ 619 \\ 935 \end{array} $		
Quick key checks	374	383	619		

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#### Prompt event validation of low-latency alerts

d DMS					Mode: Comm	issioning (24.1)		ITF State: LOCI	CED_ARMS		
Injection		SIB1_BENCH	SIB1_	BR SIB1		L_Vert SIE					SIB1_Electr
	MC_IP	MC_PAY	C_PAY MC_E		MC_Vert						
											BPC_Elect
	PD	PD_RF	QPD_B1p	QPD_B2						PicoDisable	e Shutter
Detection	SDB1_IP	SDB1_LC	SDB1_								
		PR_parking SR_parking									
	NE_ALS_Las		NE_ALS_ARM		WE_AL	S_Laser	WE_ALS_ARM			CEB_ALS_Laser	
	BS_IP			B	5_BR	BS_V	fert	BS_TE		BS_Guard	
	NLIP										
	NE_IP					NE_V	/ert	NE_TE			
	PR_IP					PR_V	/ert				
						W_V	\ert	WI_TE			
						WE_V	/ert	WE_TE			
Environment	CB_Hall					WE_H	Hall	WindActiv			
	INJ Area			AQ Room						Lights	SeaActivi

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



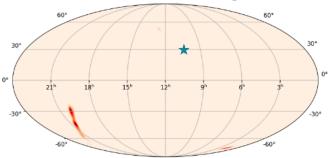
- This stage has the role to **vet those event triggers with severe noise contamination**, for which an astrophysical origin should be excluded;
- Otherwise, it serves to enforce the confidence in the event type and **sky-localization** to support **multimessenger follow-up**.
- The main DQ checks based 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:  $h_{\rm rec}$  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.



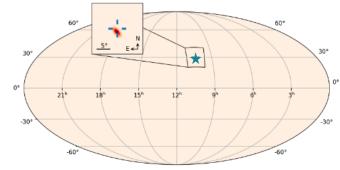
# Final validation before publications

- 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  $\mathcal{O}(1 \text{ hour})$  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; <u>CQG 35 (2018) 15, 155017</u>
- 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.





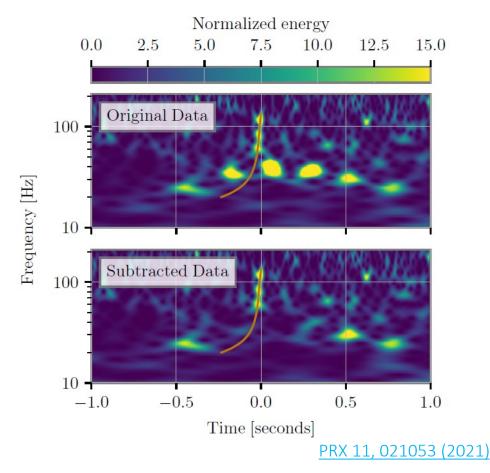




Effect on sky-localization of a blip glitch 30 ms after a GW150914-like event. <u>PRD 105 (2022) 103021</u>



# Noise artifacts mitigation of gravitational-wave detector data



- 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
03	79	42	27	37	16

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

#### 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  $\mathcal{O}(1h)$  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.



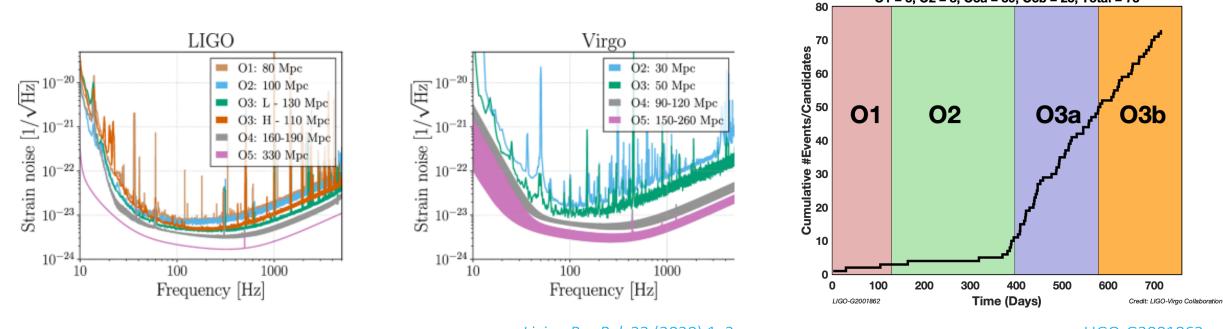
#### Thanks for the attention!





# 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



Cumulative Count of Events and (non-retracted) Alerts O1 = 3, O2 = 8, O3a = 39, O3b = 23, Total = 73