Virgo detector characterization activities during the O3 run from latency to gravitational-wave event validation

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On behalf of the Virgo Collaboration

VIR-0250A-19

EGO EUROPEAN GRAVITATIONAL OBSERVATORY   cnrs   LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE   UNIVERSITÉ PARIS SUD université PARIS-SACLAY

Outline

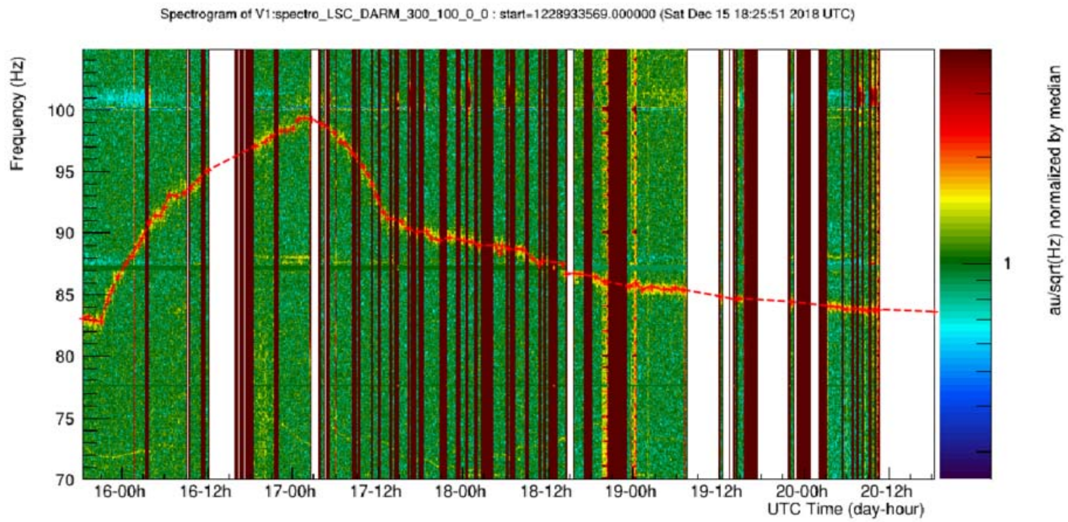
- Introduction
- Highlights
  and challenges
- DetChar in the O3 run
- Conclusions

- In the following I will focus on the Virgo Detector Characterization, but the equivalent group exists in LIGO and is extremely active
  - We are working together: common calls, joint projects, visitors, etc.
  - We are also working with KAGRA to help them setting up their DetChar group

Detector Characterization (DetChar) in a nutshell

Detector Characterization: DetChar

- Detector monitoring



- Detector noise characterization
  - Transient and spectral
  - Noise evolution: it is not stationary!

- Several partners

  → Commissioning & noise hunting
    - Data quality analysis

  → Search groups
    - Data quality information
    - Vetoes: time and frequency domains

  → DAQ / computing
    - Access to flags and vetoes for online and offline analysis

  → Physics groups
    - Vet gravitational-wave (GW) candidates

- Virgo DetChar group
  - About 5 FTE spread among O(20) people
  - Weekly meeting attendance: 15-20 participants on average

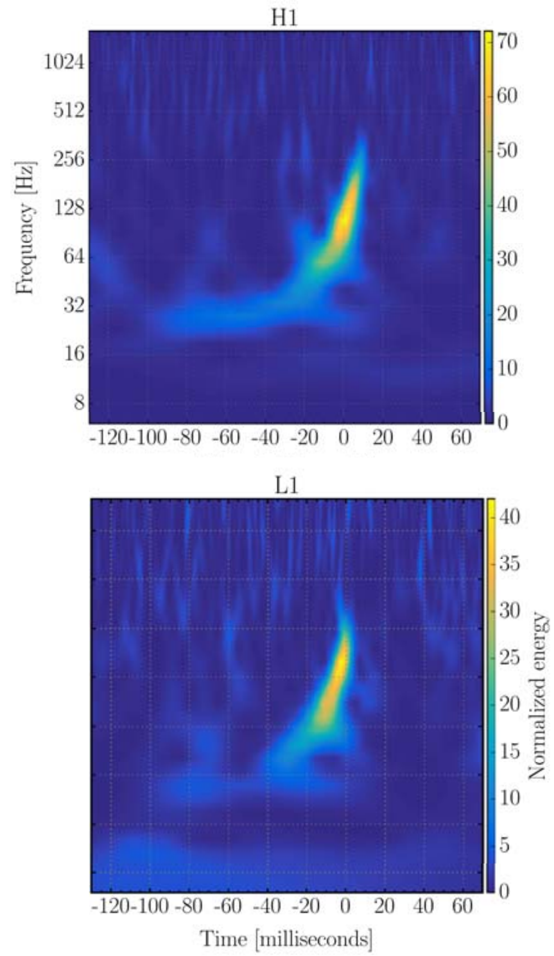
Highlights and challenges

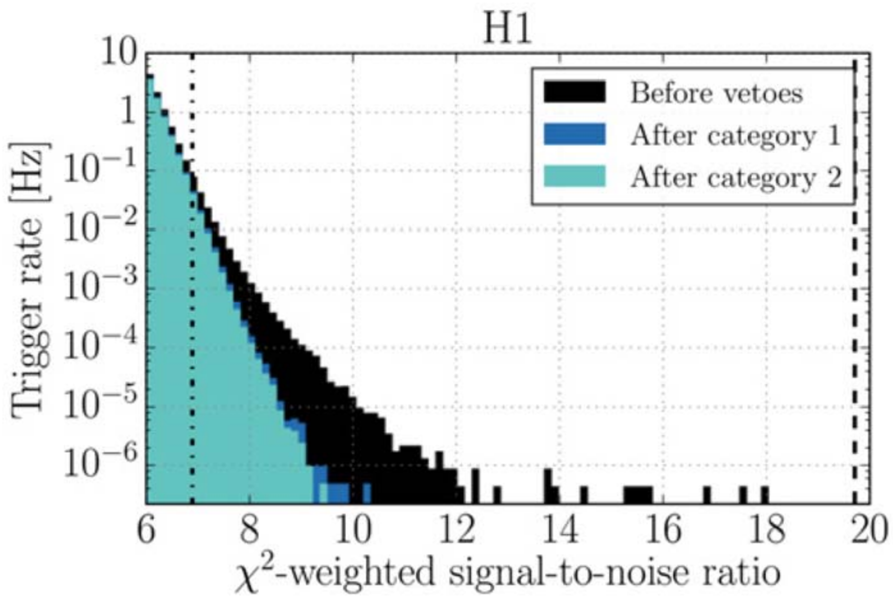
GW150914

- GW150914: first direct detection of gravitational waves
  - Data recorded: September 15th, 2015
  - Announcement: February 11th, 2016
  - → 5 month-work to acquire enough confidence that this event was a real binary black merger of astrophysical origin

