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Gravitational-wave detectors
Noise characterization

→ Introduction / motivation

→ Spectral noise
- gravitational-wave detector sensitivity
- noise budget
- noise spectral features

→ Transient noise
- monitoring and characterization
- investigation and mitigation
- search vetoes

→ Low-latency noise characterization

LIGO and Virgo detector characterization group:

→ provide tools to monitor the detector status and noise

→ characterize the detector noise (spectral and transient)

→ assist the commissioning to improve the detector sensitivity

→ provide data quality information to search groups

→ produce event vetoes both for time and frequency domain

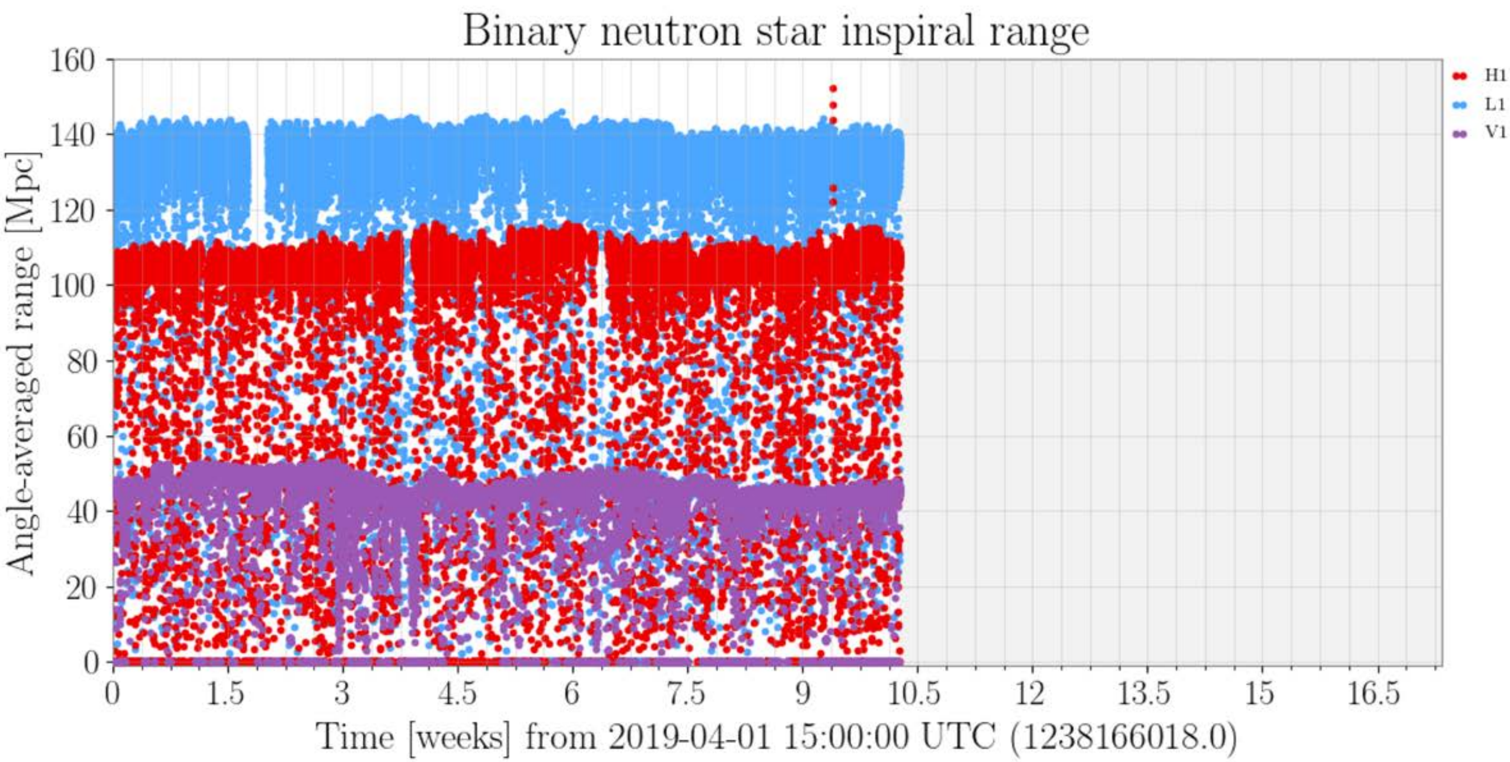
→ provide the infra-structure to access vetoes online and offline

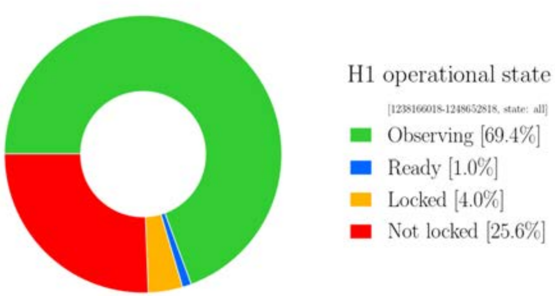
→ vet gravitational-wave detections

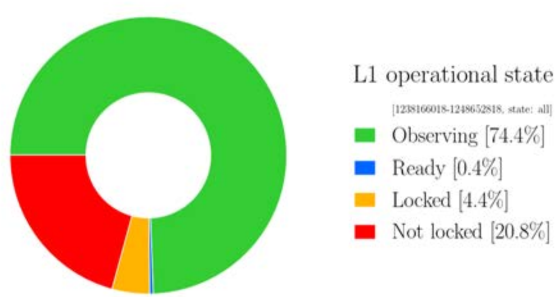
LIGO (Livingston) summary pages

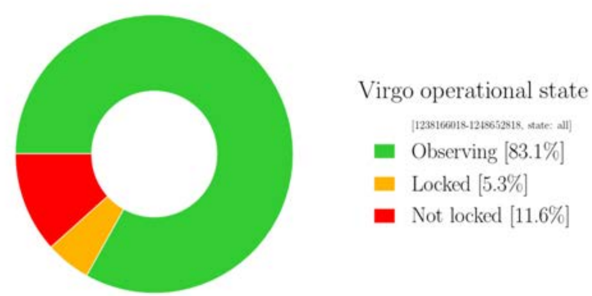
Detector monitoring

Virgo monitoring pages

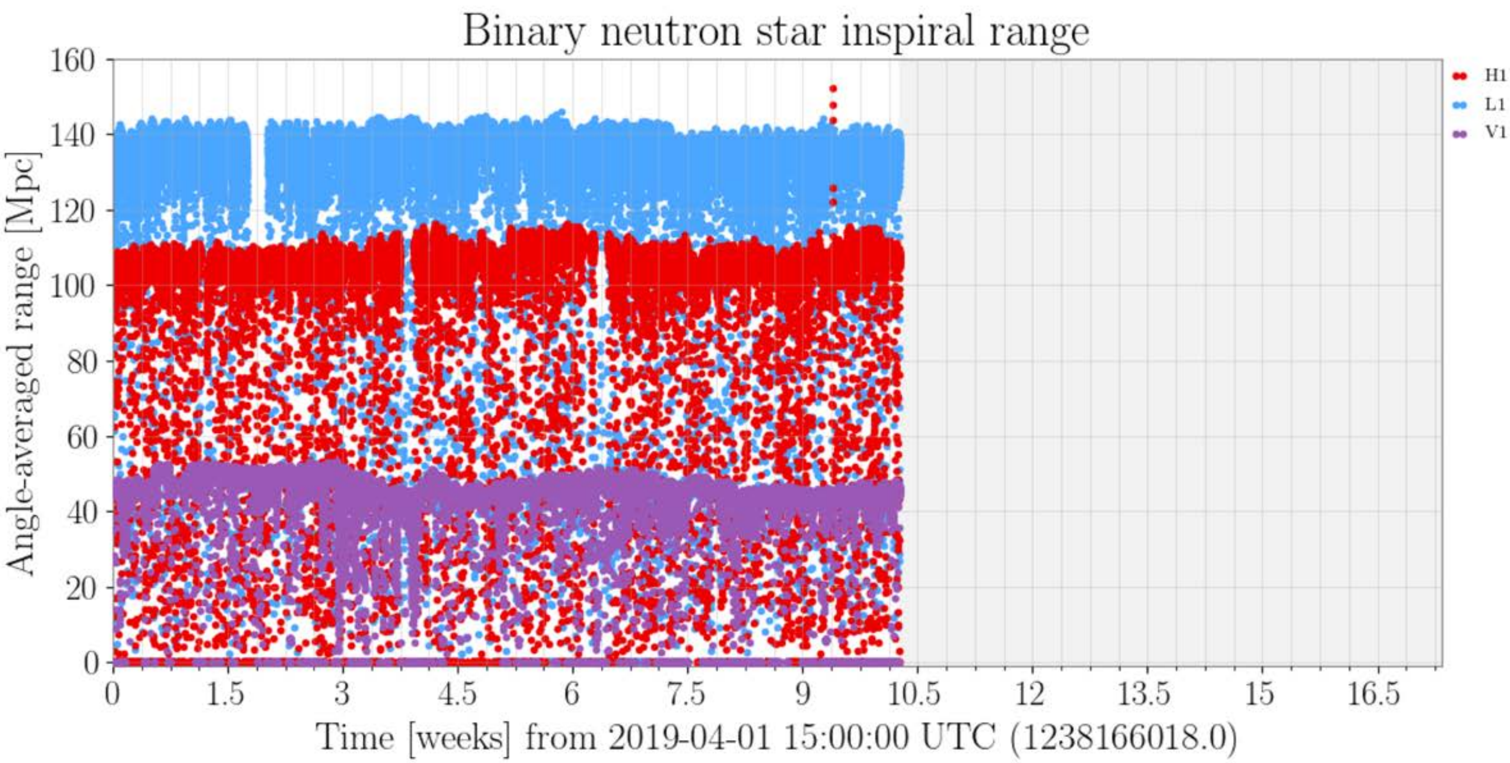

Binary neutron star inspiral range
Angle-averaged range [Mpc]
Time [weeks] from 2019-04-01 15:00:00 UTC (1238166018.0)
H1
L1
V1
0
20
40
60
80
100
120
140
160
0
1.5
3
4.5
6
7.5
9
10.5
12
13.5
15
16.5

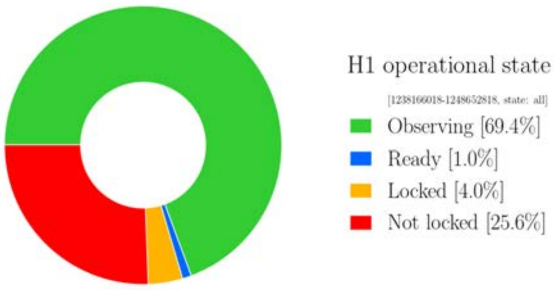

H1 operational state
[1238166018-1248652818, state: all]
Observing [69.4%]
Ready [1.0%]
Locked [4.0%]
Not locked [25.6%]

