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

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► **To cite this version:**

Nicolas Arnaud. From public alerts to gravitational-wave candidates during the LIGO-Virgo third observation run O3. 40th International Conference on High Energy Physics - ICHEP 2020, Jul 2020, Prague (virtual), Czech Republic. in2p3-03999155

HAL Id: in2p3-03999155

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Submitted on 21 Feb 2023

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

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European Gravitational Observatory (Consortium, CNRS & INFN)

On behalf of the **Virgo Collaboration** and the **LIGO Scientific Collaboration**
VIR-0158A-20 **DCC G2000184**

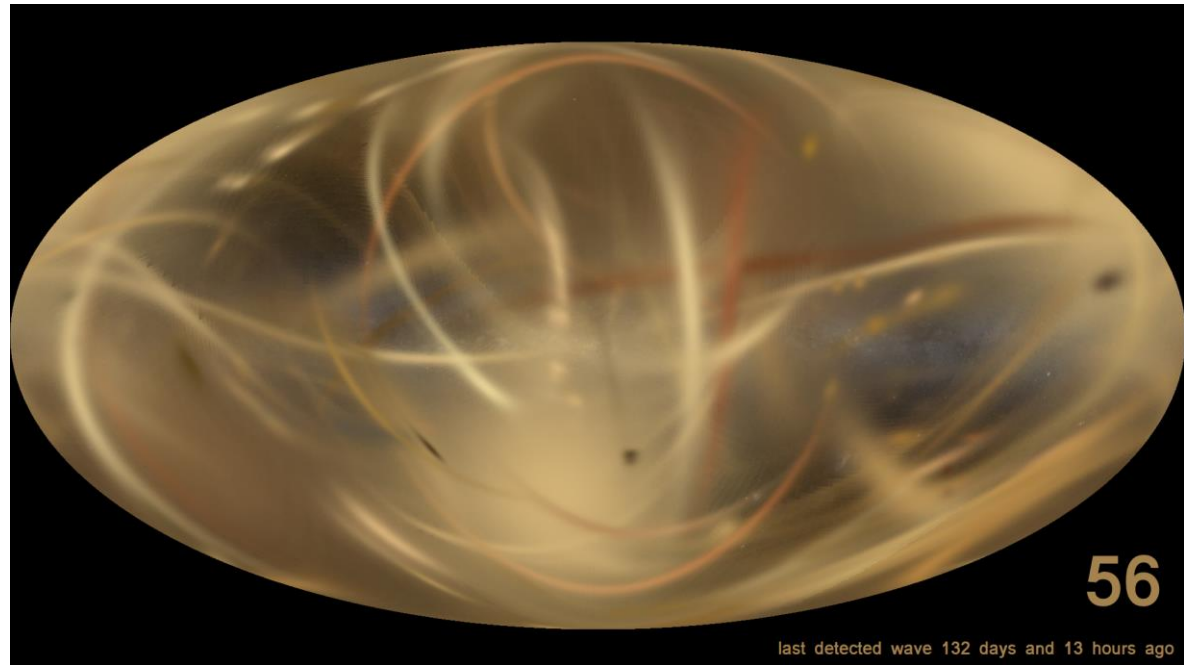


ICHEP – July 29, 2020



Outline

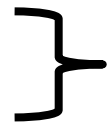
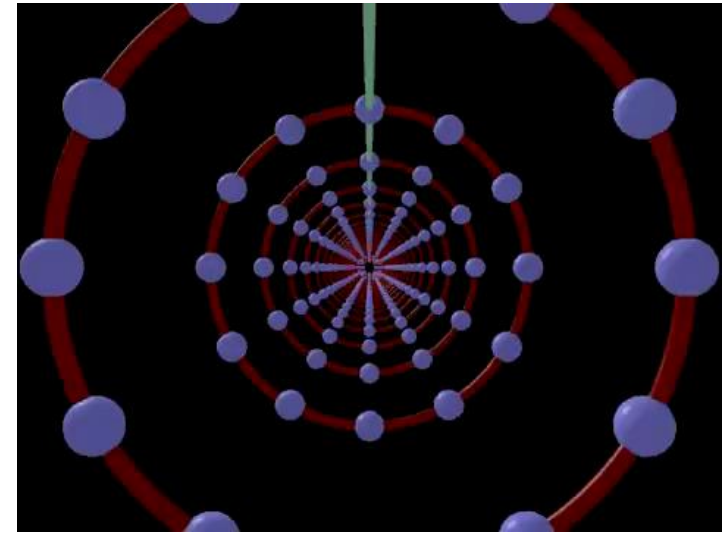
- Detecting gravitational waves with the global LIGO-Virgo network
- The LIGO-Virgo third Observing Run: O3
- Detector Characterization and Data Quality
- Public alerts
 - Dataflow and associated latency
 - Vetting alerts in real time with data quality reports
 - Statistics for O3
- Outlook
 - The path 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 $1/\text{distance}$
- Detectors directly sensitive to h
 - Small sensitivity gains can lead to large improvements in event rate
- Rough classification
 - Signal duration
 - Frequency range
 - Known/unknown waveform
 - Any/no counterpart (electromagnetic spectrum, neutrinos, etc.) expected



Detectable by the instruments

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**

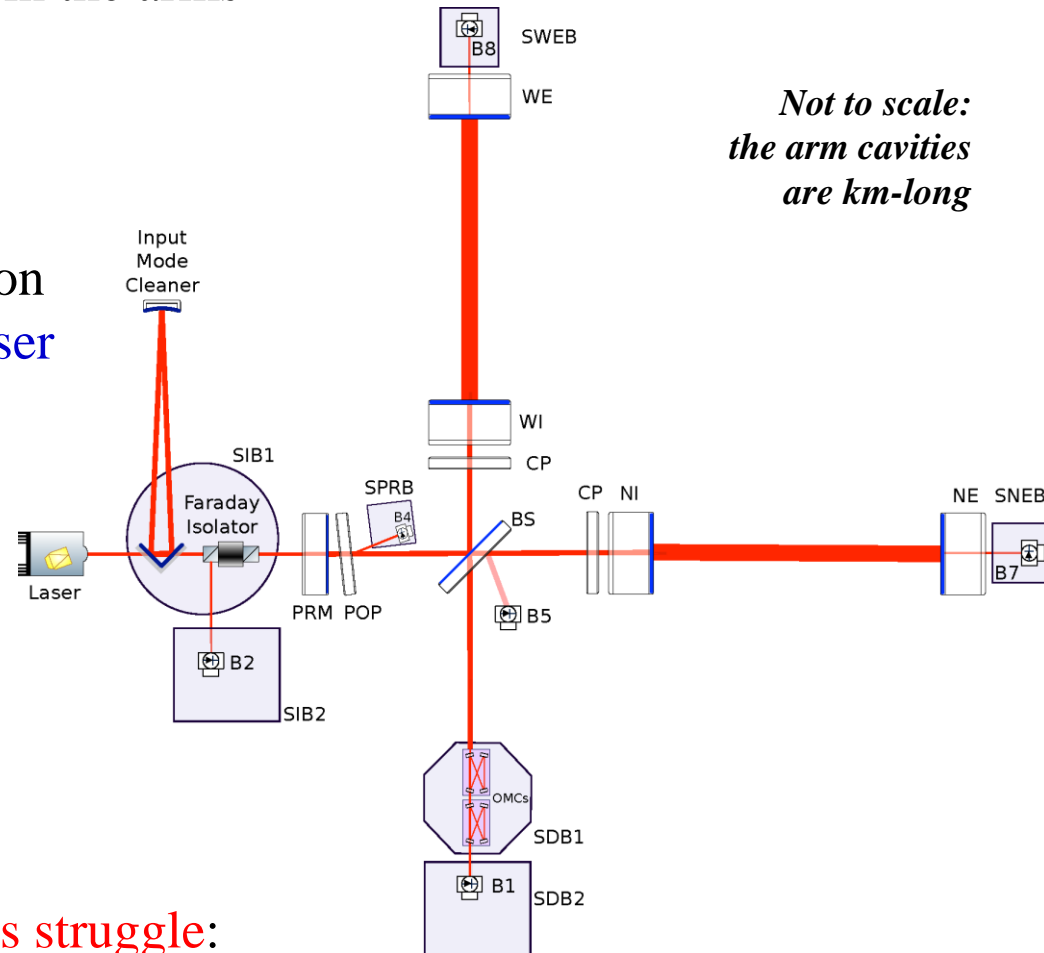
→ Change of interference condition at the detector output