- DetChar companion paper to go along the announcement
  - DetChar strategy: identifying and mitigating noise sources
  - Pipeline background studies
  - Extensive studies of the data around GW150914

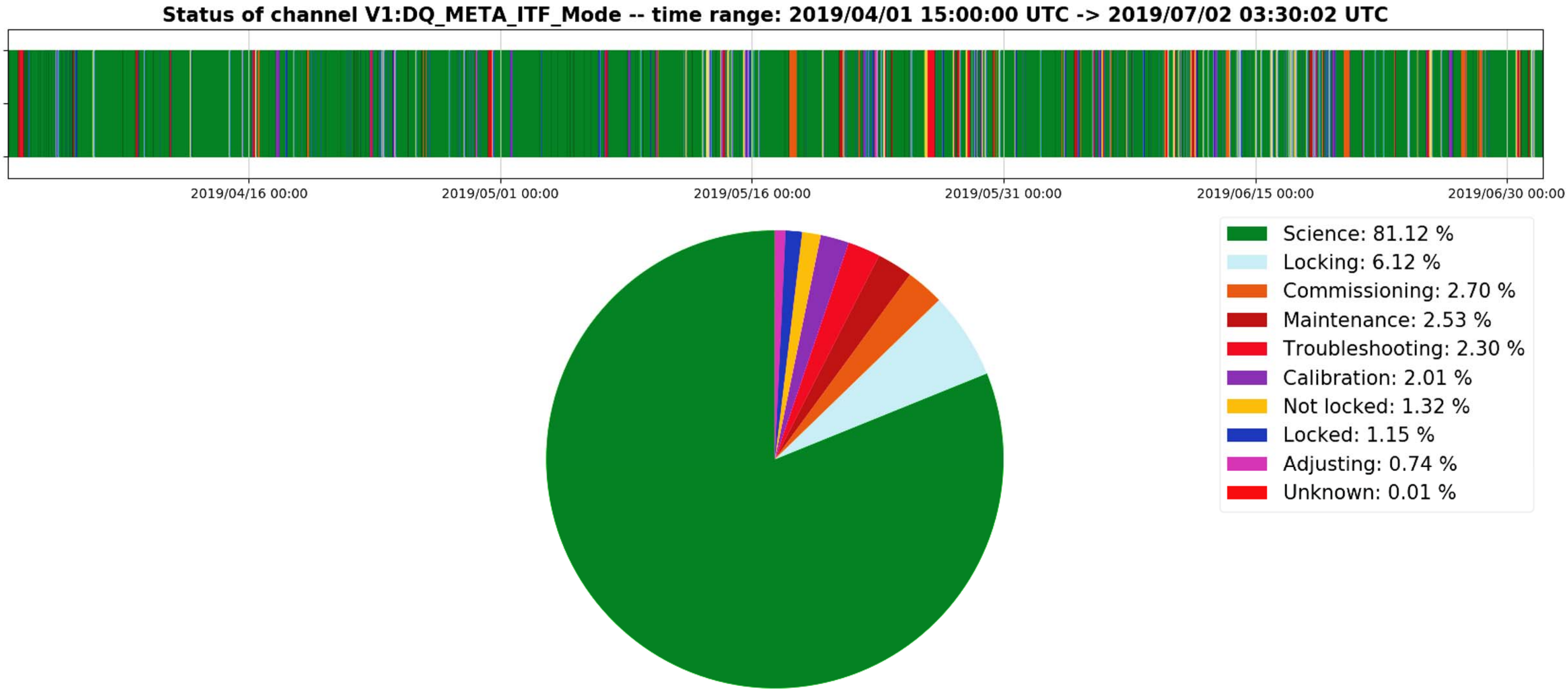
- Reference:
  [Class. Quantum Grav. 33 (2016) 134001]