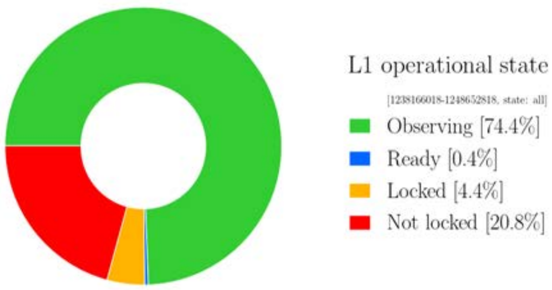

L1 operational state
[1238166018-1248652818, state: all]
Observing [74.4%]
Ready [0.4%]
Locked [4.4%]
Not locked [20.8%]

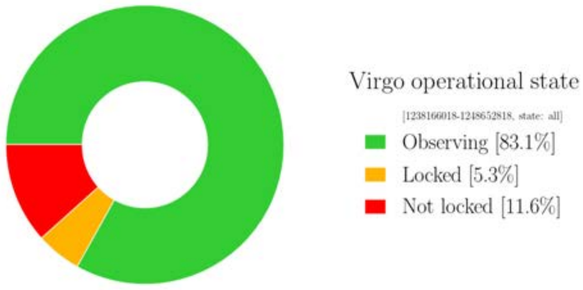

Virgo operational state
[1238166018-1248652818, state: all]
Observing [83.1%]
Locked [5.3%]
Not locked [11.6%]

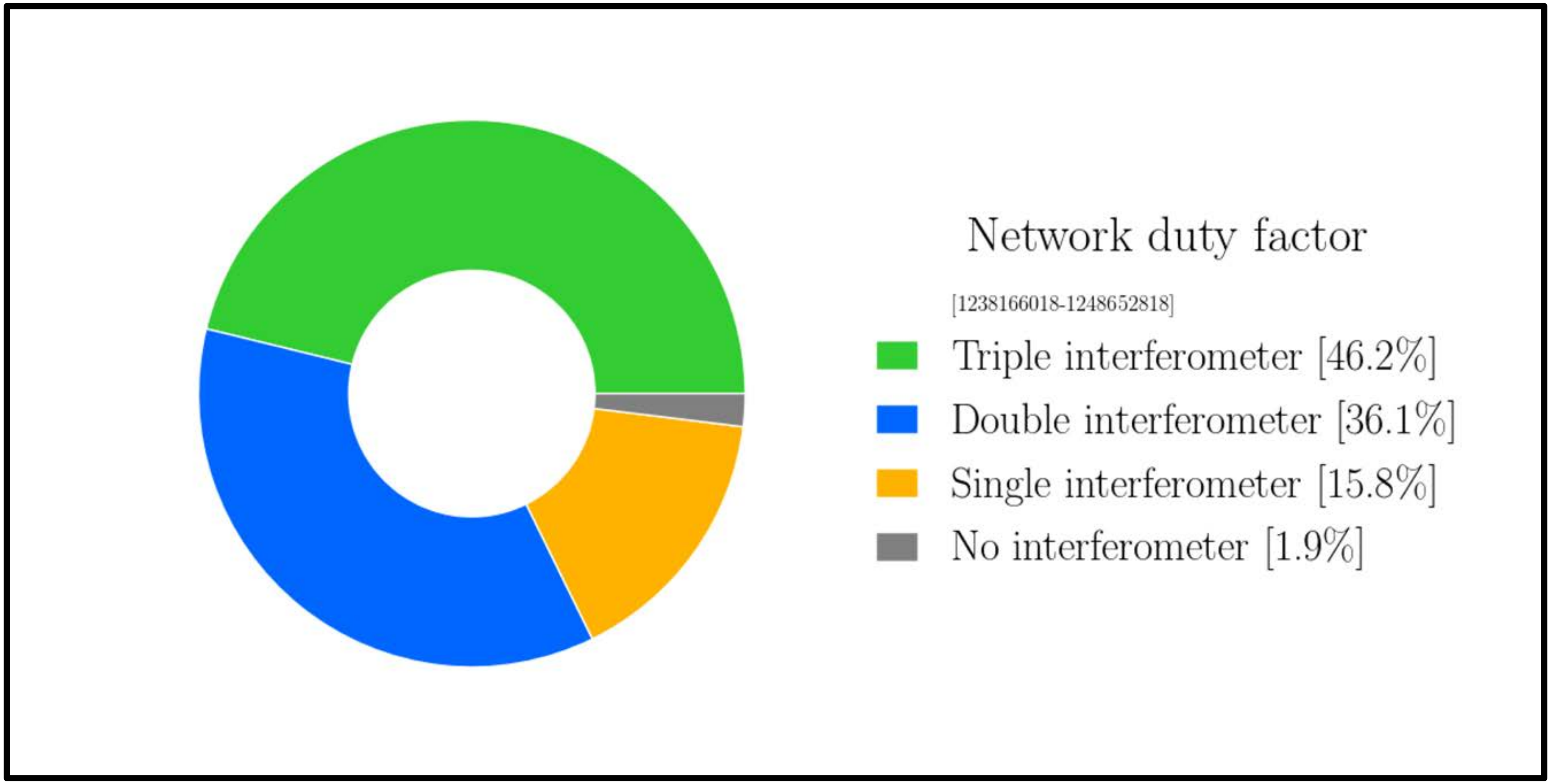
Run statistics










Network duty factor
[1238166018-1248652818]
Triple interferometer [46.2%]
Double interferometer [36.1%]
Single interferometer [15.8%]
No interferometer [1.9%]

LIGO and Virgo detector characterization group:

→ Provide tools to monitor the detector status

→ characterize the detector noise (spectral and transient)

→ Assist the commissioning to improve the detector sensitivity

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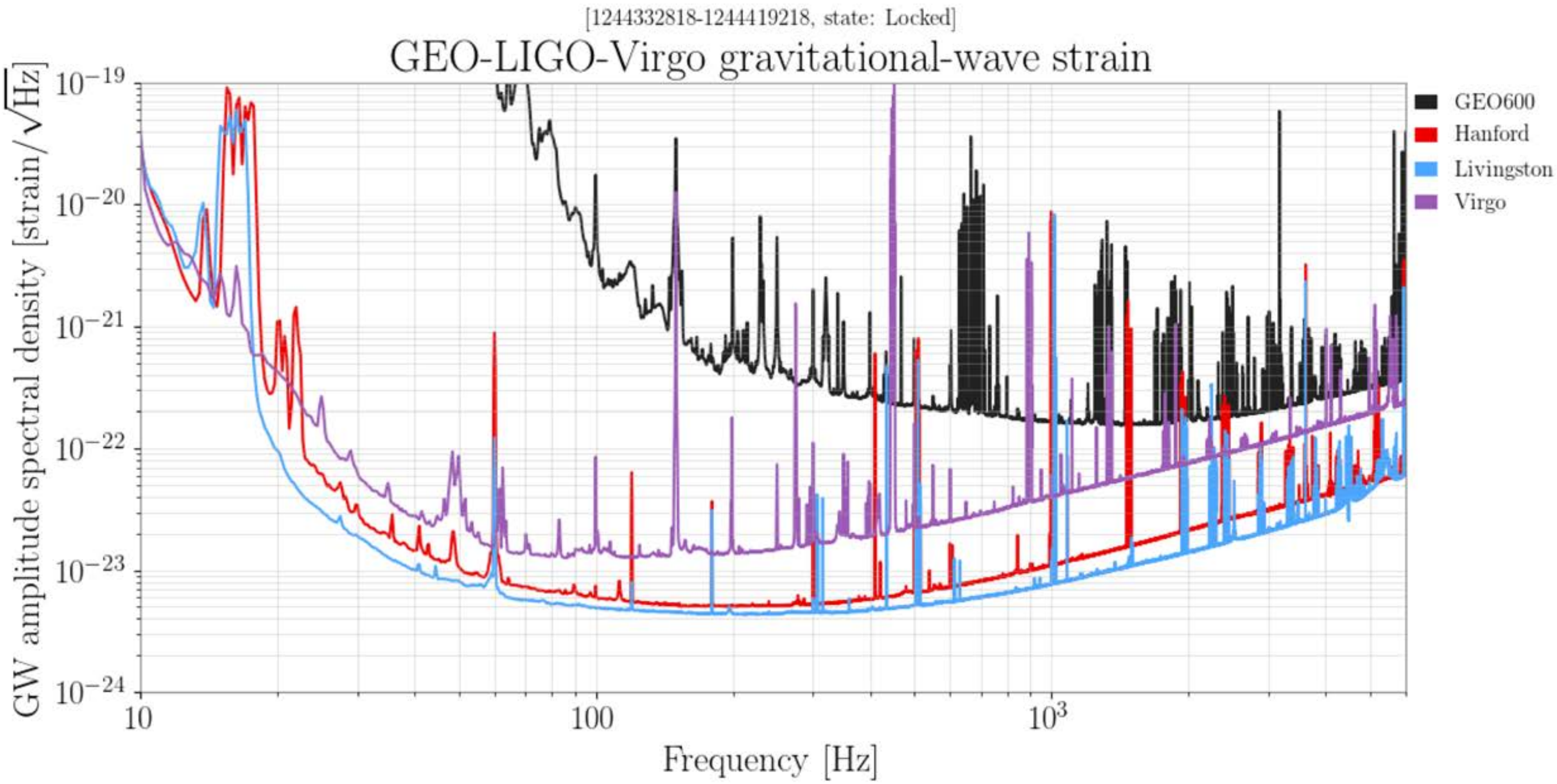
→ vet gravitational-wave detections

→ **Continuous waves** produced by a pulsar would appear as a line in the spectrum

→ A **stochastic background of gravitational-waves** would appear as a specific structure in tl

→ The detector characterization group studies noise spectral features to exclude an instrument



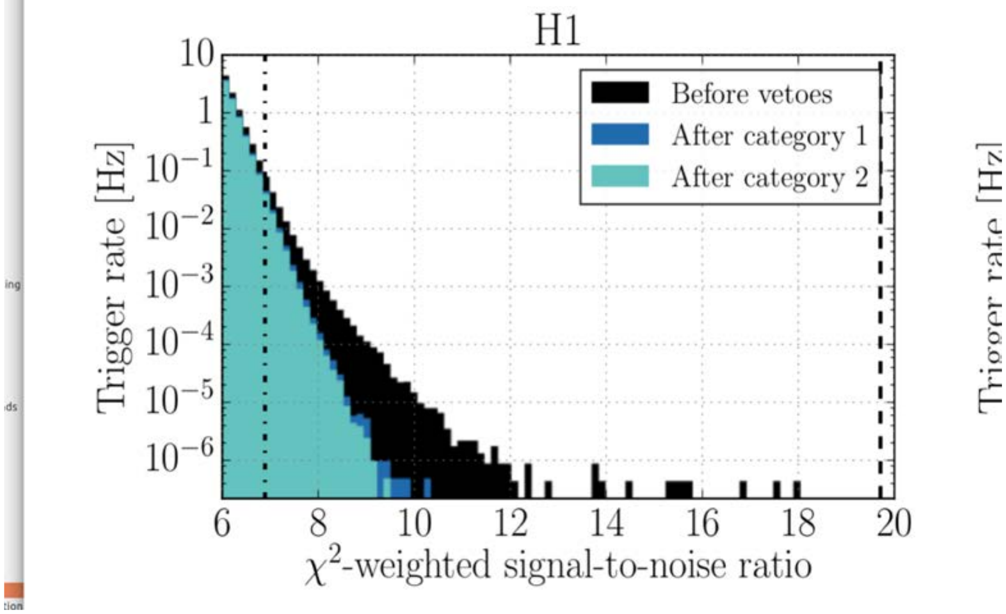
Motivation: transient searches

→ Transient searches are contaminated by spurious noise events mimicking GW signals