→ 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*

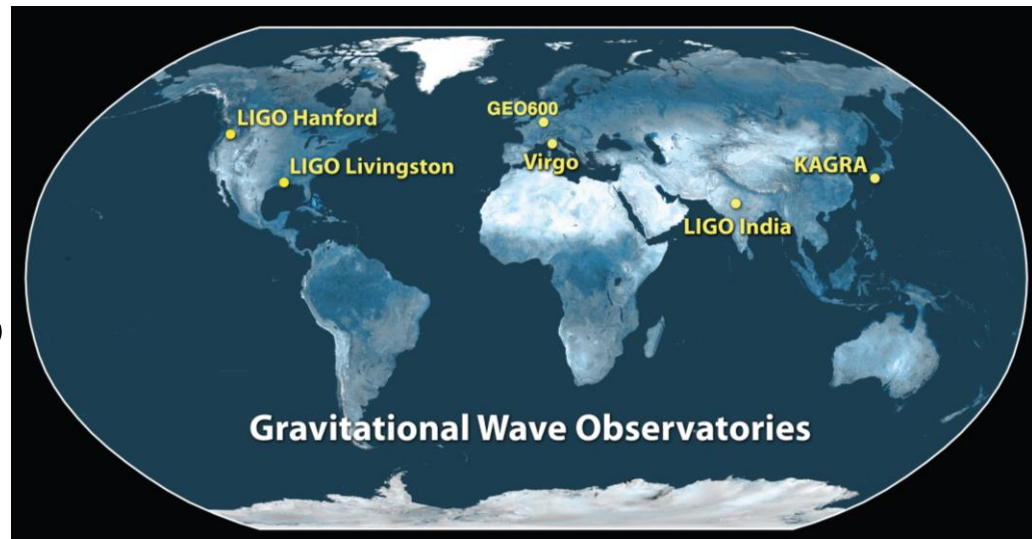
(* *LIGO detectors are conceptually the same*

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**

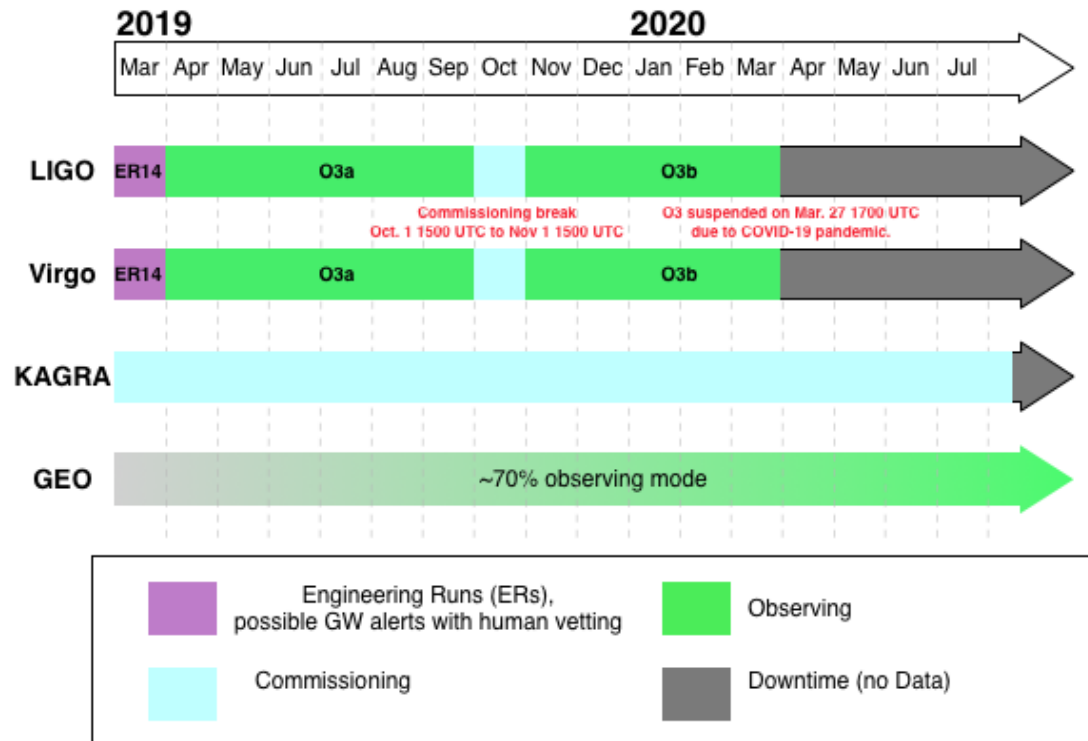
- 2nd generation: « **Advanced** »
 - ◆ **LIGO Hanford**: 2015
 - ◆ **LIGO Livingston**: 2015
 - ◆ **Virgo**: 2017
- **GEO-600**: « Astrowatch » + R&D
- **KAGRA**: 2020+
- **LIGO-India**: coming decade



- 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**

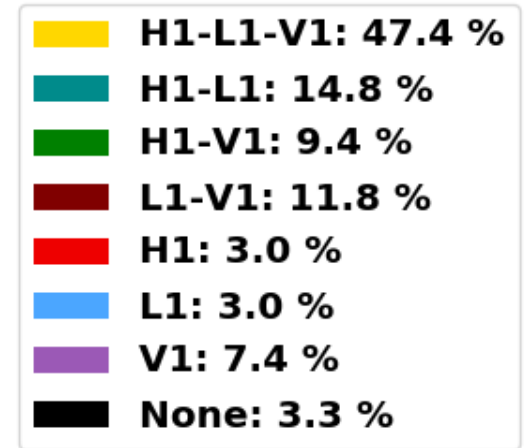
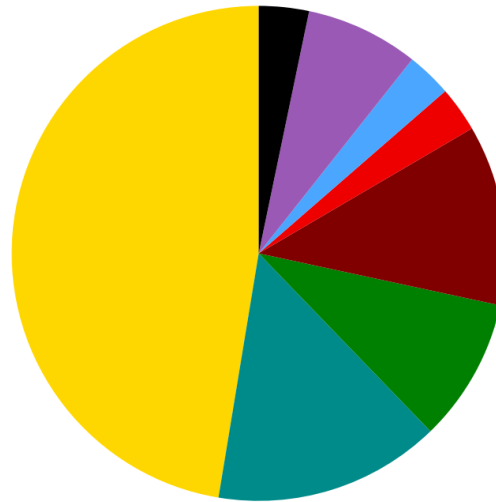
The O3 schedule