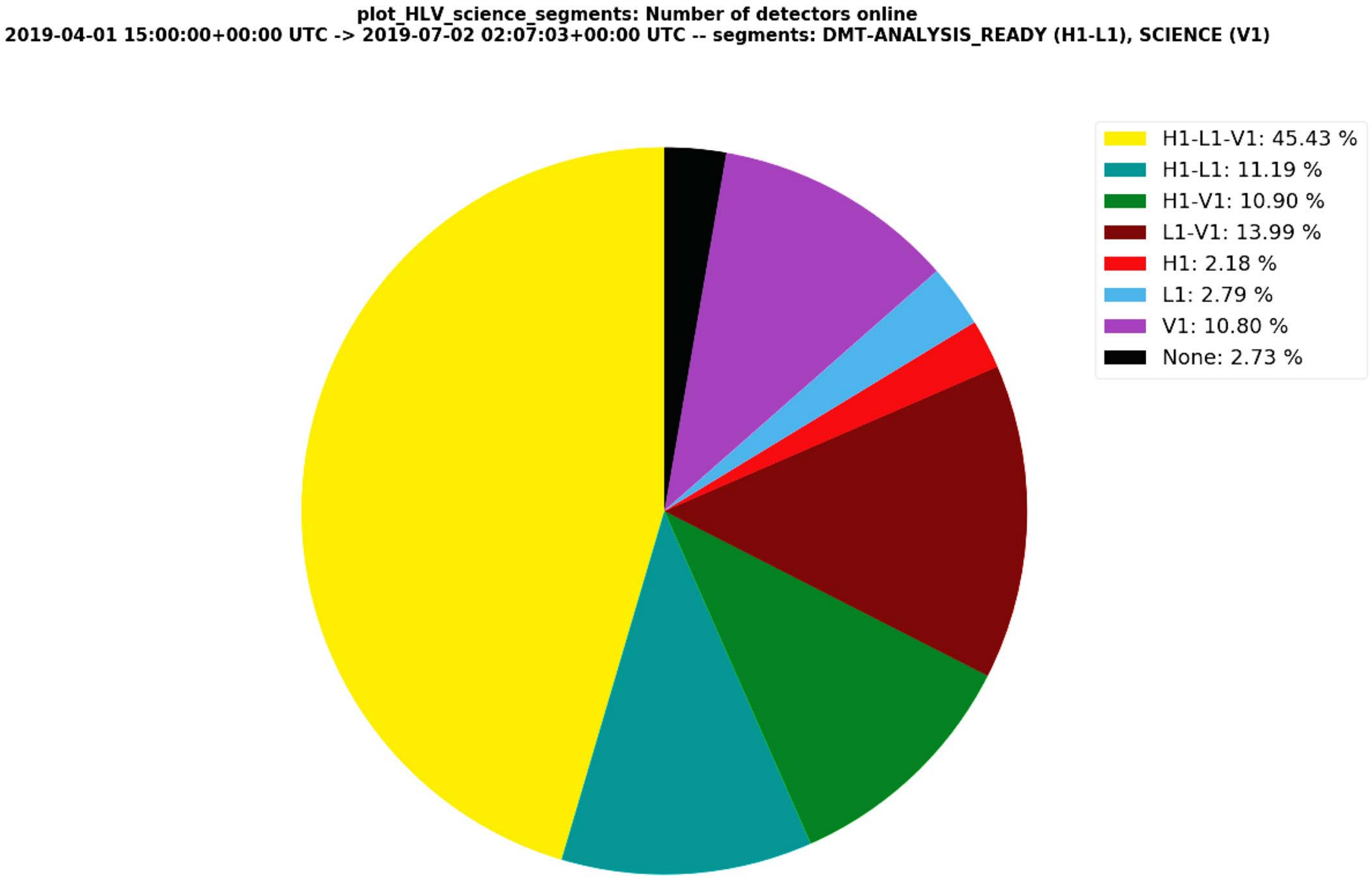
Global 3-detector running

- Individual detector duty cycle: example of Virgo



Global 3-detector running

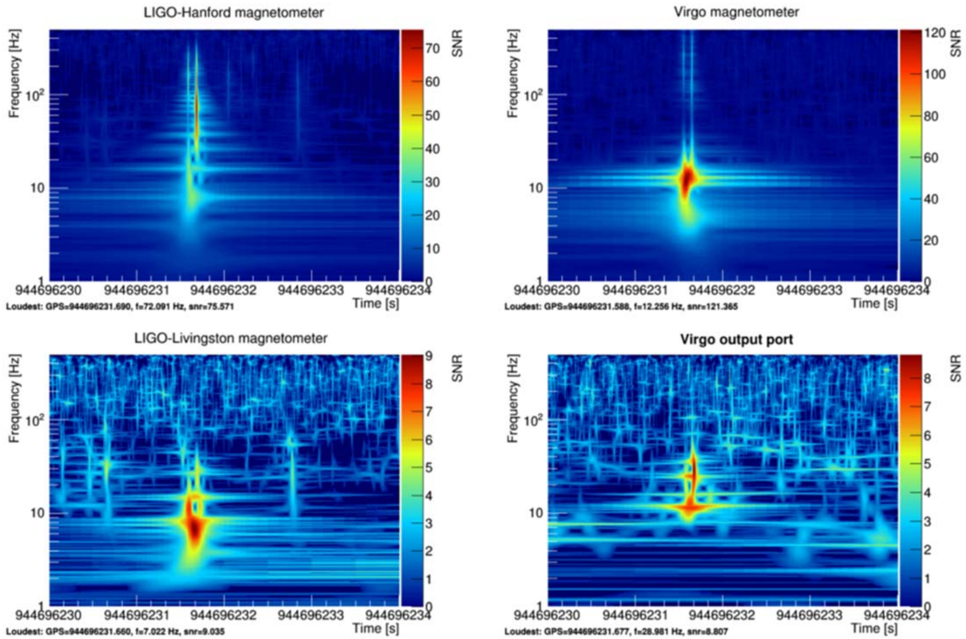
- Network duty cycle



Schumann resonances

- Global electromagnetic resonances of the Earth-ionosphere ‘waveguide’
  - Extremely low-frequency
  - Generated and excited by lightning
  - Magnetic fields coherent over global distances

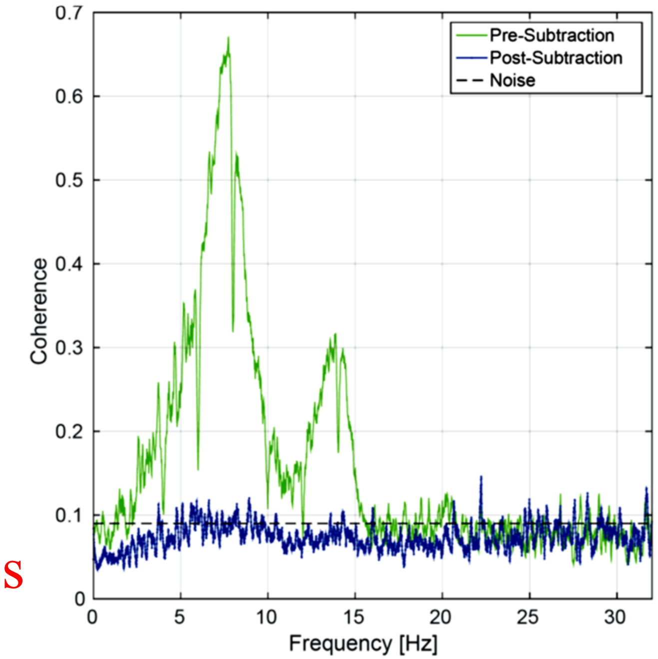
→ Potential issue for stochastic background searches



- Use data from a network of magnetometers
  - At GW detector locations
  - At other sites (magnetically quiet)

  → Compute correlations

  → Remove them using Wiener filtering techniques



- References: Class. Quantum Grav. 33 (2016) 224003 [arXiv:1606.01011]
  Class. Quantum Grav. 34 (2017) 074002 [arXiv:1612.01102]
  Phys. Rev. D 97, 102007 (2018) [arXiv:1802.00885]

Observation run 3

- April 1st 2019: start of Observation run 3
  - One year of global network data taking
  - Three detectors initially: LIGO Hanford, LIGO Livingston, Virgo
    - KAGRA should join the network during O3
      → 4-detector configuration for the first time!