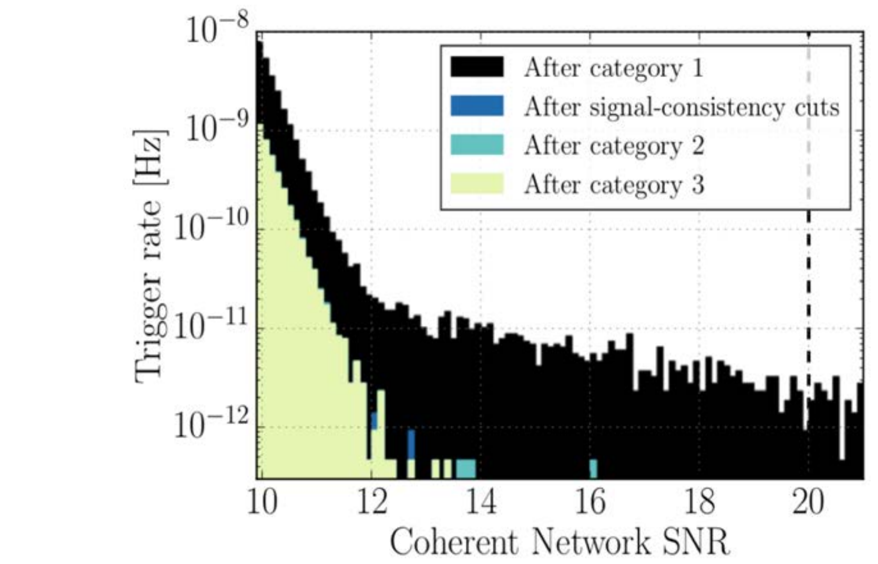
→ Background distribution is highly non-Gaussian

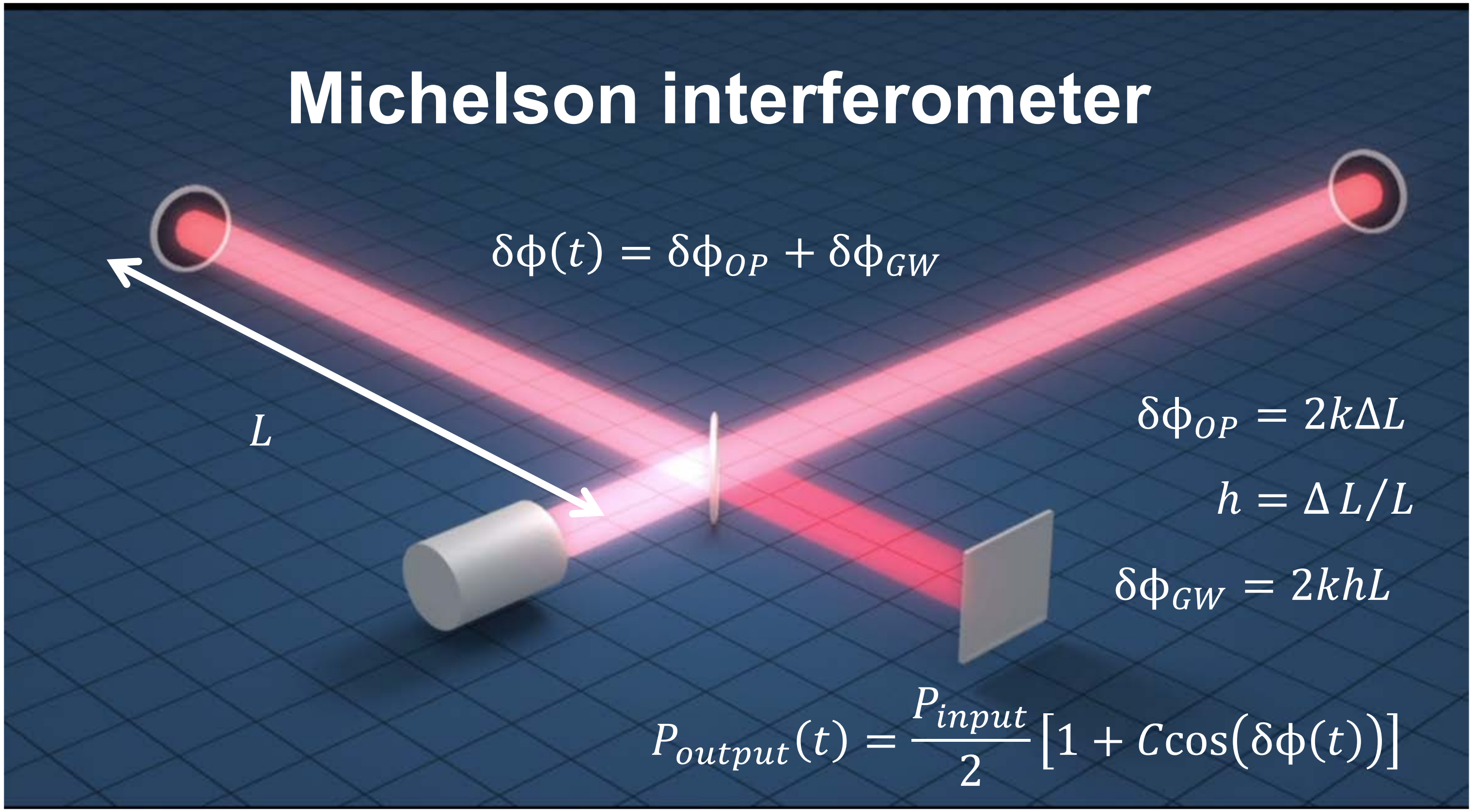
→ The detector characterization group studies the events in the tails and designs vetoes

CBC search



Burst search





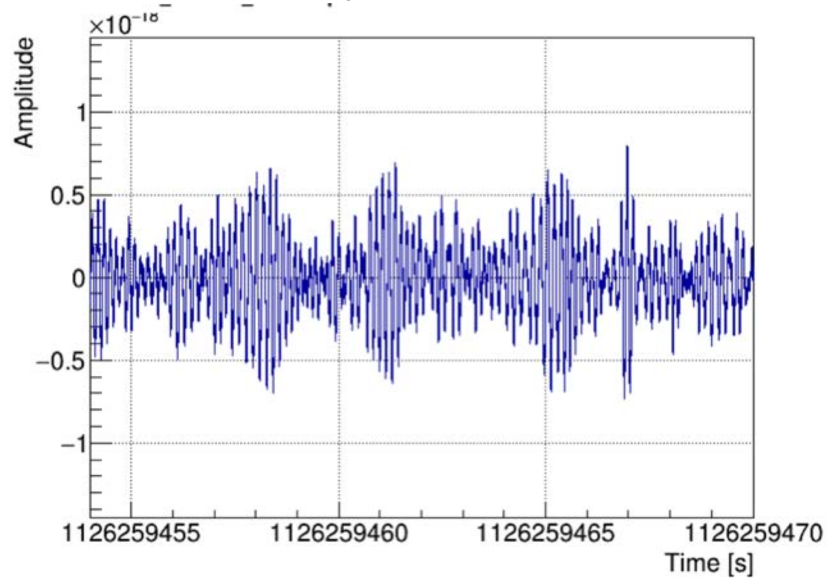
$$P_{output}(t) \simeq \frac{P_{input}}{2}\left[1 + C\cos(\delta\phi_{OP}) - C\sin(\delta\phi_{OP})\times\delta\phi_{GW}(t)\right]$$

→ A gravitational wave is detected as a power variation

→ Many noise sources can produce a power variation

GW detectors' readout system provides at any instant an estimate of strain: a quantity that is sensitive to arms' length difference:

⟶ Digitized discrete time series: raw(t) (sampled at 16384 Hz or 20000 Hz) and synchronized with GPS clocks.
→ Calibration of raw(t): apply a frequency dependent factor (in reality this is a bit more complicated : see Joseph’s talk!)



⟶ $h_{det}(t)$ time series = detector noise + all hypothetical GW signals

$$h_{det}(t) = n(t) + GW(t)$$

GW detectors' readout system provides at any instant an estimate of strain: a quantity that is sensitive to arms' length difference:

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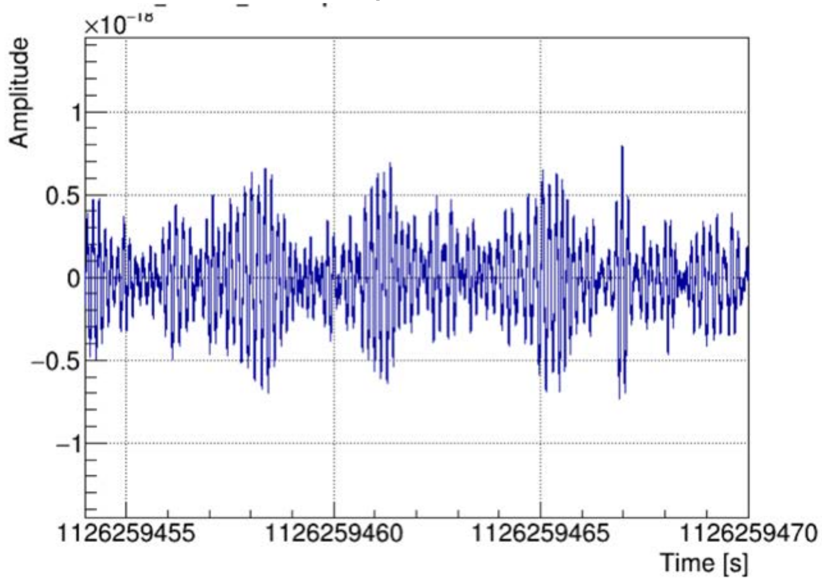


→ $h_{det}(t)$ time series = detector noise + all hypothetical GW signals

$$h_{det}(t) = n(t) + GW(t)$$

Noise power spectral density

The level of noise is measured using the power spectral density (PSD)

$$S_n(f) = \int_{-\infty}^{+\infty} \langle n(\tau) n(\tau + t) \rangle e^{-2i\pi f t} dt$$

= Fourier transform of the noise autocorrelation function (Wiener-Khinchin theorem)

Several elements to consider:

→ We only want the power of stationary noise (excluding signals and transient noise)

→ We work with a finite data set

→ The noise is non-stationary

Noise power spectral density

→ Power spectral density estimator for finite data set: periodogram = $\frac{1}{T}|\tilde{x}_T(f)|^2$

→ Improved estimator:

- average multiple periodograms (*M*) to reduce the variance
- noise is non-stationary: *T* should not be too long (a few minutes)
- use windowed data to limit spectral leakage
- Welch approach: average of periodograms computed over overlapping windowed data segments

→ Sensitivity measured using the noise power spectral density :

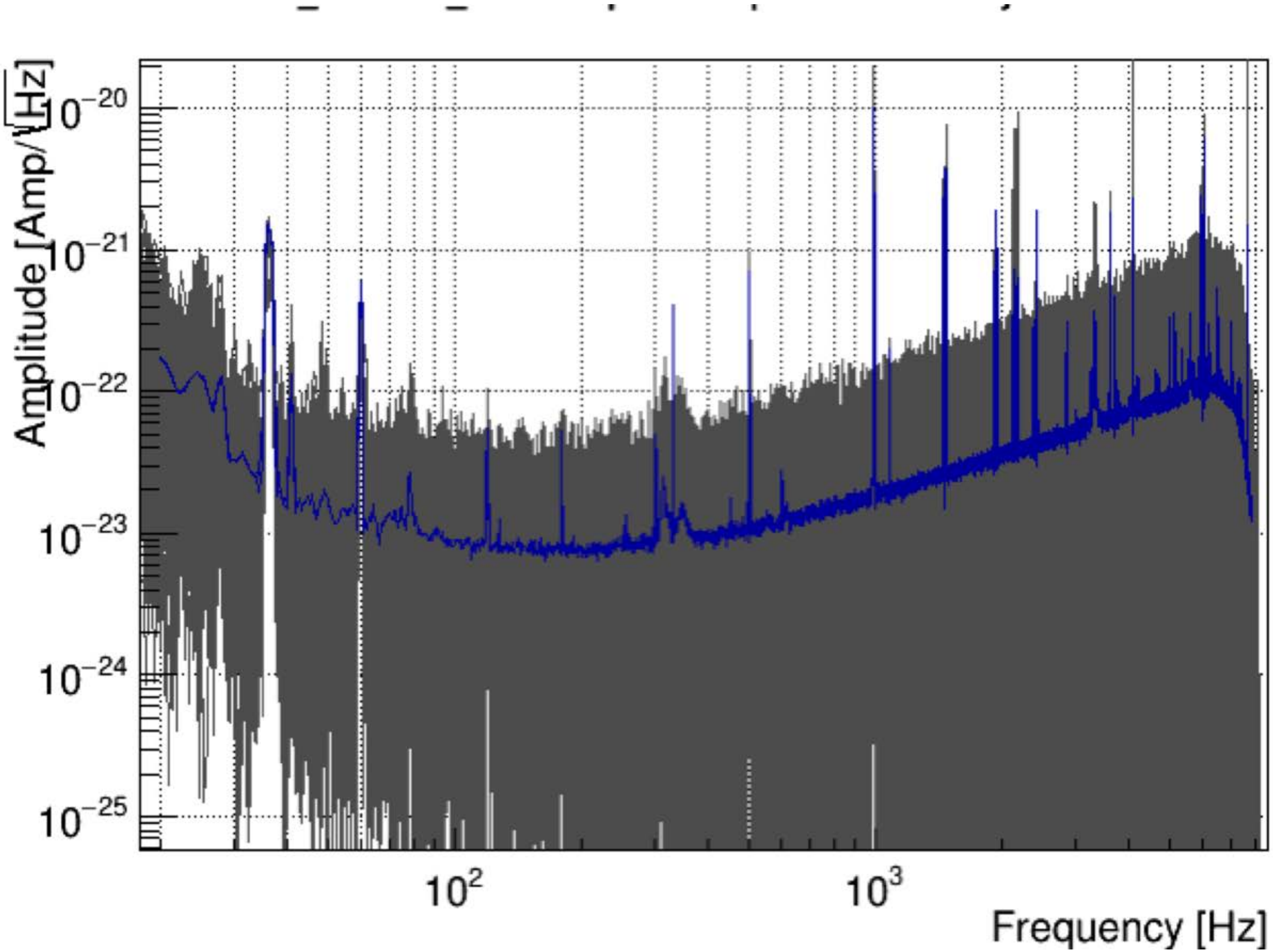
$$S_n(k) = Median_{0\leq m<M}\left\{\frac{1}{Nf_s}\left|\sum_{j=0}^{N-1} x_m[j]w[j]e^{-2i\pi jk/N}\right|^2\right\}$$

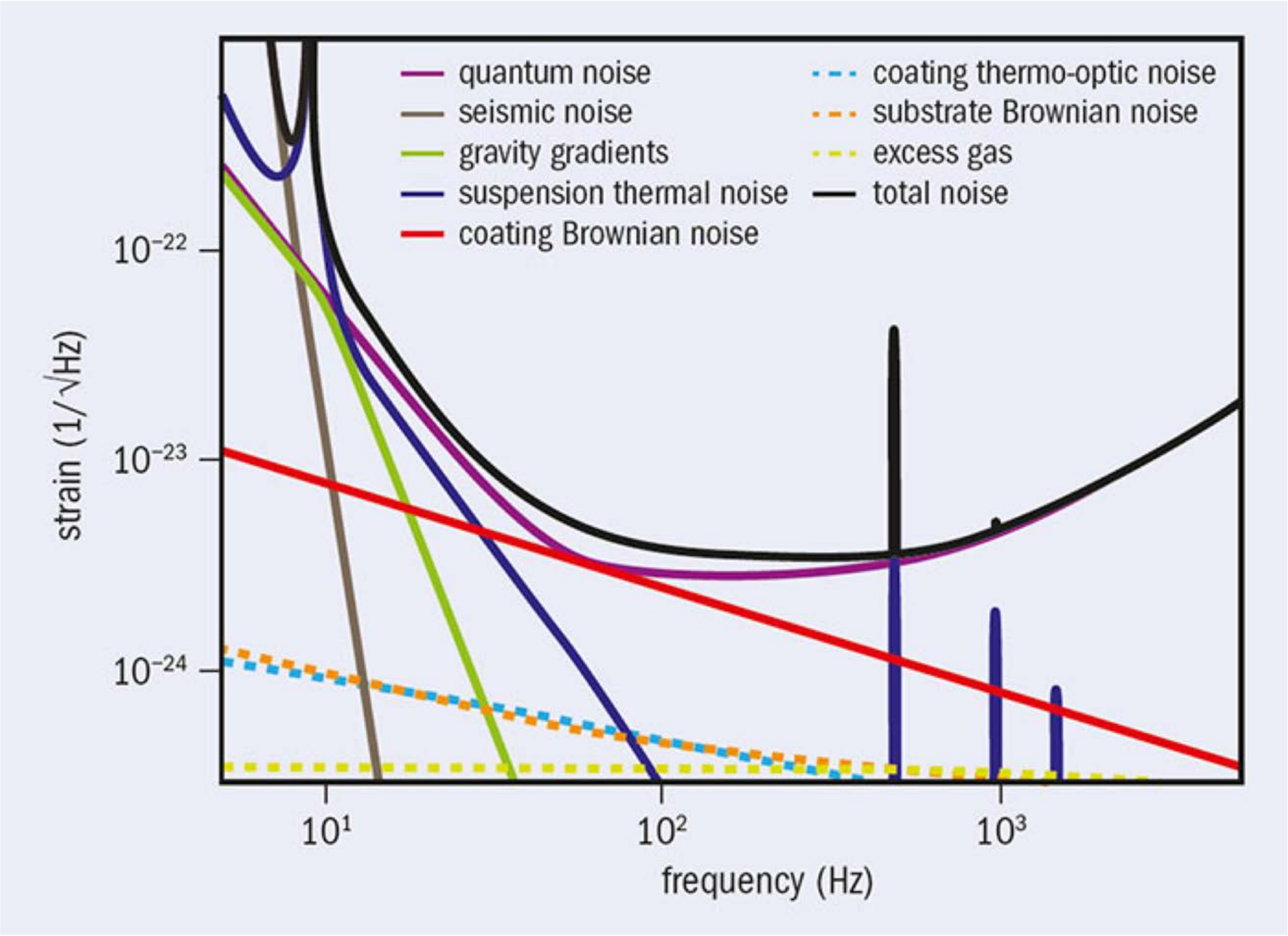
+ median-to-mean correction

→ One-sided / Two sided PSDs

→ Amplitude power spectral density: $\sqrt{S_n(k)}$

Noise amplitude spectral density estimate for gravitational-wave detectors




quantum noise
seismic noise
gravity gradients
suspension thermal noise
coating Brownian noise
coating thermo-optic noise
substrate Brownian noise
excess gas
total noise
strain (1/√Hz)
10^{-22}
10^{-23}
10^{-24}
10^1
10^2
10^3
frequency (Hz)

Technical noise

On top of fundamental noise, many technical noises must be considered

→ beam pointing / alignment

→ control noise

→ light scattered by detector components (mirror defects, towers, optical parts, …)

→ instrumental noise: laser, thermal compensation system, electronics...

→ environmental noise:
- cooling fans, air conditioning, power lines...
- human, sea activity, weather, airplanes...

Noise budget = consider all possible noise sources and try to estimate the contribution to the r