- **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**



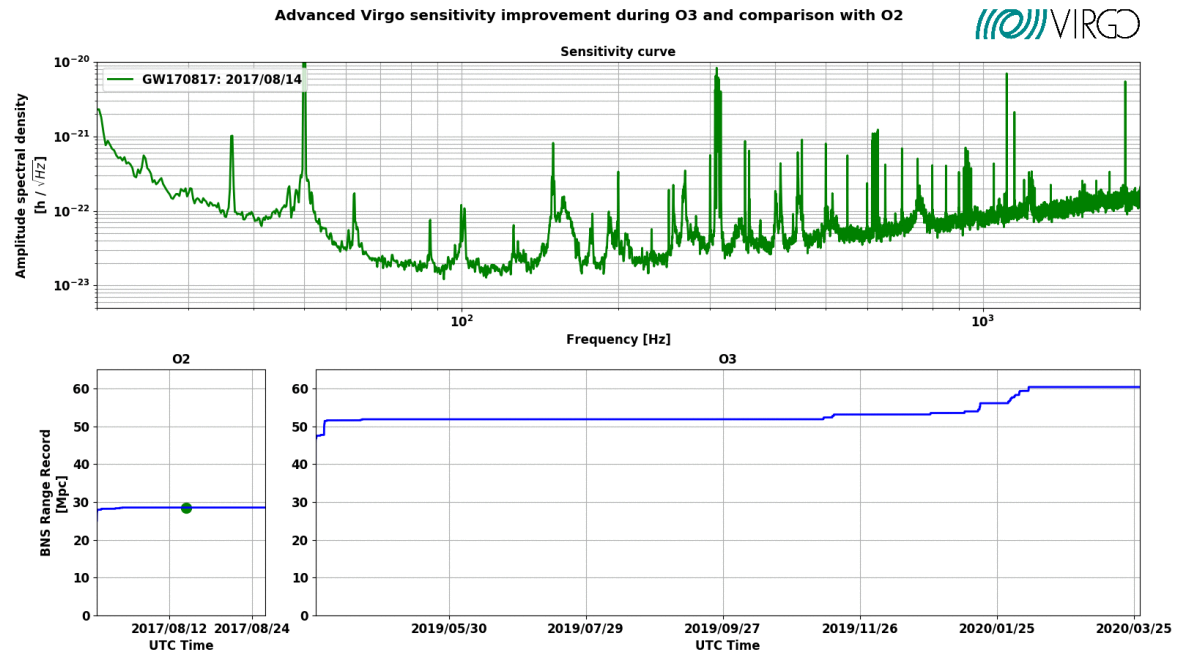
O3 performance

- 3-Detector network duty cycle



- O2-O3 sensitivity improvement for Virgo

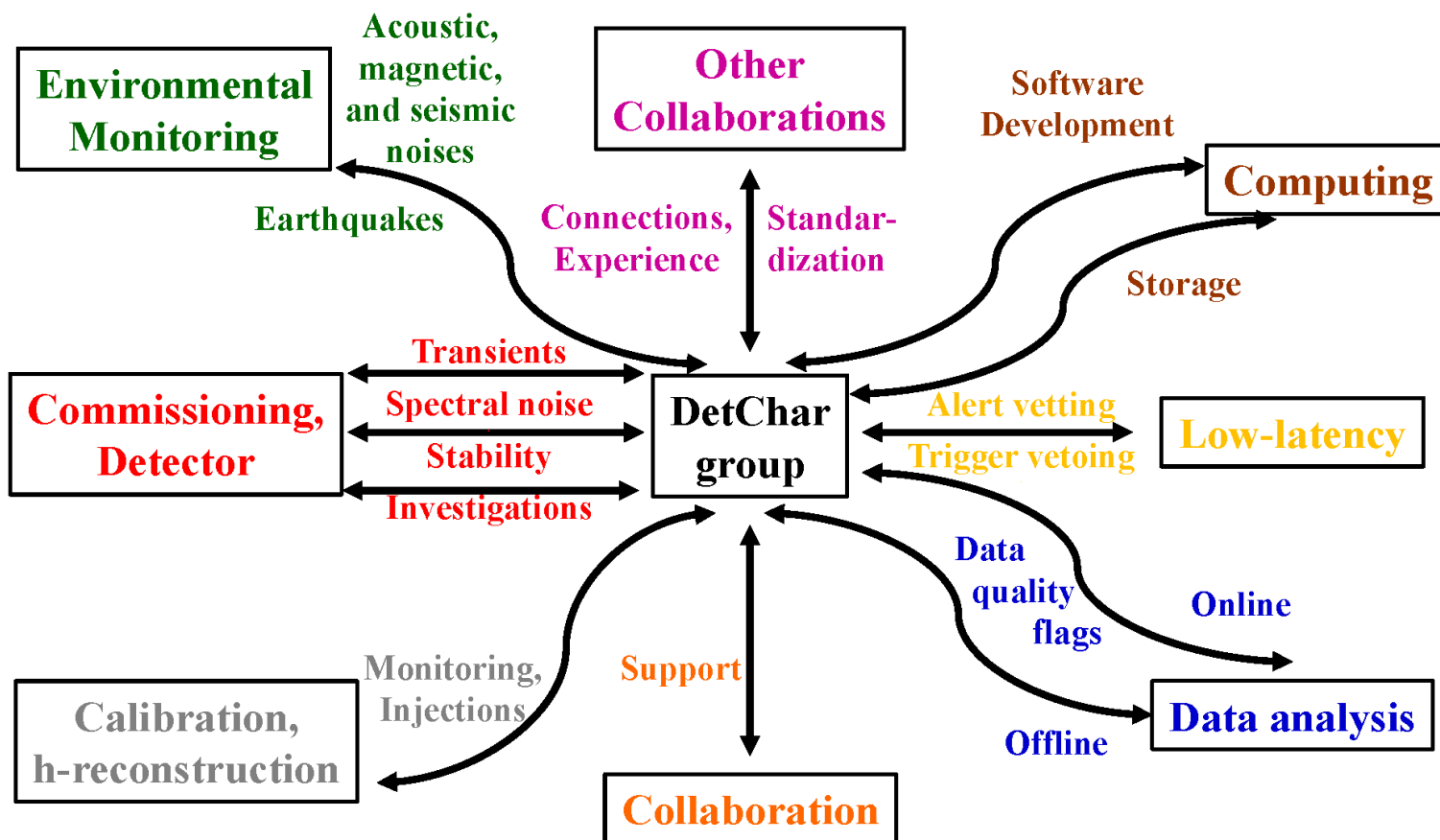
- Significant progress for the LIGO detectors as well