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
S190701ah	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246048403.576563	1246048404.577637	1246048405.814941	1.916e-08	2019-07-01 20:33:24 UTC
S190630ag	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1245955942.175325	1245955943.179550	1245955944.183184	1.435e-13	2019-06-30 18:52:28 UTC
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

- Open public alerts
  - Lowest possible latency
  - Preceed vetting in most cases
    → Possible retractions at a later stage
    - Automate tasks as much as possible
      → More events: compact binary coalescences (black holes, neutron stars), etc.

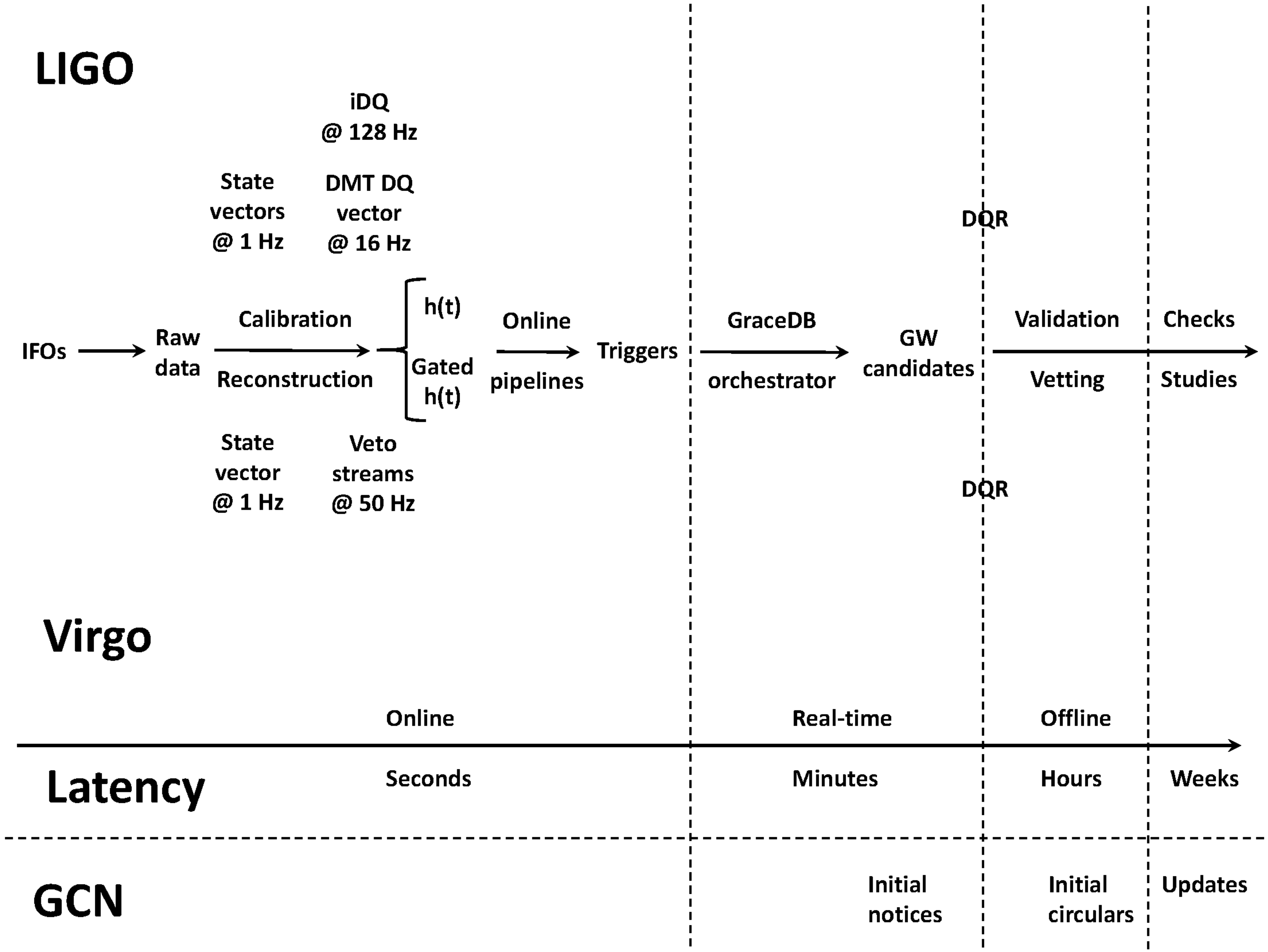
Open data releases

- Gravitational Wave Open Science Center
- Data public around each event when published
- Current policy: given dataset published 18 months after data taking is over
  → Tough schedule for the LIGO and Virgo collaborations
    - (Re)processings, analysis, validation, publication
  - O2 data to be released in a couple of weeks
- Tens of projects already based on LIGO-Virgo open data
  - At all scientific levels, art & science, etc.
- Goal: users should be able to reproduce LIGO-Virgo results
  → Document everything
    - For scientific consistency and with future open data releases in mind

Virgo DetChar in the O3 era

Dataflow

- From the detectors, to the offline validation of online events



State Vector

- Live interferometer status
  - 1 Hz channel
  - Bit structure
- Bits 0-1: science data taking
- Bit 10: online data quality assessment
  - 1 ⇔ Data OK
  - 0 ⇔ Data is bad
  - Inputs: saturation flags
    - Output port photodiodes
    - Suspension coil drivers
    - DARM (differential Fabry-Perot arm length) glitch rate