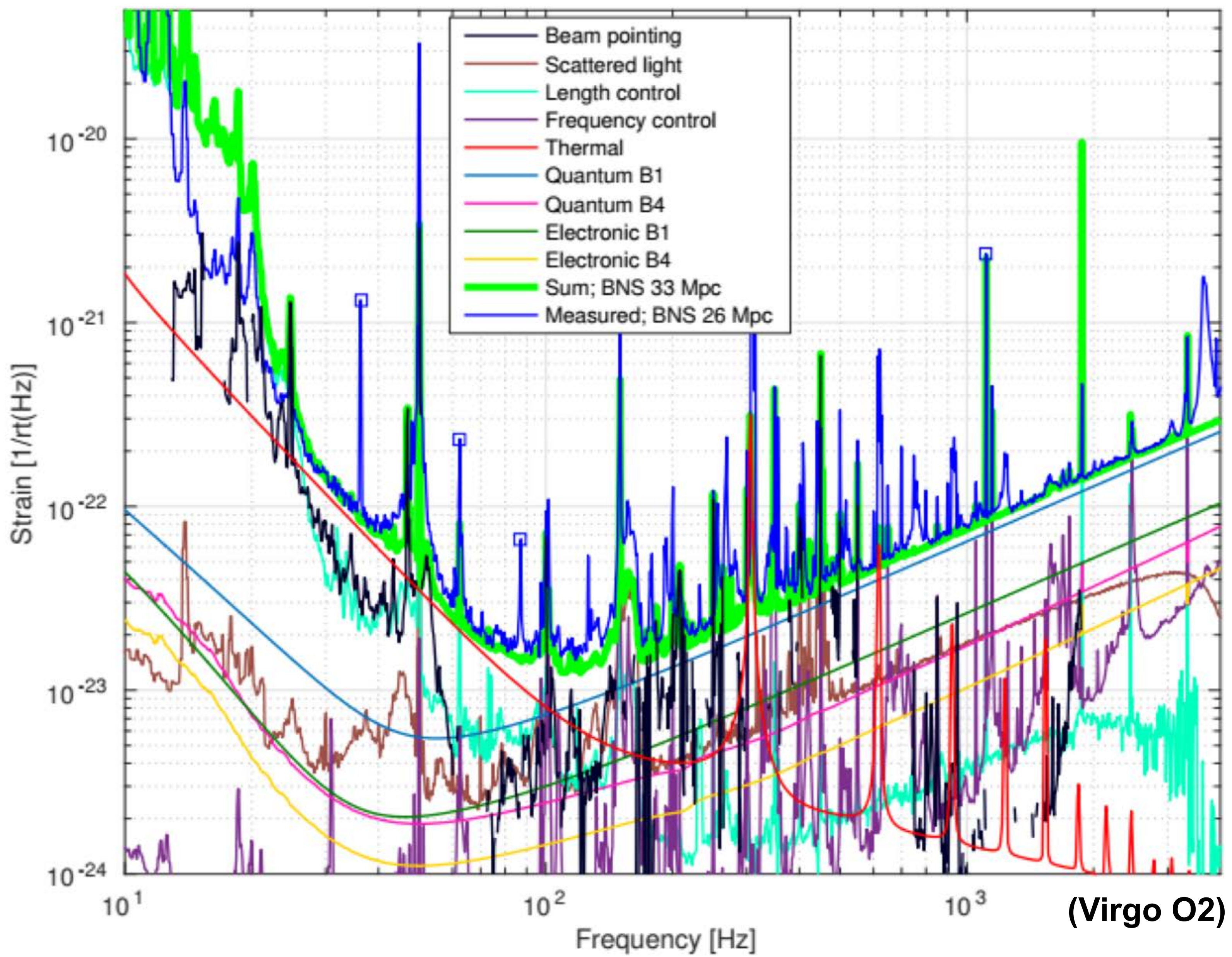
A noise source is described by
1/ an amplitude
2/ the way it couples to the detector (transfer function)

Amplitude:
→ modeled (ex: shot noise)
→ measured offline
→ measured online with auxiliary channels (ex: control noise)

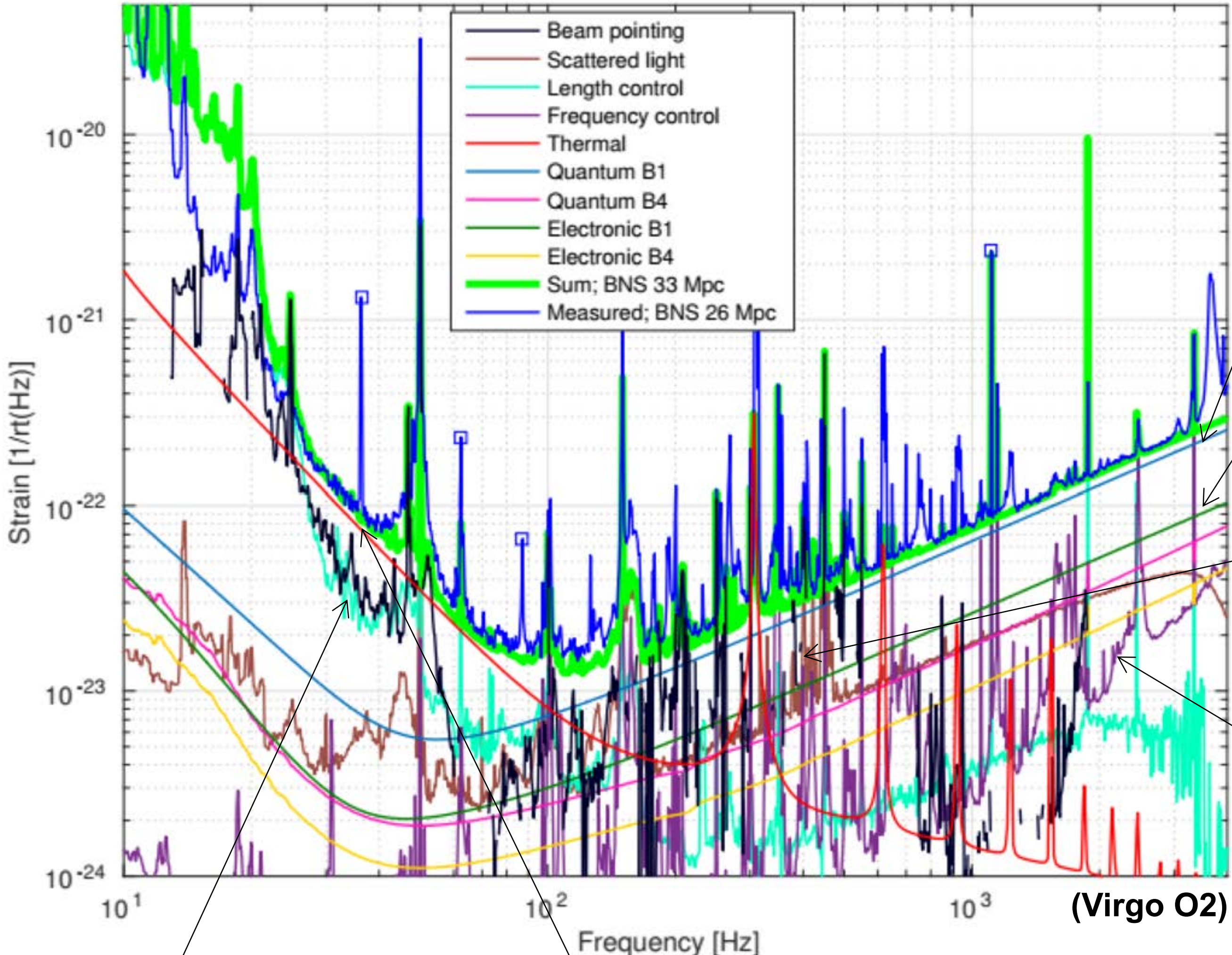
Transfer function:
→ modeled
→ modeled with factors measured experimentally
→ measured with noise injections

Over 100 noise sources must be considered.

→ Add in quadrature all the noise contributions
→ Compare with the measured noise curve


Beam pointing
Scattered light
Length control
Frequency control
Thermal
Quantum B1
Quantum B4
Electronic B1
Electronic B4
Sum; BNS 33 Mpc
Measured; BNS 26 Mpc
Strain [1/rt(Hz)]
Frequency [Hz]
(Virgo O2)

Noise budget (selection)



(Virgo O2)

Shot noise (analytical model)

$$\delta P_{shot} = \sqrt{\frac{2P_0\hbar c}{\lambda}}$$

PD electronic noise
measured with shutter closed

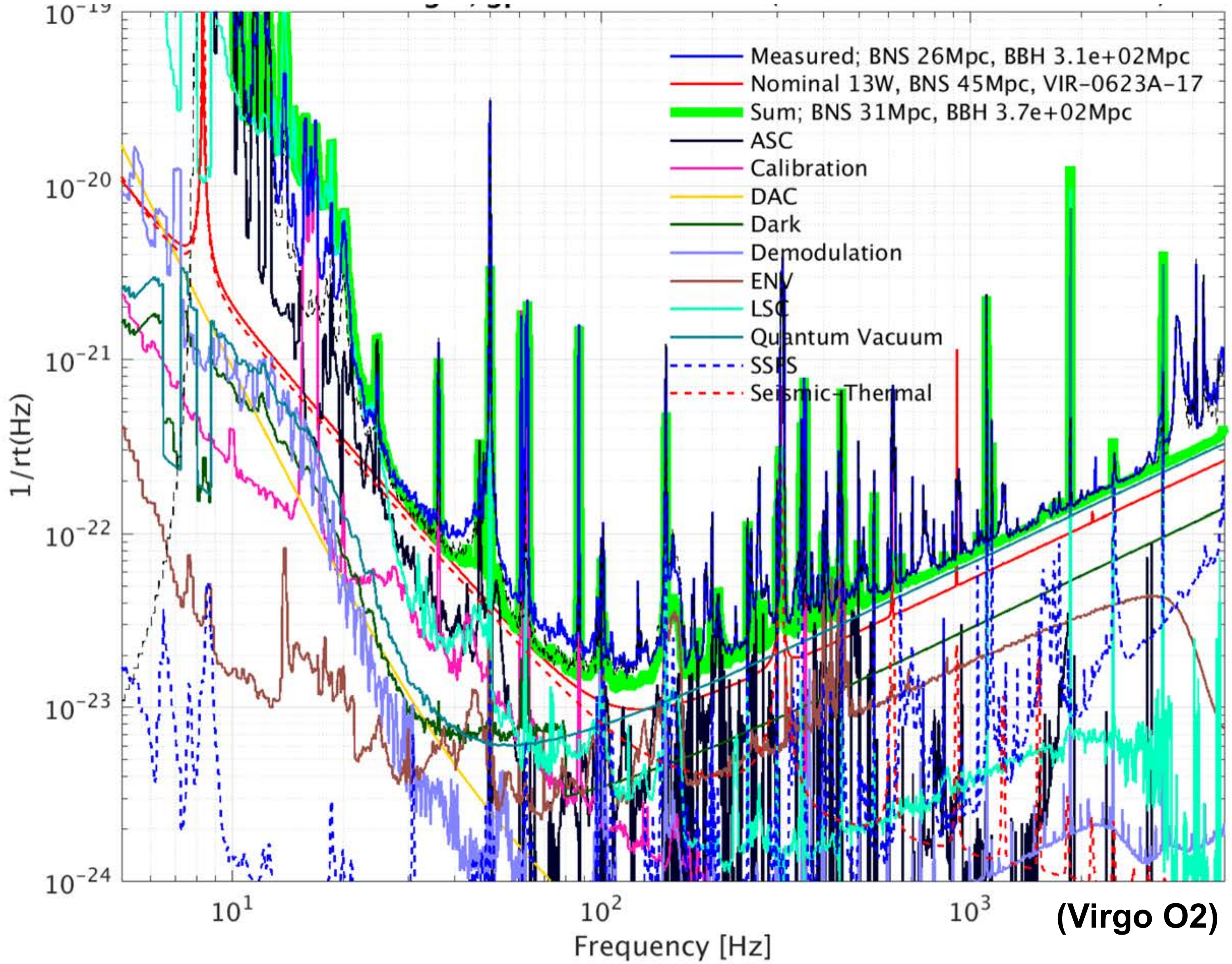
Scattered light
monitored using the DC power
In the central interferometer

Laser frequency control
(spectral lines)

Control noise (MICH dof)
dominant for f < 25 Hz
(subtracted by active feed-forward)

Thermal noise from wire suspensions (steel in O2)
(analytical model)

Noise budget



(Virgo O2)

Noise spectral features

Noise spectral features can be classified based on the morphology and time evolution

→ **“Bumps”** are typically associated to non-stationary sources

→ **Lines associated to mechanical resonant modes** (mirror or suspension): typical Lorentzi

→ **A line can appear/disappear**: often associated to devices switching on and off

→ **Wandering lines** have a frequency evolving with time, sometime in a periodic way (followin