Detector characterization and data quality

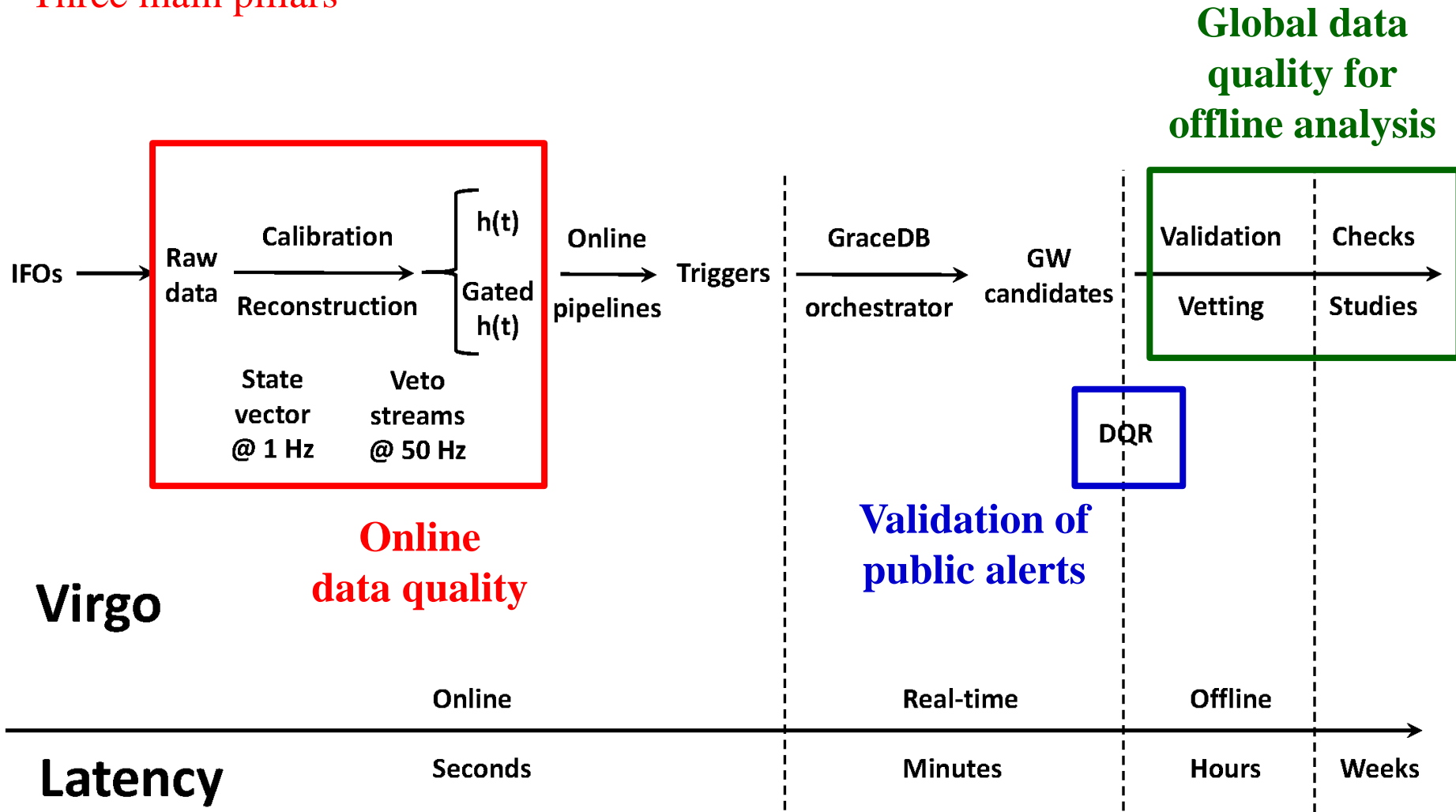
- « **DetChar** » groups
 - Experiment-specific but **collaborating closely**
 - ◆ Same goals, similar issues, tools sharing

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



Dataflow: from raw data to detections

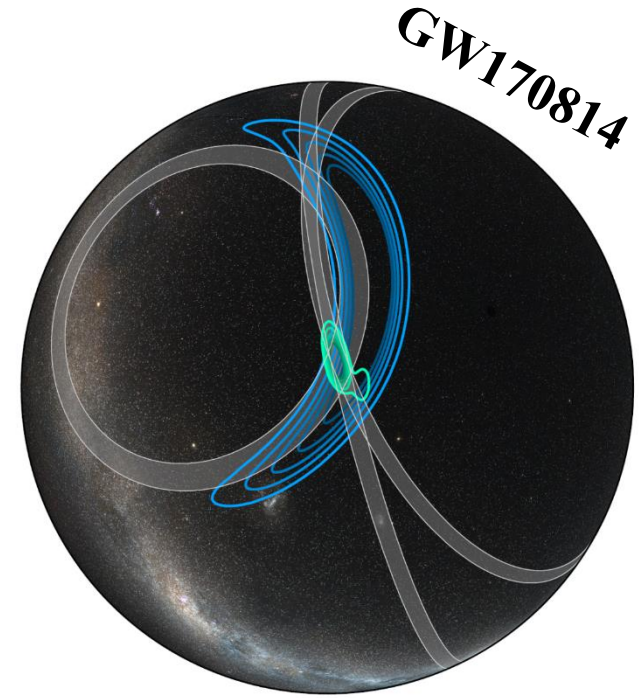
- Three main pillars



- Plus **monitoring**: online & offline products

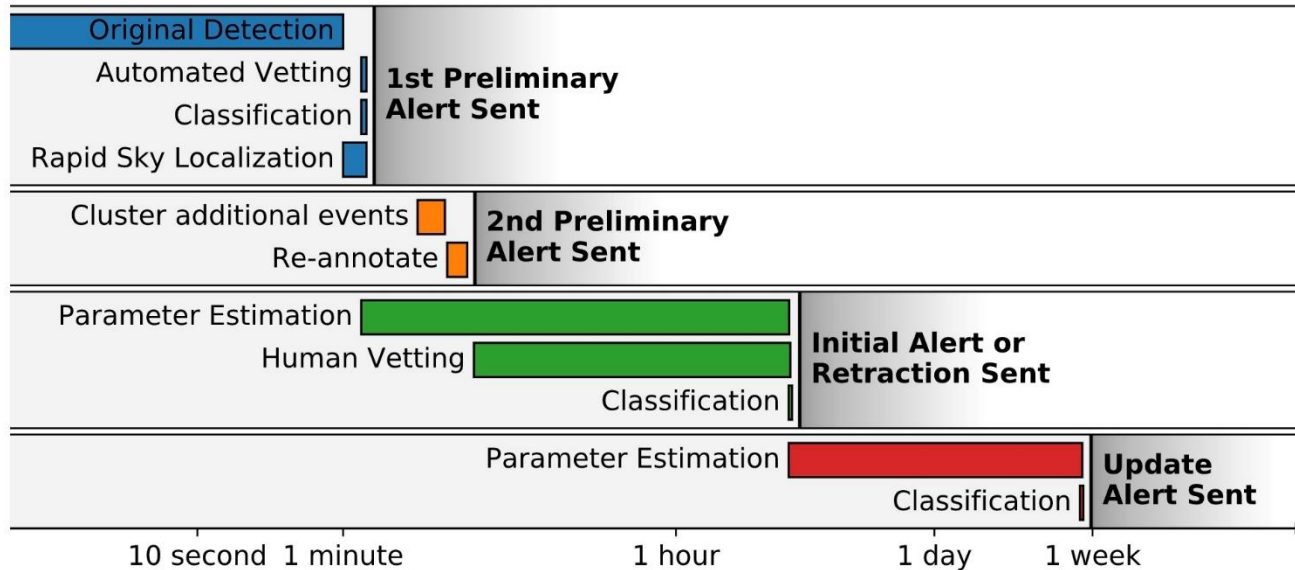
O3 public alerts

- 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 distortions**
- **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
- } O3 median values
- Quicker decision in average to retract an alert