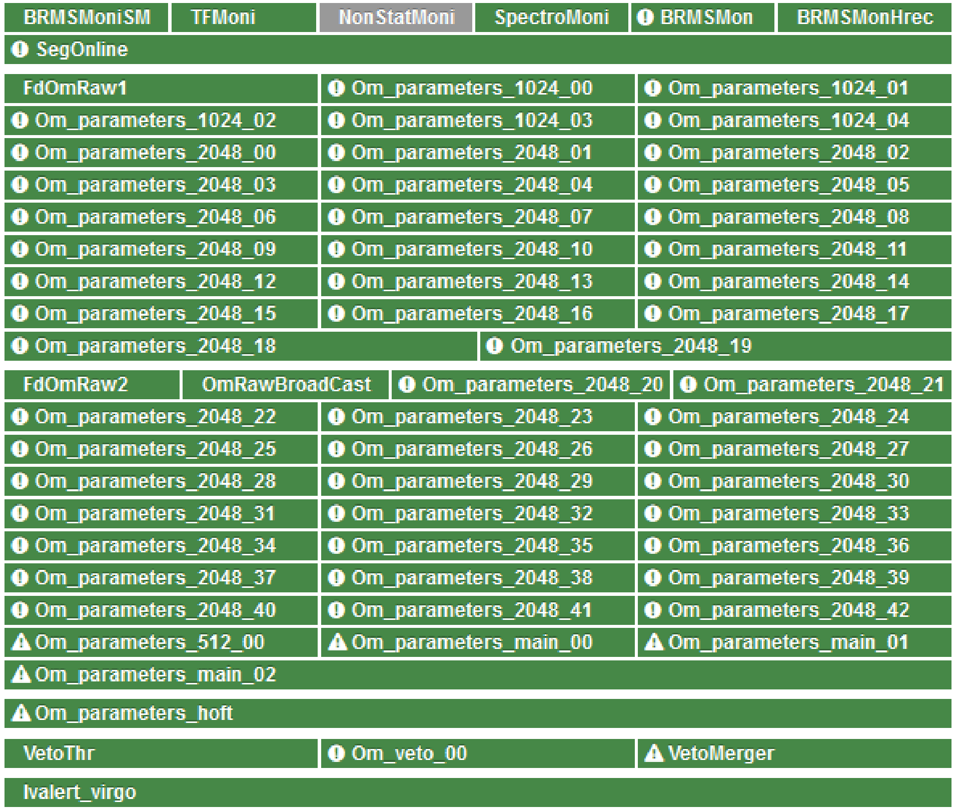
0: h(t) was successfully computed
1: science mode button is pushed
2: observation ready
3: h(t) was produced by the calibration pipeline
4: calibration filters settled in
5: No stochastic HW injections
6: No CBC HW injection
7: No burst HW injection
8: No HW injections for detector characterization
9: No continuous wave HW injection
10: good data quality (CAT1 type)
11: interferometer is locked

- Constant monitoring of the SCIENCE segments
  - State Vector should match information from the Virgo automated control system
- Bit 10 is only flagging a very small fraction of the data

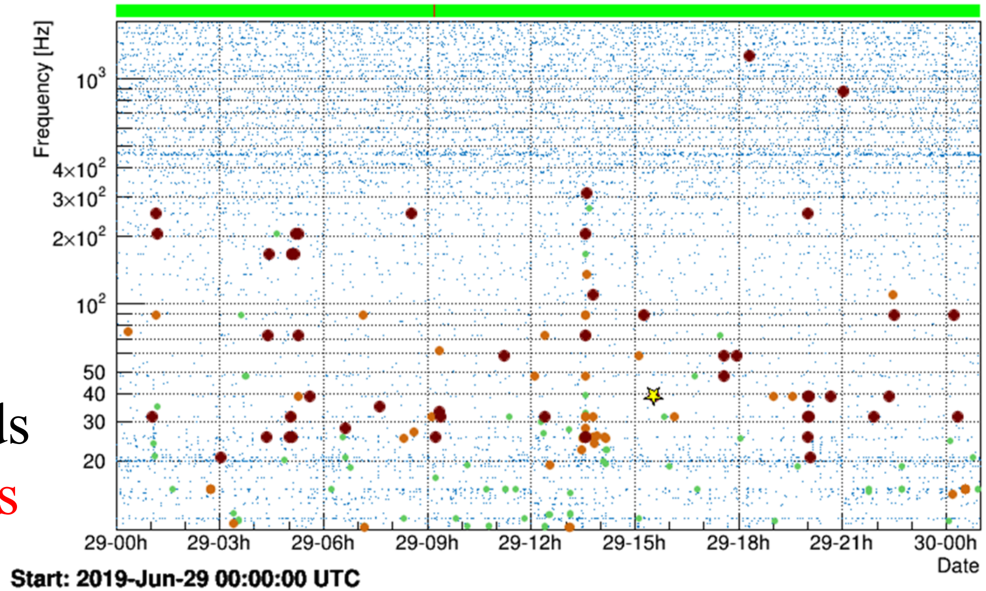
Glitches

- Omicron tool
  - 400 channels processed online
  - 3,000 channels reprocessed offline
  - Based on the Q-transform: overcomplete basis of sinusoidal Gaussian functions
    - Glitches defined by {time, frequency, SNR}