→ **Very narrow lines** are often associated to electronic devices

→ **Line combs**, often associated to digitized clocks

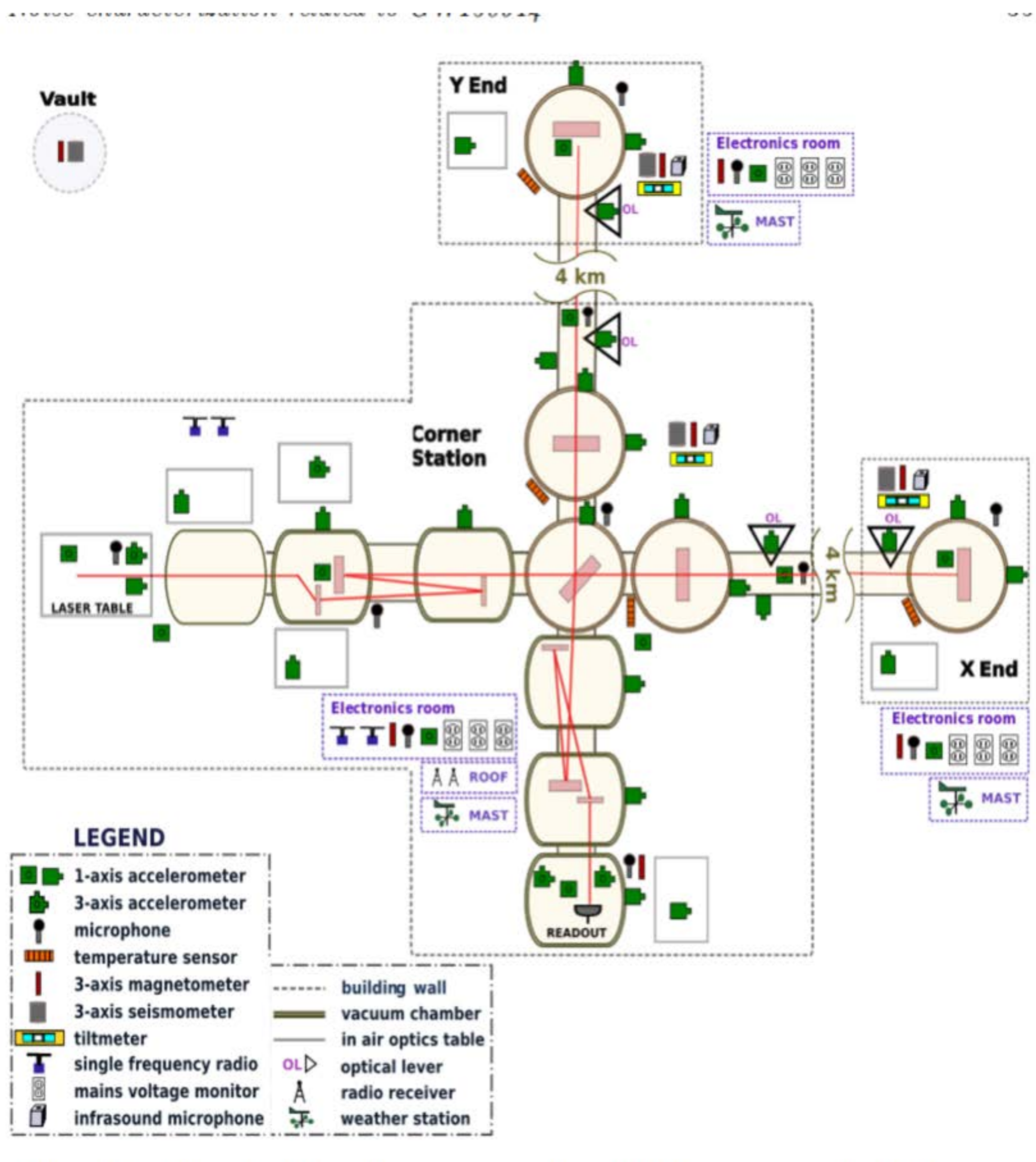
→ **Line harmonics** resulting from the coupling of 2+ frequencies

→ The **line frequency** can be associated to electronic devices: cooling fans, vacuum pumps,

→ Spectral noise investigation is often based on a deep knowledge of the detector and its env

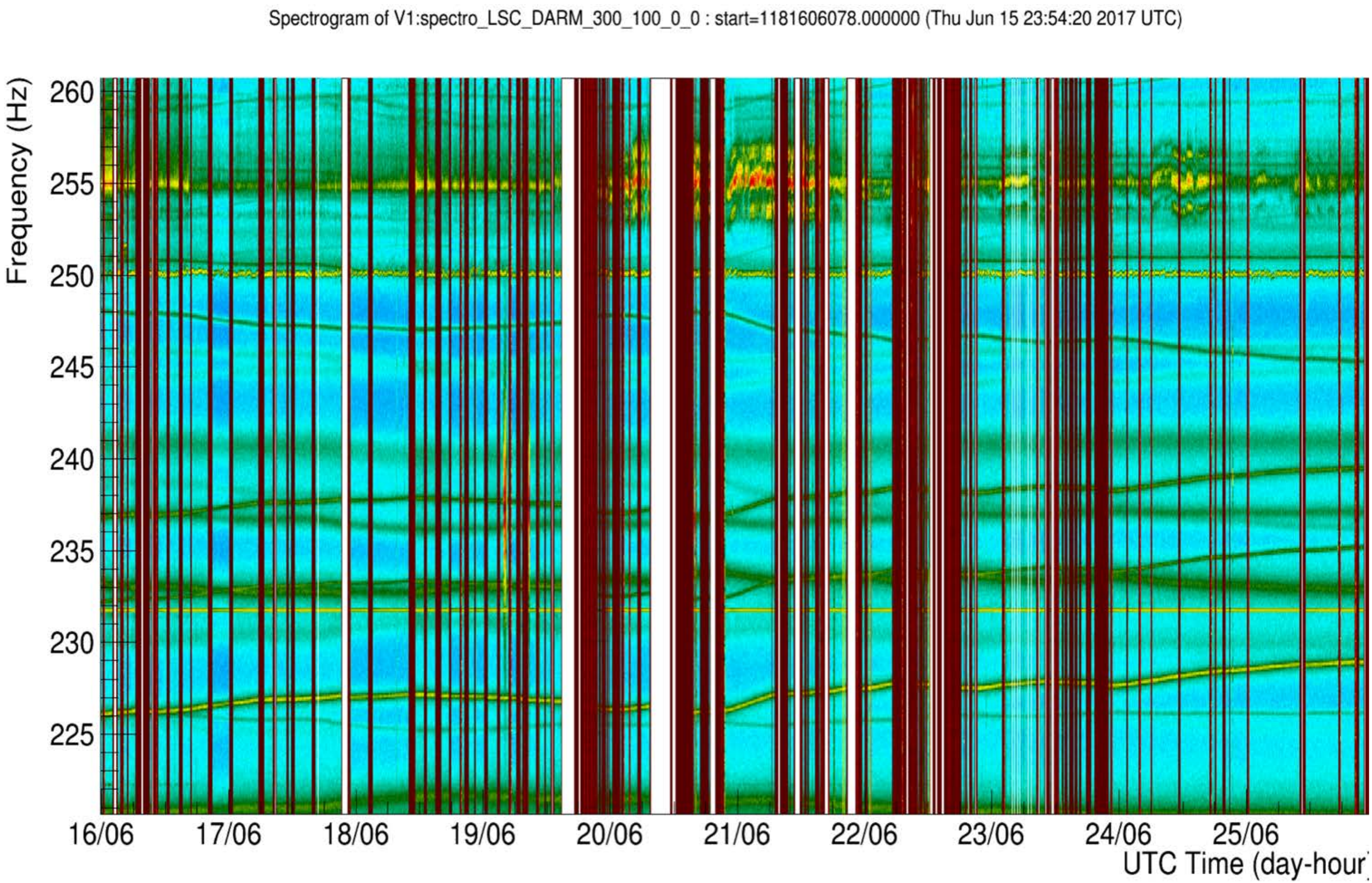
Monitoring the noise

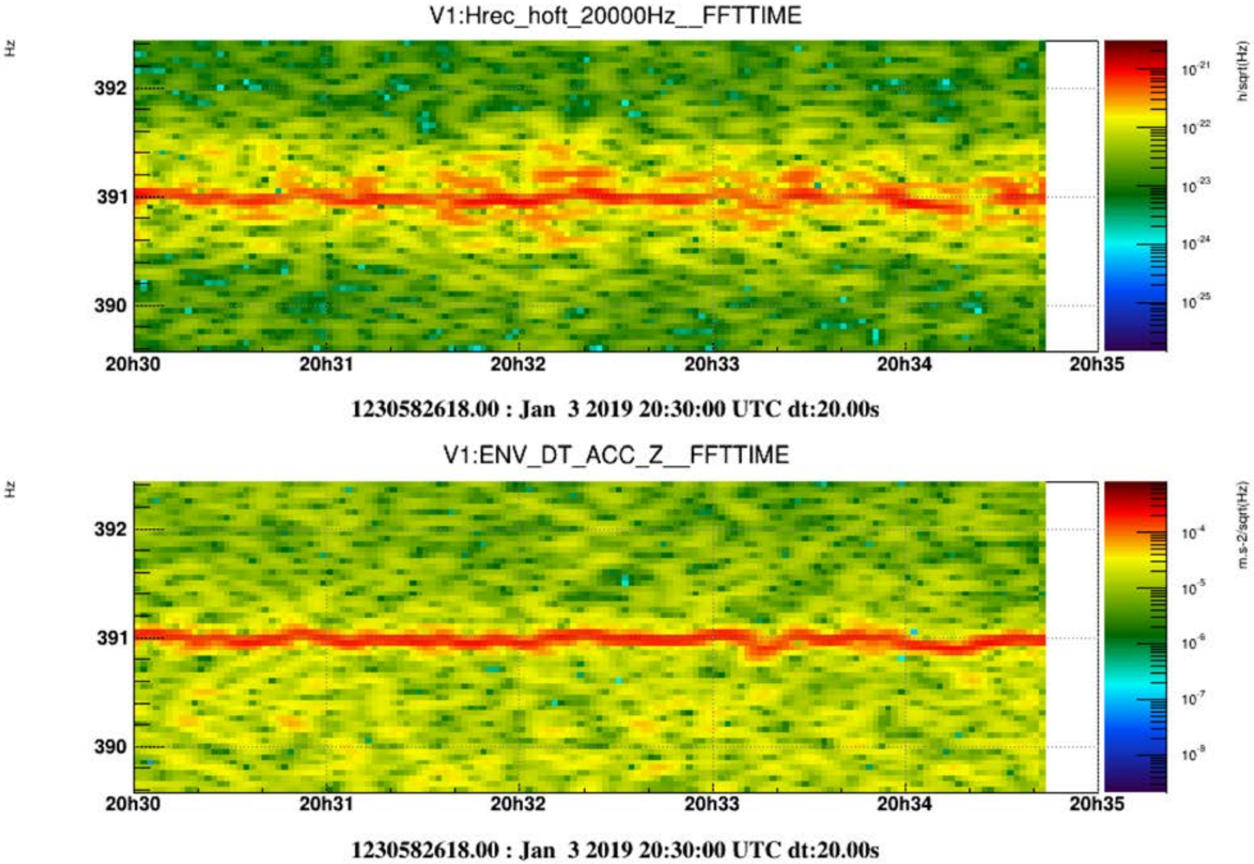
Thousands of auxiliary channels are used to monitor the instruments
– environmental sensors
– detector sub-systems
– detector control