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

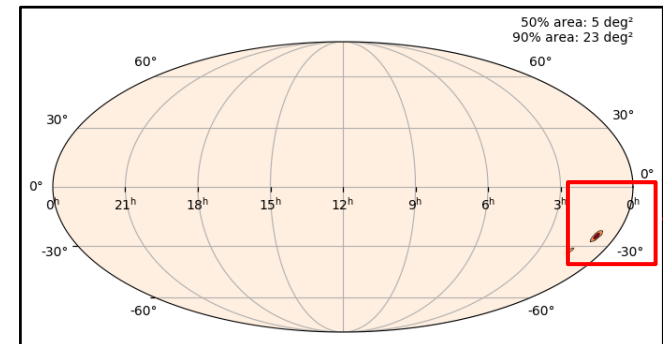
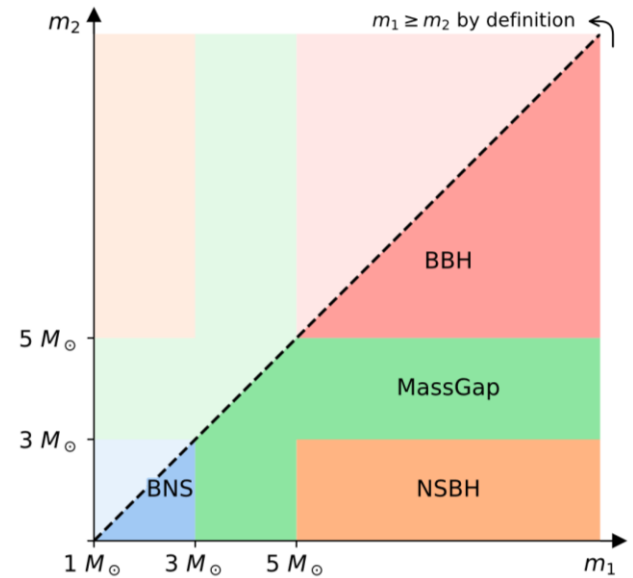
HOME PUBLIC ALERTS SEARCH LATEST DOCUMENTATION

LIGO/Virgo O3 Public Alerts

Detection candidates: 56

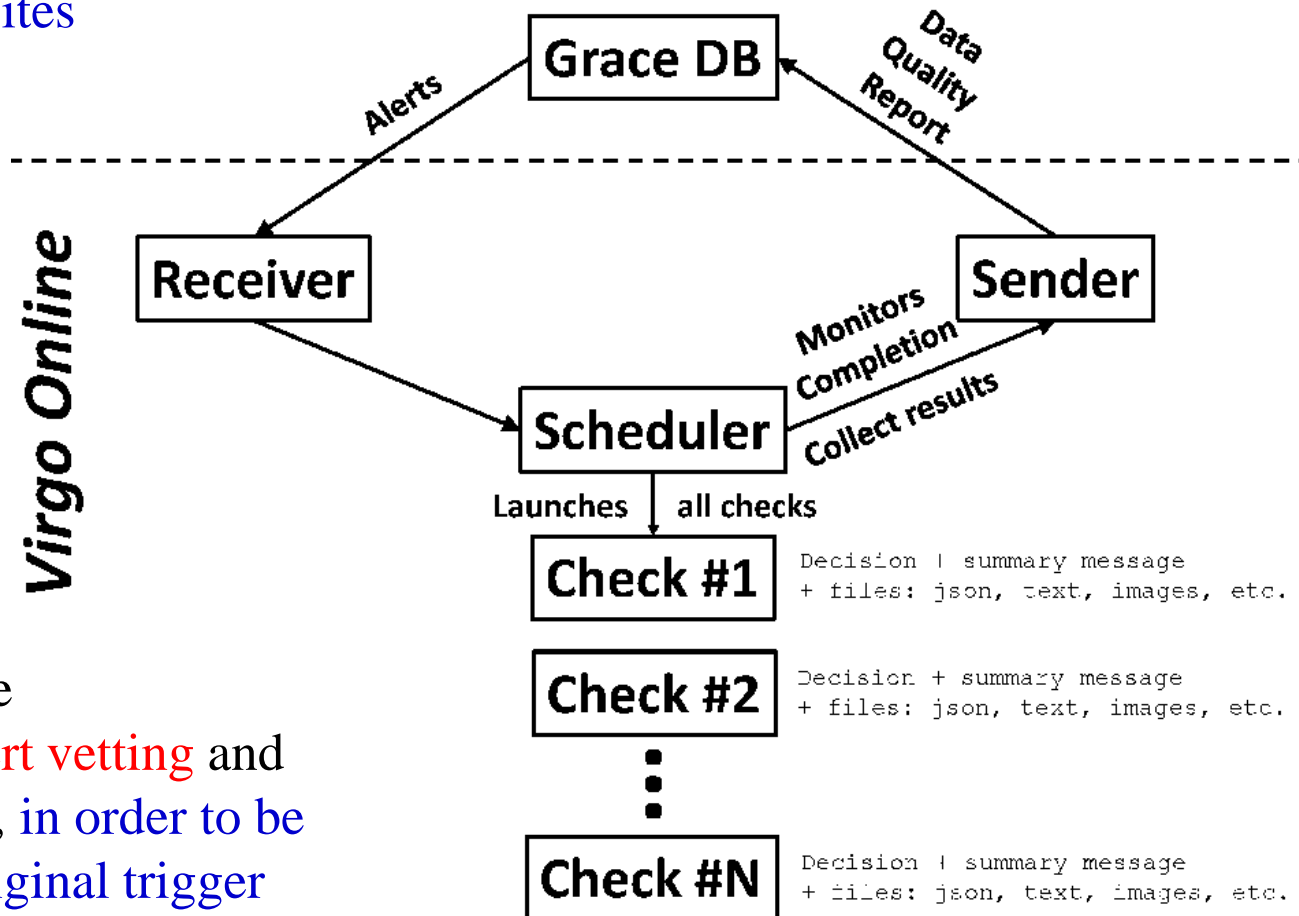
SORT: EVENT ID (A-Z)

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

Data Quality Report for S190814bv
Event: GPS = 1249852257.012957 (2019-08-14 21:10:39.012957+00:00 UTC) -- DQR generation starting at 2019-08-14 21:17:39+00:00 UTC

Clickable buttons: GraceDB event, GraceDB joint LIGO-Virgo DQR, Condor monitoring

Color caption: pass [Data OK], fail [Data not OK], human_input_needed [No automated decision], error or bad_state [Code crash or processing problem], missing [Check still running], higher latency tier

Virgo DQR documentation: Introduction, Checks, FAQ, Instructions for shifters and RRT, For experts