→ Reference: public Virgo note



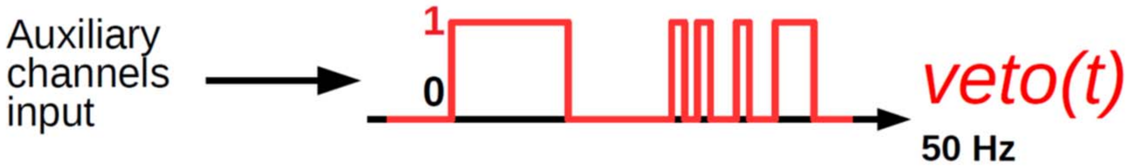
- Two main channels
  - h(t)
  - DARM

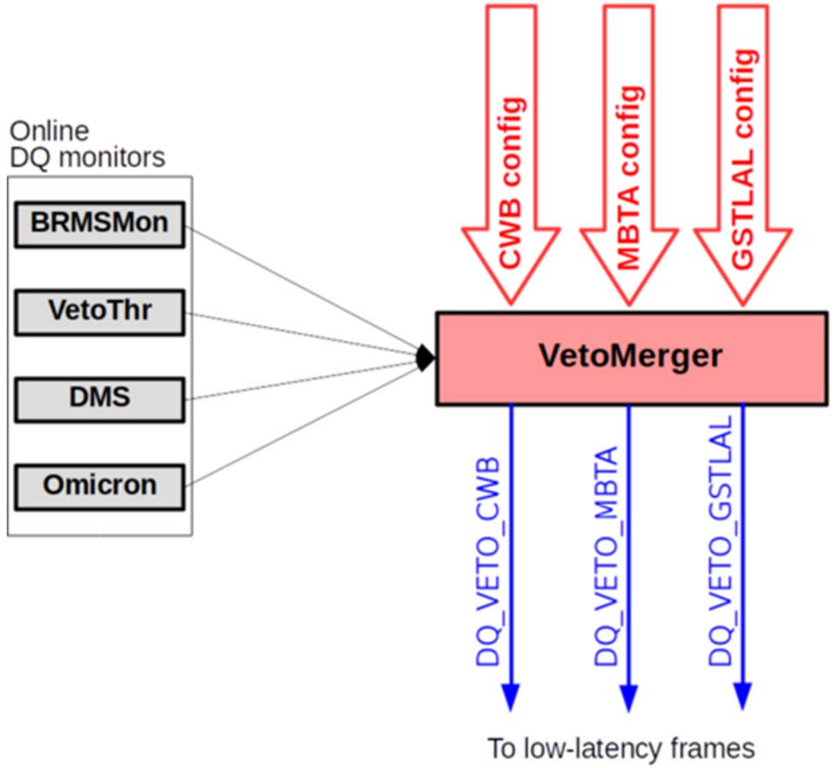


- Analysis window
  - Gating + windowing applied on both ends
  - Only central part used to produce triggers
  - Overlap between analysis windows

Veto streams

- Goal: reject online triggers likely due to glitches
  - 50 Hz channels
  - Veto flags: 1 ↔ veto 0 ↔ pass



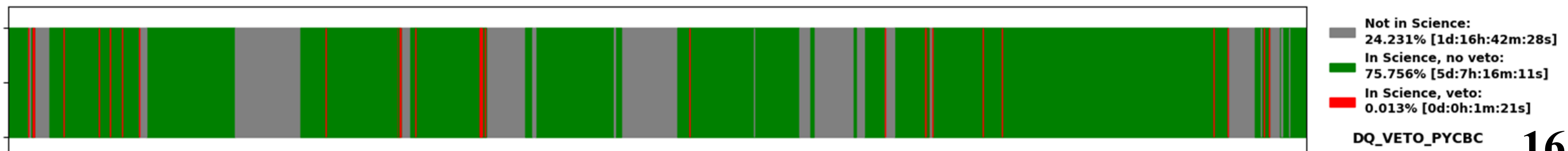


  - Inputs: all data quality flags available online
  - One stream per pipeline
    - Pipeline-specific configurations

Burst V1:DQ_VETO_CWB

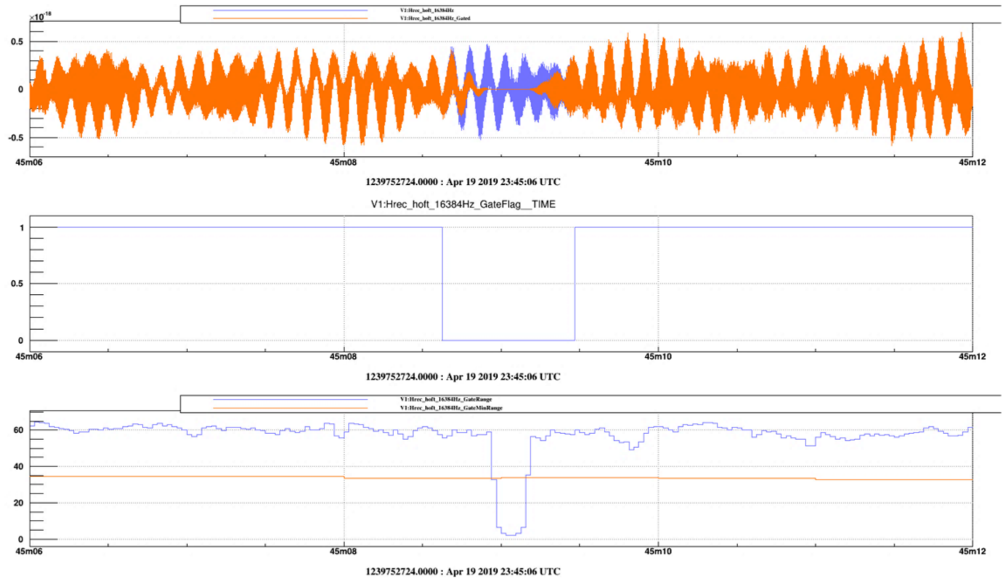
CBC V1:DQ_VETO_GSTLAL
V1:DQ_VETO_MBTA
V1:DQ_VETO_PYCBC → Being tested on live data

…



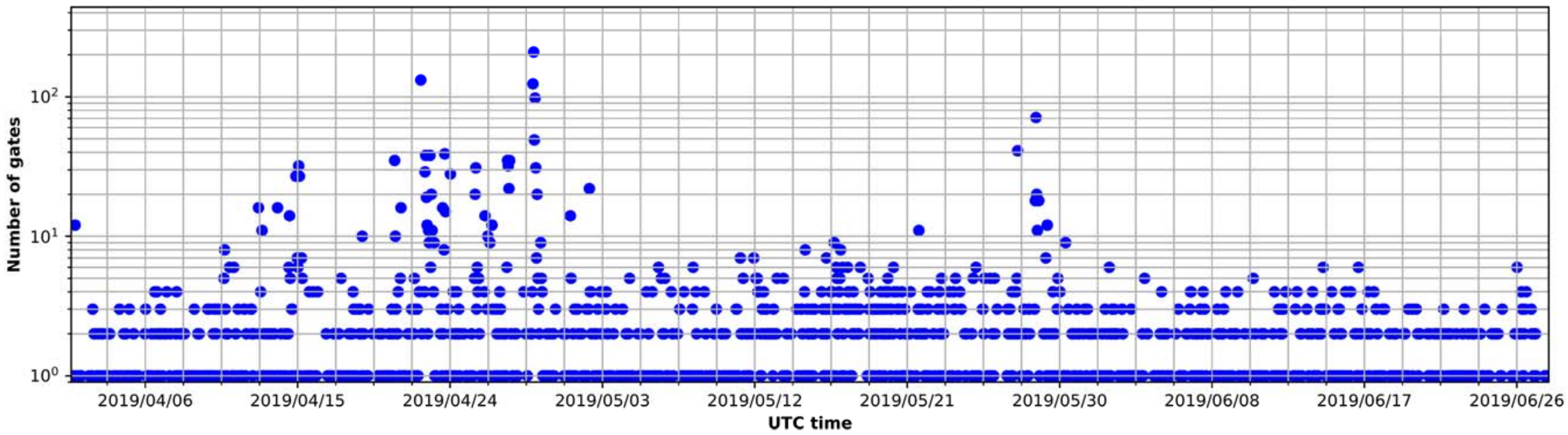
Gated h(t)