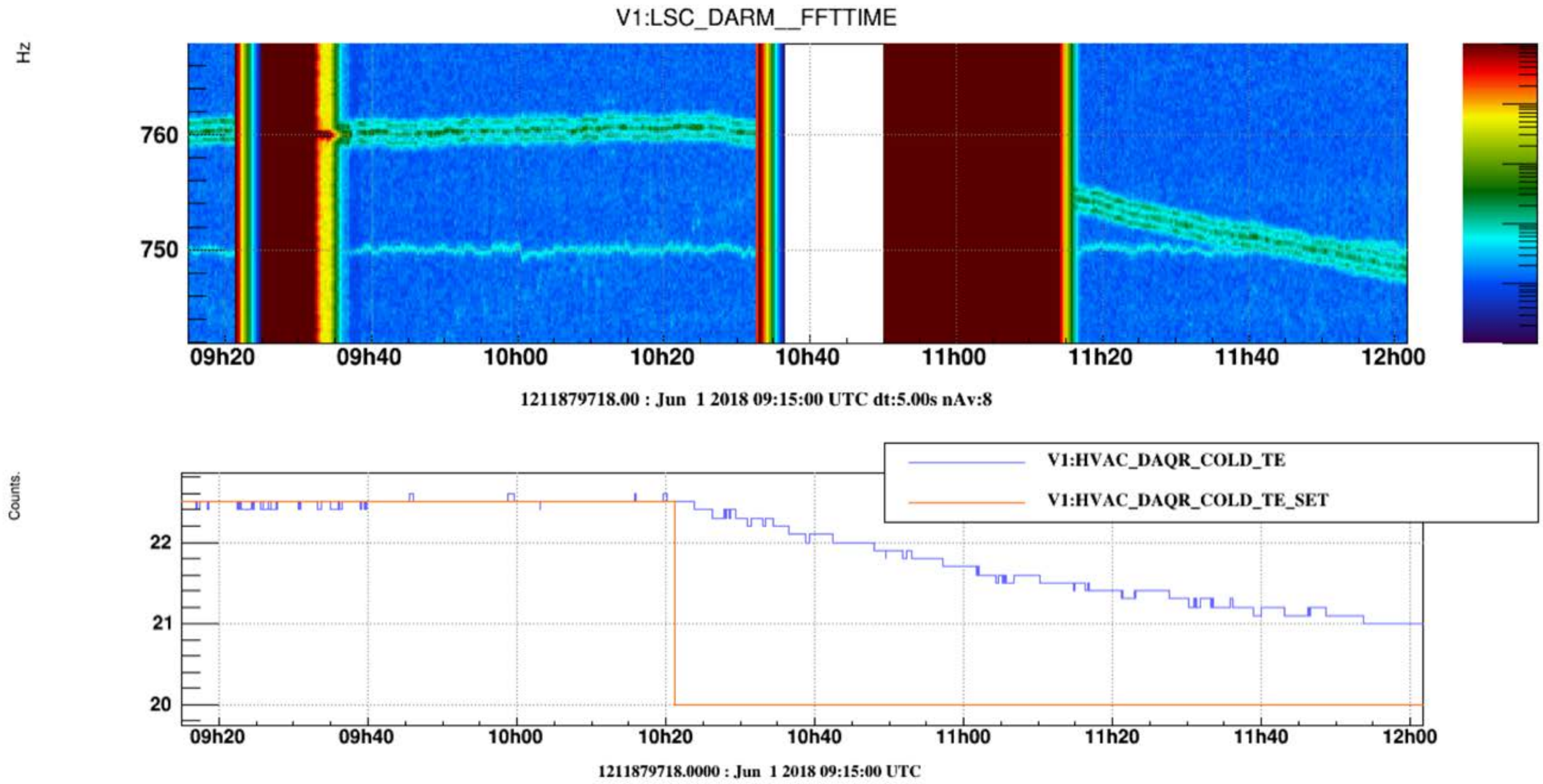
Noise injection campaigns are con

Auxiliary signals are analyzed to fi

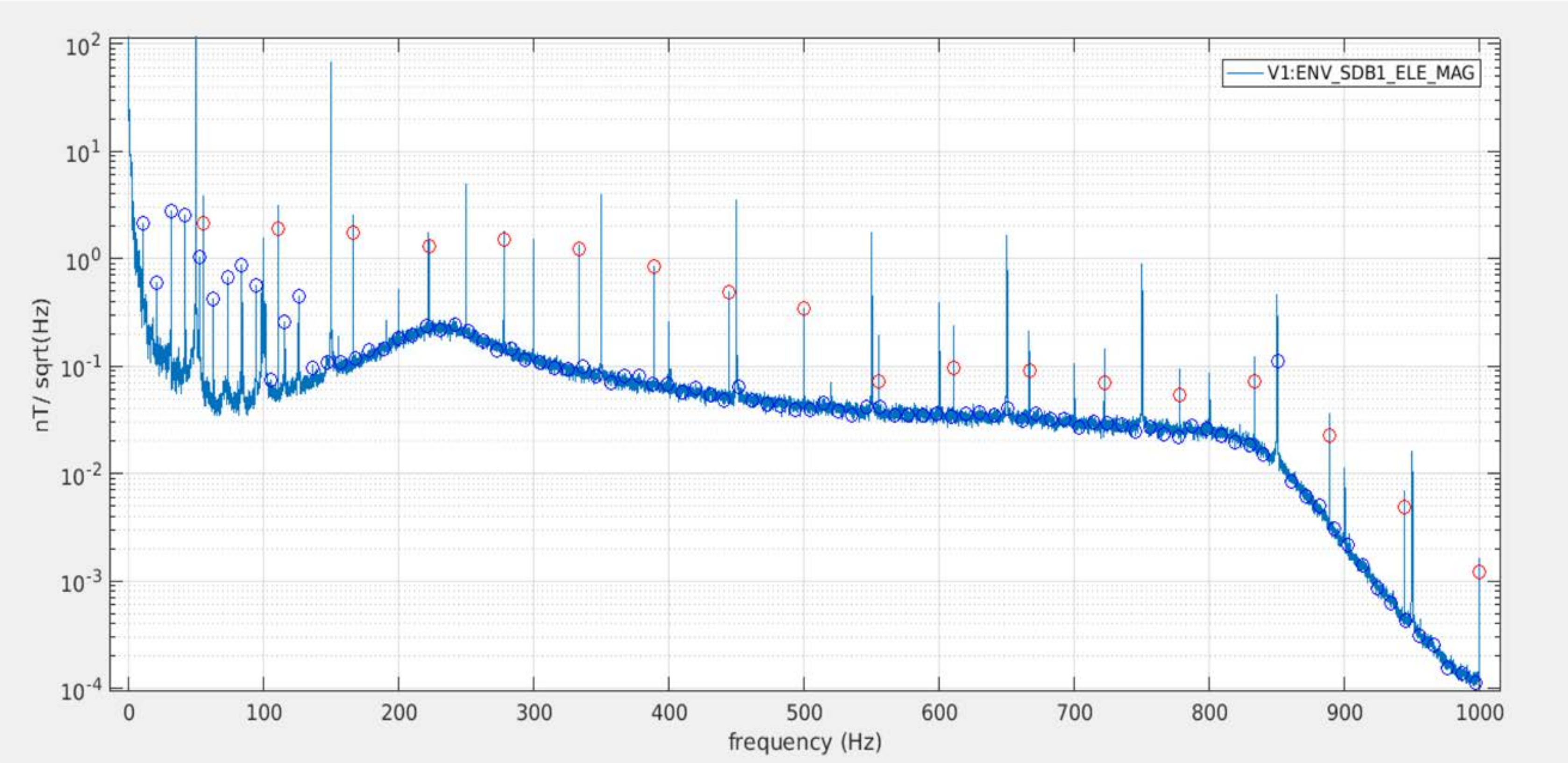

Spectrogram of V1:spectro_LSC_DARM_300_100_0_0 : start=1181606078.000000 (Thu Jun 15 23:54:20 2017 UTC)
Frequency (Hz)
260
255
250
245
240
235
230
225
16/06
17/06
18/06
19/06
20/06
21/06
22/06
23/06
24/06
25/06
UTC Time (day-hour)