LIGO DQR documentation: Introduction

THE MOST IMPORTANT CHECKS: TO BE CHECKED FIRST

Brute-force coherence reports (bruco), Is the candidate GPS time in Virgo suspicious?, Status of the Virgo systems, UPV on last 24 hours

Virgo data quality antifiags, Virgo data quality flags, Virgo glitch characterization

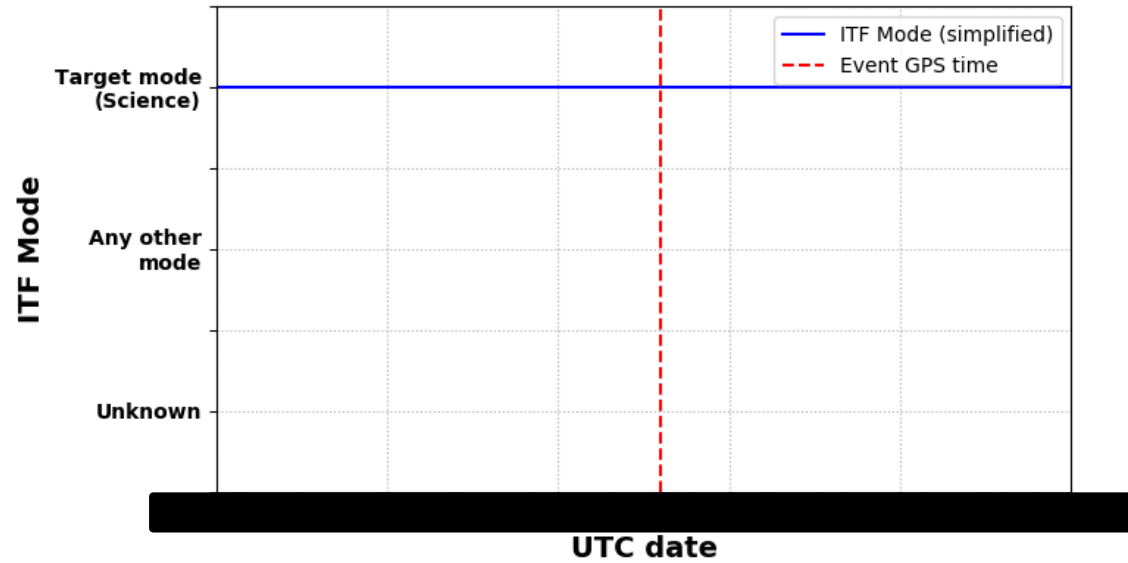
What was the Virgo noise stationarity while the candidate signal was observed?, What was the Virgo status while the candidate signal was observed?

What was the status of the environment around Virgo at the time of the candidate?

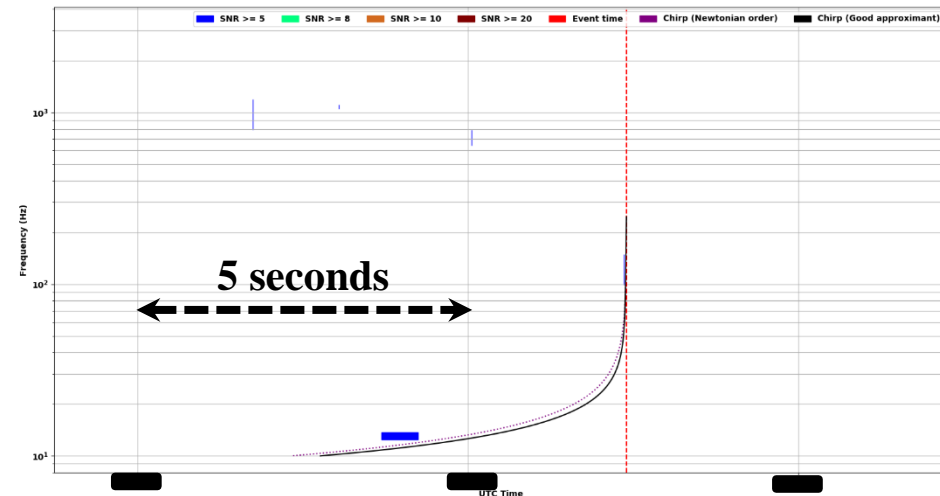
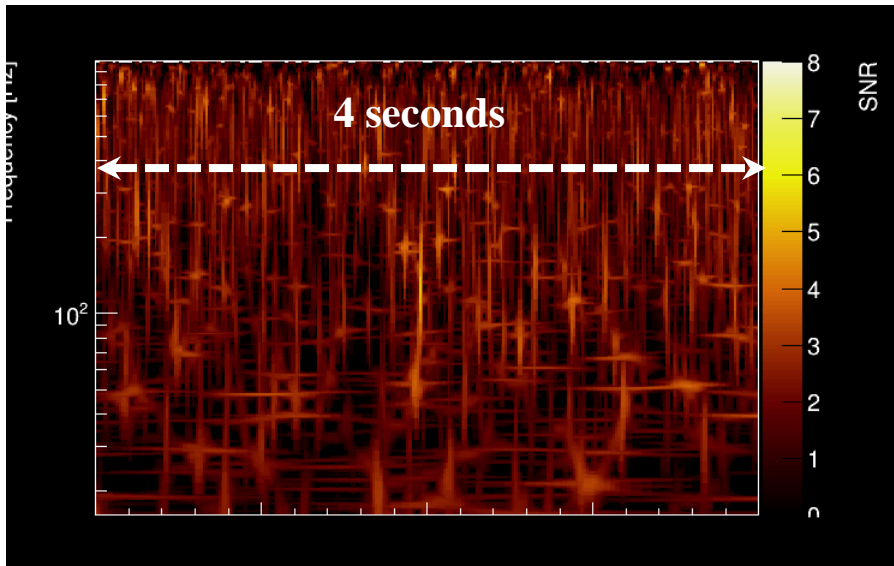
Virgo status (process: virgo_status) (V1)

Example: the Virgo data quality reports

- Virgo detector status



- Time-frequency spectrograms



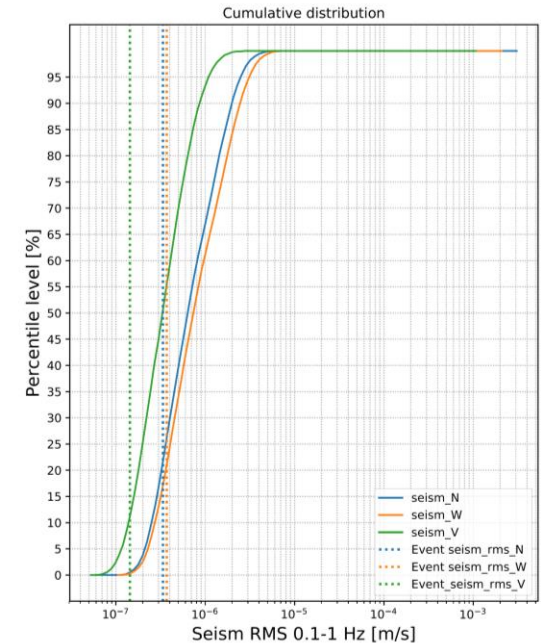
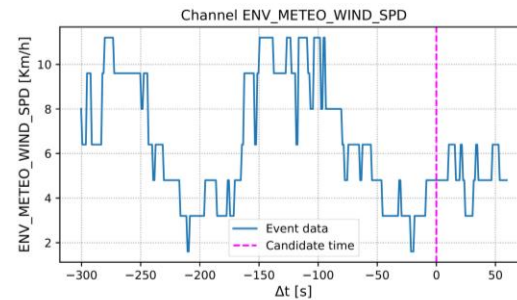
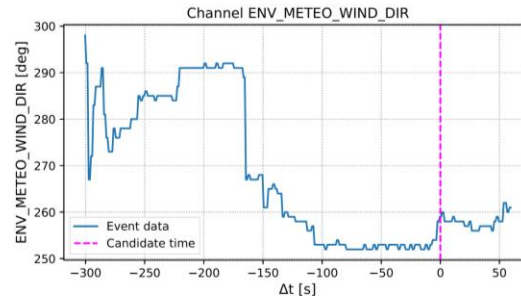
Example: the Virgo data quality reports