- Goal: getting round of extremely loud glitches, while keeping the pipelines running
  - Glitches pollute PSD estimation
  - Gate out data instead of interrupting the data analysis



- In Virgo, based on MBTA internal gating
  - Triggered by significant downwards excursions of the BNS range

→ Promising to help identifying hopefully short but quite pathological data segments

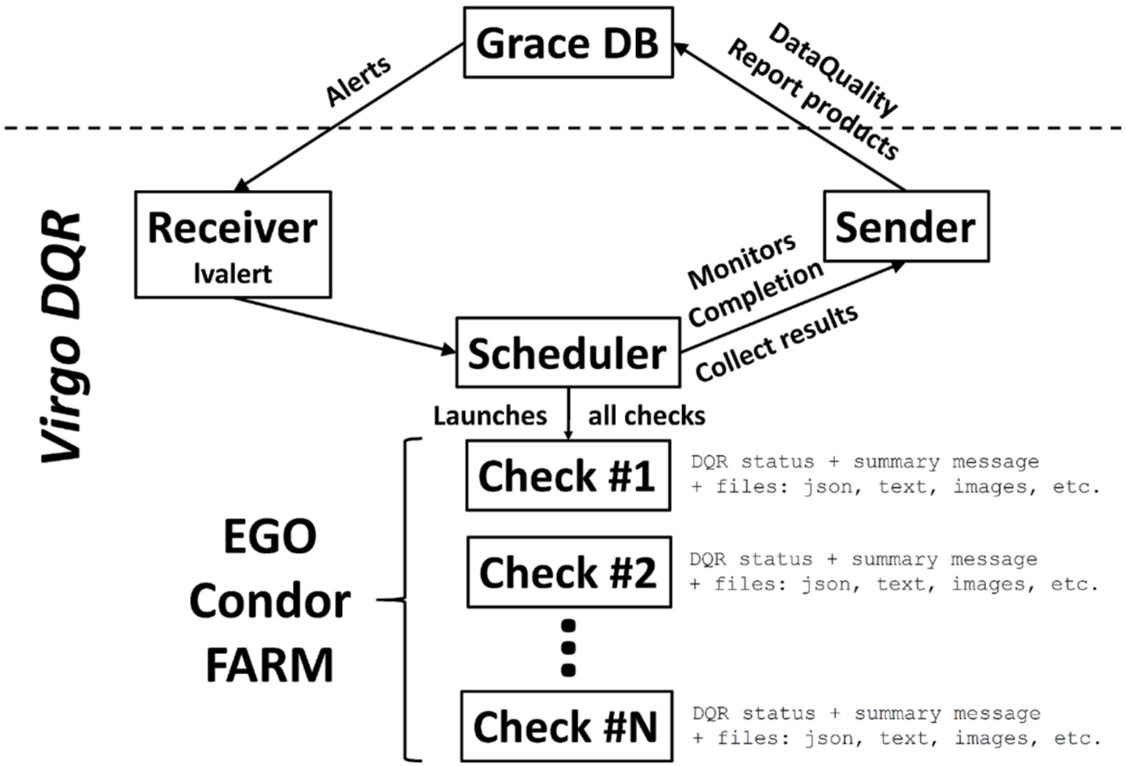


Data quality reports

- Data Quality Report (DQR)
  - Triggered by each (online) GW trigger
  - Runs various analysis on the available data: from basic to complex
    - Detector status, environment status, noise analysis, more expert plots, etc.
  - Each task reports a status

    → Helps final decision: keep or reject event
  - Runs independently on data from all three detectors

    → Virgo flavour of the DQR
    - Results gathered and linked back to the event that triggered the DQR
- Fully automated
  - 4,000+ DQRs since O3 began
  - Actual response now depends on significance
  - Extremely reliable framework



DQR workflow example: S190630ag

- One of the recent LIGO-Virgo triggers
  - Public information: https://gracedb.ligo.org/superevents/S190630ag/view

- Timeline (EGO local time)
  - Event t0 — 20:52:05
  - S-event creation in GraceDB — 20:52:28
  - Virgo DQR triggered by GraceDB — 20:52:35
  - Virgo DQR generation — 20:57:40
  - Virgo DQR processing — 20:58:00
  - Key information available — 21:03:56
    21:13:42
  - Virgo DQR processing completed — 21:50:23

300 s configurable latency *[Conservative]*

→ LIGO-Virgo internal monitoring of that task

Log Entry Created	Submitter	Comment
Jun 30, 2019 19:50:24 UTC	Virgo Detchar	Condor DAG is done: monitoring has ended.
Jun 30, 2019 18:58:03 UTC	Virgo Detchar	Condor DAG is running.
Jun 30, 2019 18:57:59 UTC	Virgo Detchar	Virgo DQR being initialized.
Jun 30, 2019 18:57:58 UTC	Virgo Detchar	Condor DAG successfully generated.