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

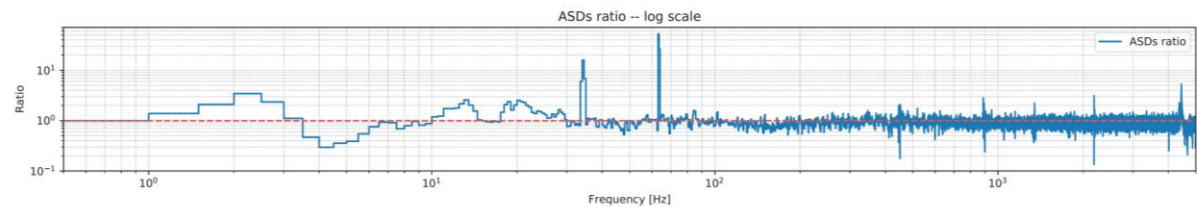
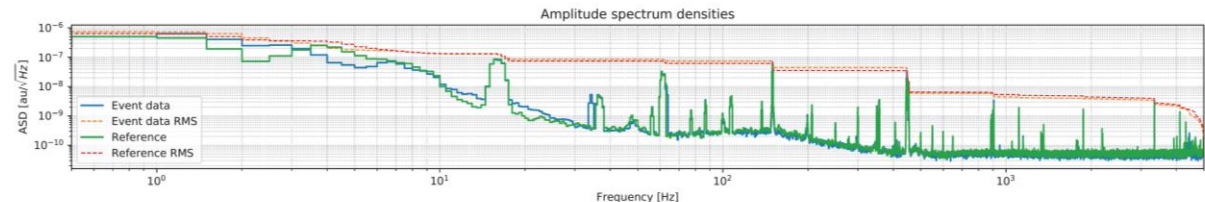
DMS												ITF Mode: Science (0d 1h 13m 14s)				ITF State: LOW_NOISE_3_SQZ (0d 0h 40m 49s)			
Injection	SIB1_IP		SIB1_BENCH		SIB1_BR		SIB1_Vert		SIB1_TE		SIB1_Guard		SIB1_Electr						
	MC_IP		MC_PAY		MC_BR		MC_Vert		MC_TE		MC_Guard		MC_Electr						
	Laser		LaserAmpli		LaserChiller		SL_TempController		RFC		LNFS		PC						
	MC_Power		PSTAB		IMC_AA		IMC_AA_GALVO		MC_F0_z		BPC		BPC_Electr						
Detection	PD		QPD_B1p		QPD_B2		QPD_B5		OMC		PicoDisable		Shutter						
	SDB1_IP		SDB1_LC		SDB1_BR		SDB1_Vert		SDB1_TE		SDB1_Guard		SDB1_Electr						
ISC	B2_8MHz_DPFI		B4_56MHz_DPFI		DARM_UGF		UNLOCK		SSFS_UGF		FmodErr		Etalon						
	GIPC		DARM_Corr		EQ_Mode		ViolinModes		50Hz_FF		ASC_rms		DIFFp_AA						
Suspensions	B1p_DC		B4_112MHz_MAG		B7_DC		B8_DC		LSC_rms		ASC_rms		DIFFp_AA						
	BS_IP		BS_F7		BS_PAY		BS_BR		BS_Vert		BS_TE		BS_Guard						
	BS_Vert		BS_Electr		BS_Guard		BS_Electr		NI_IP		NI_F7		NI_PAY						
	NI_IP		NI_F7		NI_PAY		NI_BR		NI_Vert		NI_TE		NI_Guard						
	NE_IP		NE_F7		NE_PAY		NE_BR		NE_Vert		NE_TE		NE_Guard						
	PR_IP		PR_F7		PR_PAY		PR_BR		PR_Vert		PR_TE		PR_Guard						
Environment	SR_IP		SR_F7		SR_PAY		SR_BR		SR_Vert		SR_TE		SR_Guard						
	WI_IP		WI_F7		WI_PAY		WI_BR		WI_Vert		WI_TE		WI_Guard						
	WE_IP		WE_F7		WE_PAY		WE_BR		WE_Vert		WE_TE		WE_Guard						
Infrastructures	CB_Hall		MC_Hall		TCS_zones		NE_Hall		WE_Hall		WindActivity		Seismon						
	BRMSMon		WAB		SeaActivity		Lights		DeadChannel		External		DAQ_Room						
SBE	INI_Area		DET_Area		EE_Room		ACS_TB		ACS_DAO_Room		ACS_EE_Room		ACS_MC						
	ACS_CB_Hall		ACS_TCS_CHILROK		ACS_TB		ACS_DAO_Room		ACS_EE_Room		ACS_MC		ACS_INJ						
TCS	UPS_TB		UPS_CB		UPS_MC		UPS_NE		UPS_WE		FlatChannel		ExistChannel						
	ACS_WE		ACS_CB_CR		ACS_COB		SWEB_SBE		SWEB_LC		SPRB_SBE		SPRB_LC						
SQZ	EIB_SBE		SDB2_SBE		SDB2_LC		SNEB_SBE		SNEB_LC		SWEB_SBE		SWEB_LC						
	NE_RH		WE_RH		NI_CO2_Laser		WI_CO2_Laser		Chillers		TCS_Electr		TCS_Electr						
Vacuum	PLL		Squeezer		SQZ_AA		SQZ_Shutter		Cohe_CTRL		SQZ_Inj		Rack_TE						
	LargeValves		Clean_Air		TubeStations		TubePumps		MiniTowers		TurboLinks		RemDryPMP						
VPM	Pressure		CompressedAir		TowerServers		TowerPumps		CryoTrap		O2_Sensors		Tank						
	HLS		VPM		DetectorEnvironment		ControlRoom		Minitowers		ISC		Injection						
DAQ-Computing	TCS		Suspension		Vacuum		Metatron		DataCollection		Storage		DataAccess						
	Automation		DetChar		LowLatencyDataTransfer-RealLiveData		BroadcastOnlineDataForCWB		Latency		Disk		Timing						
Calib_Hrec	CalNE		CalWE		CalINJ		CalBS		CalPR		PCalNE		PCalWE						
	HOFT		NCAL		NoiseInjection		ITFOnCall		SoftwareAl		TemperaturesAl		InjectionAl						
DetChar-Ex.Trigger	Hrec_RANGE_BNS		GraceDB_Alert		GRB_Alert		KAMLAND_Alert		SNEWS_Alert		STATE_VECTOR		TcsAl						
	Hrec_RANGE_BNS		GraceDB_Alert		GRB_Alert		KAMLAND_Alert		SNEWS_Alert		STATE_VECTOR		TcsAl						