Offline data quality

- Goals
  - Final data quality assessment for the new detections
  - Final dataset for offline analysis

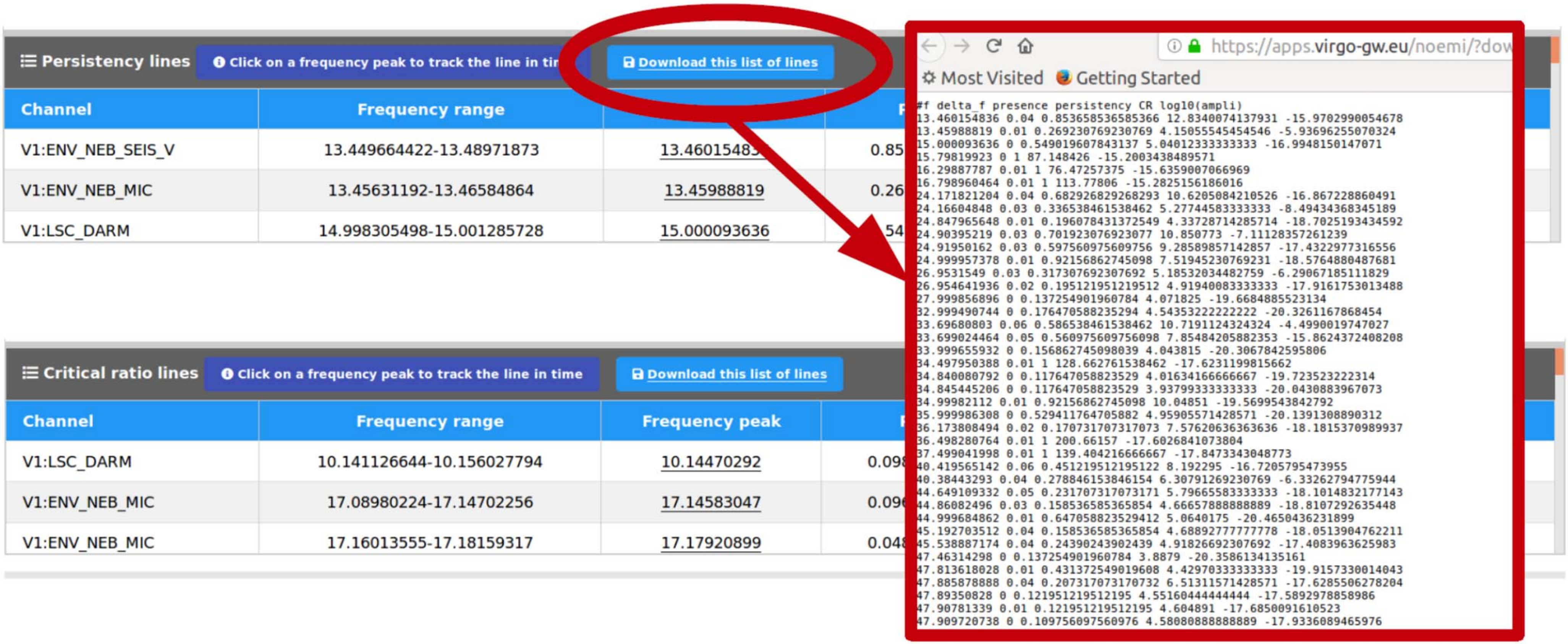
→ Basic container: time segments

- SCIENCE segments
- Primary data quality vetoes: segments during which the data are definitely bad
  - Using online-computed flags
  - Adding flags for offline-identified issues
- Additional, optional, data quality flags
  - Available to optimize the cuts of each analysis
- Flags keeping track of changes in the interferometer configuration with SCIENCE segments
  → Action not causing the loss of the detector control nor visible in the data
  - Example: switching on/off some correction

- Framework in its final stages
  - First segment lists available to analysts
  - Plan is to update them regularly, following the data taking progress

Spectral lines

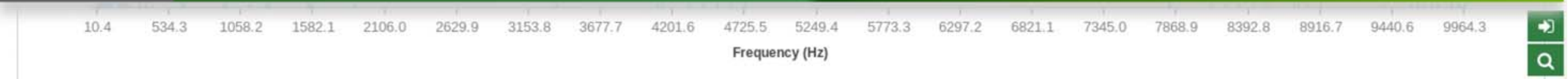
- Noise Frequency Event Miner: NoEMi
  - Monitoring and identification of spectral noise lines
  - → Major rewriting for O3: “quicker, smaller, lighter, easier”



Spectral lines

- Lines Database
  - Collect all information about lines found in the data
    → Many new functionalities added for O3

Lines DB



Click on a line frequency to view additional associated information.

Frequency (Hz)	Tags	Width (Hz)	Stationarity	Notes	Line source
10.53	O2	0.1	Stationary	CAL noise line49 Observed in O2	Calibration
12.5	O2	0.1	Stationary	CALnoise PR_MIR_perline0 Observed in O2	Calibration
16.3	O2	0.1	Stationary	CALnoise BS_MAR_permline0 Observed in O2	Calibration

ID	Type	Locations	Recording devices	Added by	Date added
66		Central Building (CEB)	Magnetometer	hemming	02-08-2017

Frequency (Hz)	Tags	Width (Hz)	Stationarity	Notes	Line source
18.6	O2	0.1	Stationary	Observed in O2	Air conditioner
20	O2	1	Stationary	Mechanical mode of External Injection Bench Observed in O2	Mechanical mode
24.6	O2	0	Stationary	DAQ room air conditioner (elog 38709). Seen in O2.	Air conditioner
29.2	O2	0.1	Stationary	Eliminated 25/7/17	Vacuum pump
29.68	O2	0.5	Stationary	Excited with white z shaking of SDB1 (elog 38625)	Mechanical

DetChar shifts

- Supplement DetChar experts
  - Nominally 2 shifters / week, from a maintenance period to the next one

  → Collaboration-wide service task
    - Contribution proportional to the number of Virgo authors in a given group

- Main tasks
  - Data quality monitoring
  - Rapid Response Team for online triggers

→ Effective since pre-O3 commissioning last Fall
  - Positive experience overall
    - Training and documentation are keys to the success of such initiatives

Virgo DQR documentation: Introduction | Checks | FAQ | Instructions for shifters and RRT | For experts ***LIGO DQR documentation:*** Introduction

Conclusions

Outlook

→ When writing that slide…

- 3 months into O3
- 74+ days of SCIENCE data
- 4,000+ DQRs processed
- 16 open public alerts
- 57 DetChar shifts
- ~20 people involved in regular DetChar activities

→ Work (always) in progress!

- ~Quarter of the expected data taking completed
- Offline work
- Next campaign of upgrades: Advanced Virgo Plus