Example: the Virgo data quality reports

- Environment
 - Wind and seismic motion



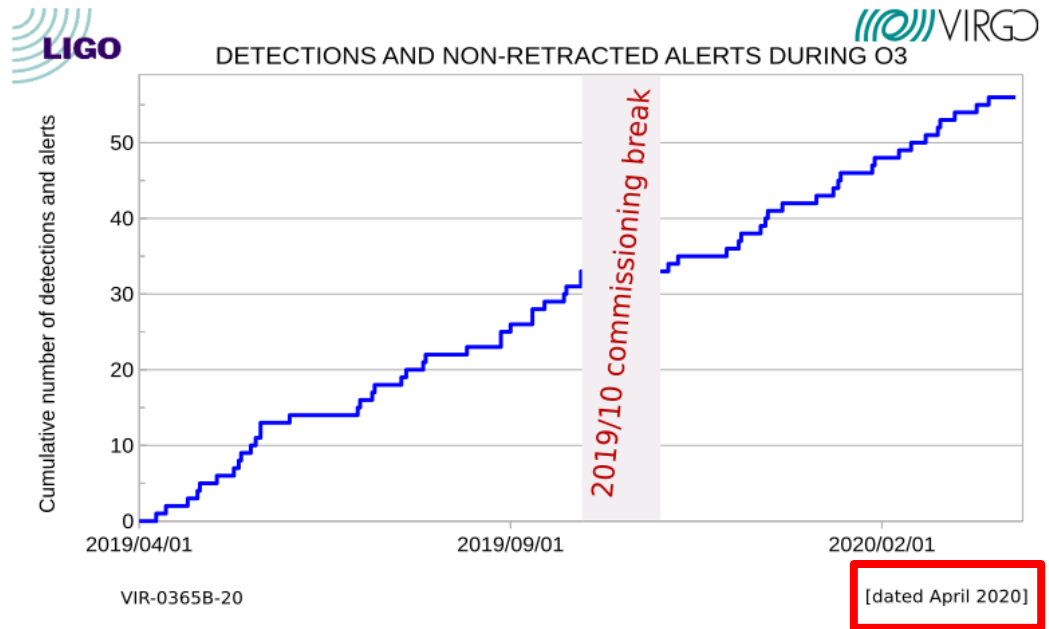
- Control signal spectra
 - Comparison to reference



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

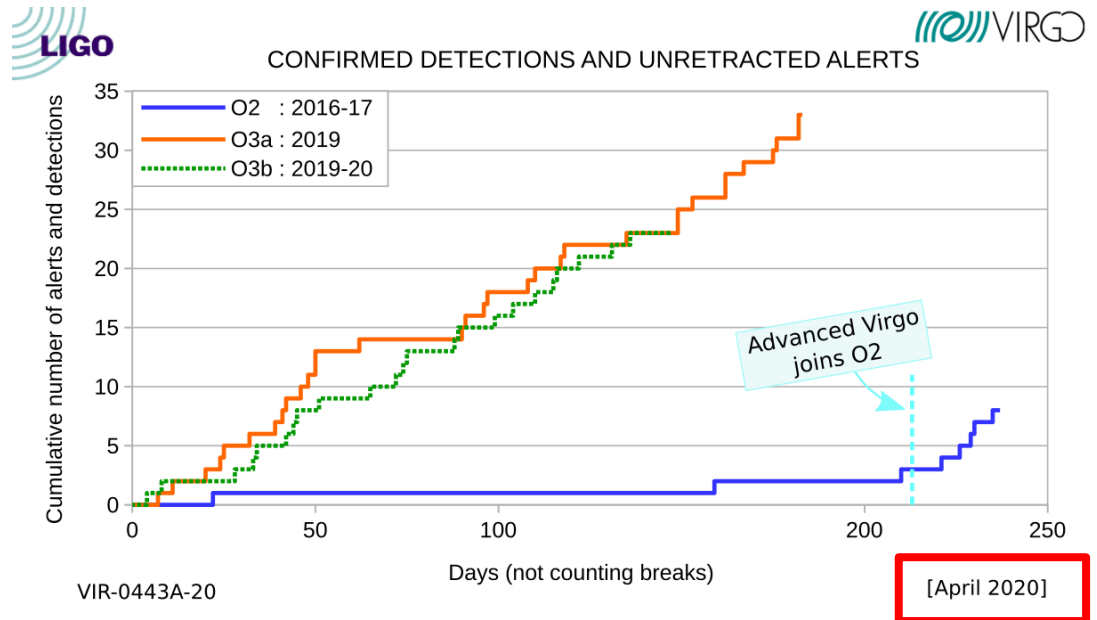
O3 public alerts

- 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



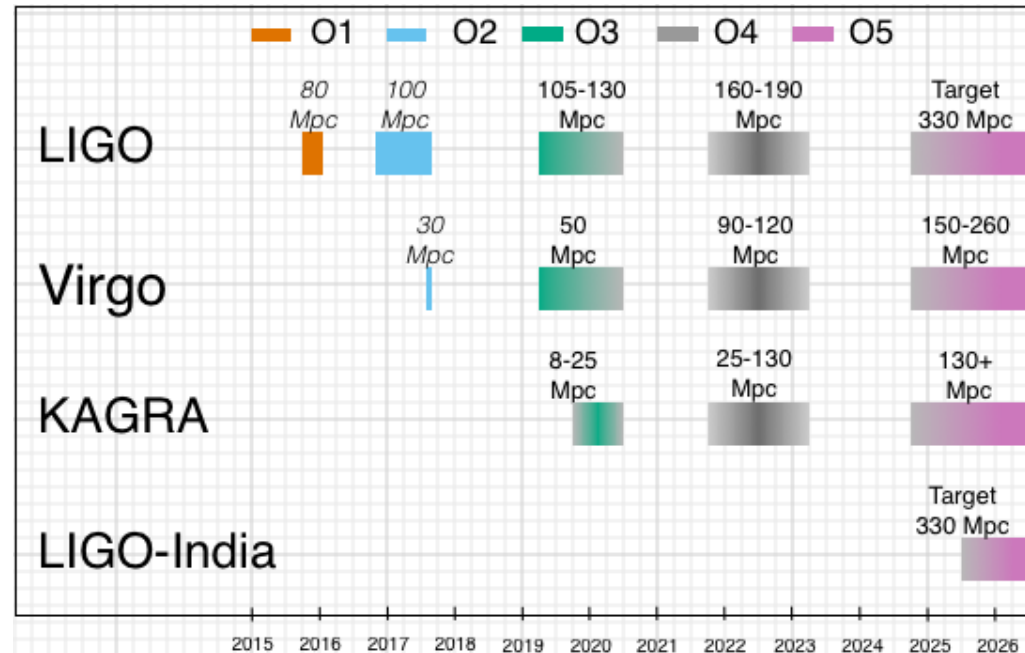
First published detections from O3

- **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 asymmetric 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