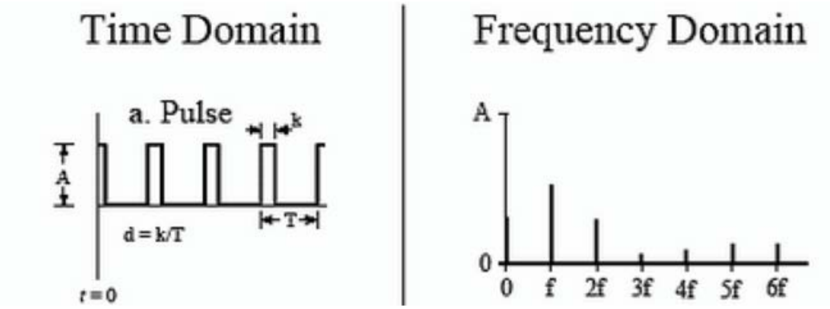


Cooling fans: mechanical vibrations coupling to the detector



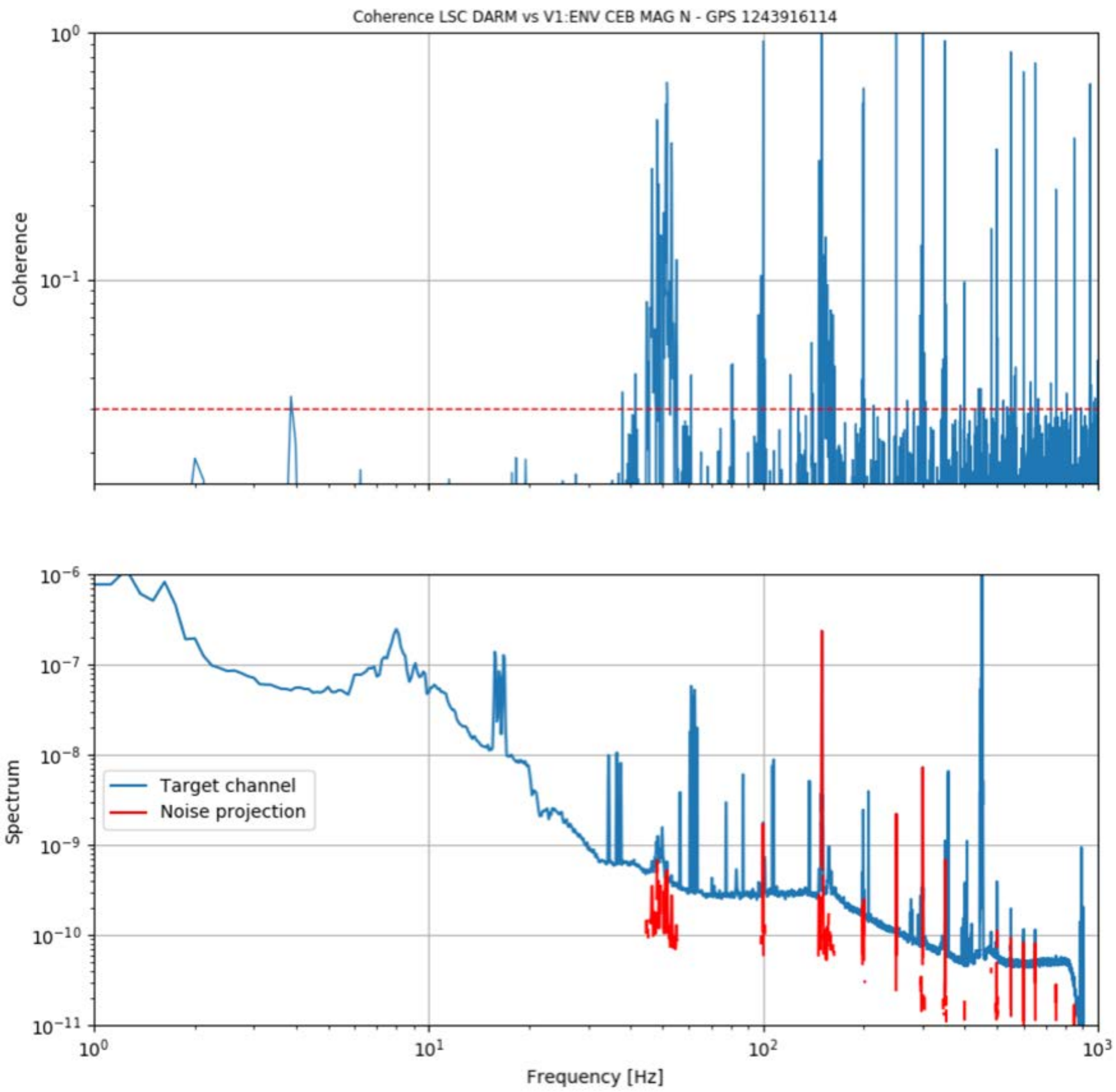
Noise disturbances (EM) produced by electronic devices are typically very sensitive to





Combs are often produced by clocks

Measure the coherence between spectra of 2 channels
Brute force: examine all auxiliary channels



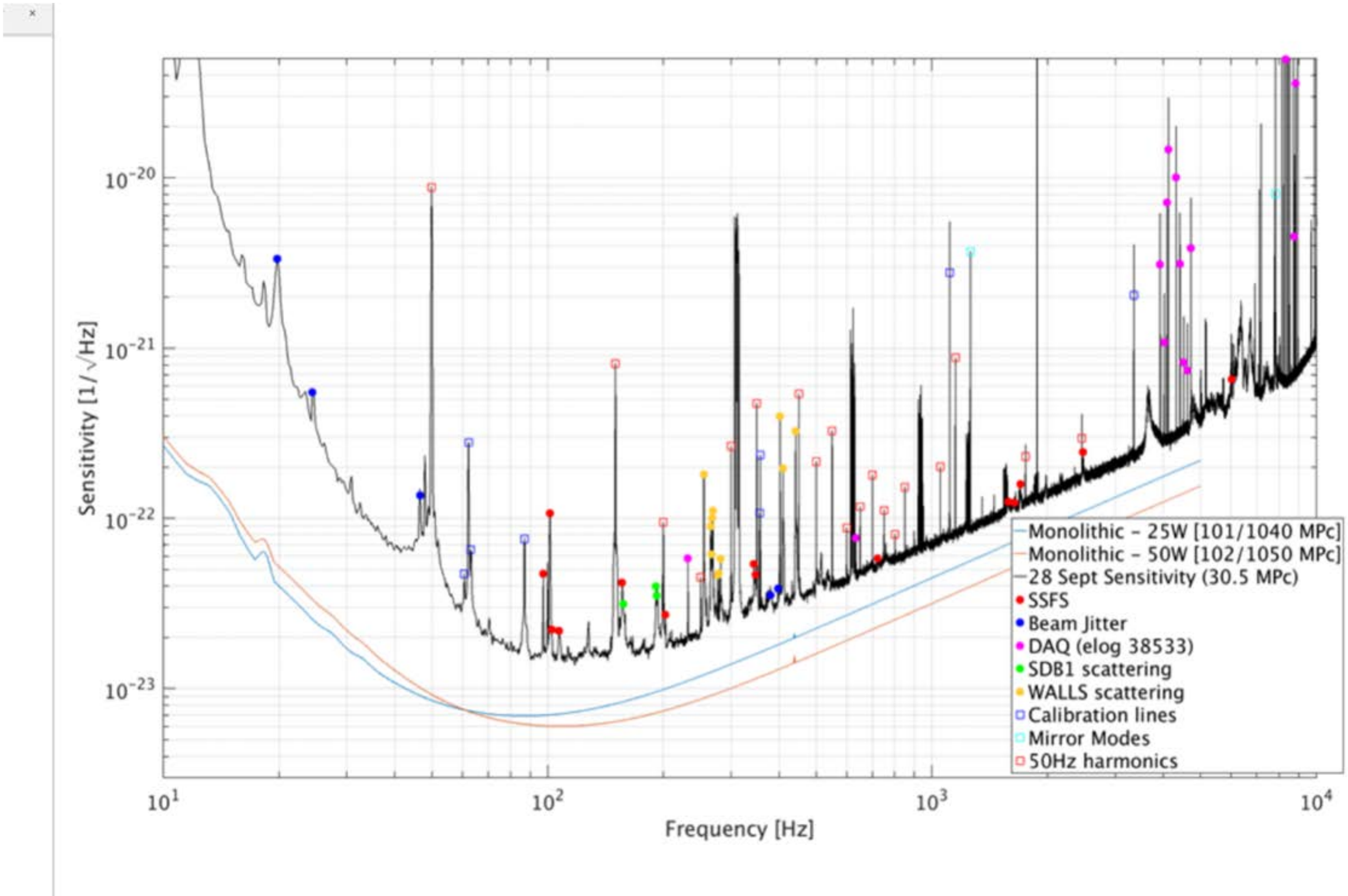
Example:

50 Hz line + harmonics have a very high

--> Europe mains frequency = 50 Hz

Investiagtion tools are run every day to r

Spectral noise summary



A database is used to record our knowledge of spectral features
→ time of appearance/disapearence
→ central frequency
→ bandwidth
→ origin, if known

Transient noise

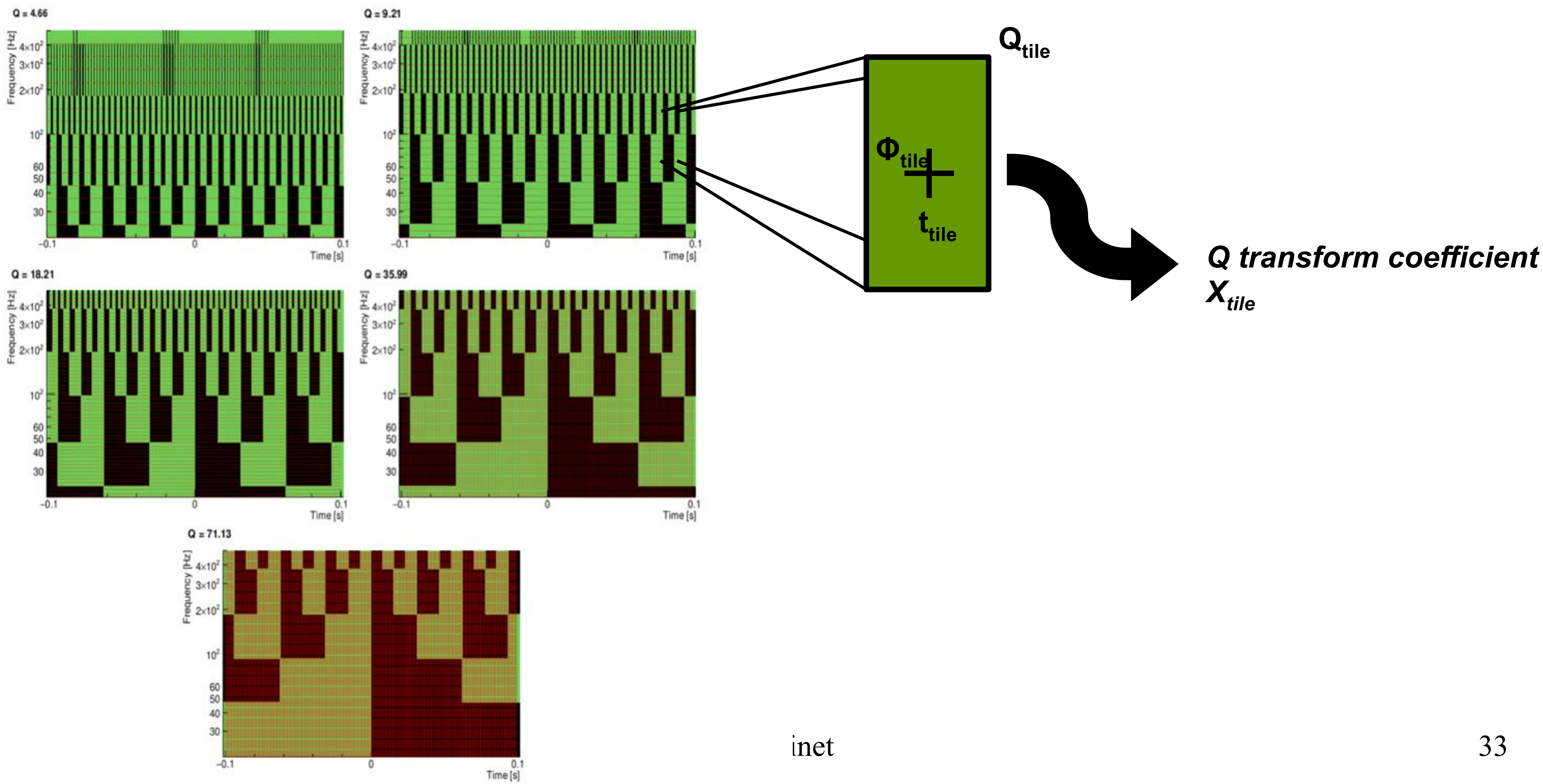
Q transform = short Fourier Transform with a Gaussian window (window size ~ 1/f)

lti-resolution analysis motivated in the introduction, the data are proces
ınsform is a modification of the standard short time Fourier transform
es inversely with frequency such that the time-frequency plane is covere
signal time series, $x(t)$, is projected onto a basis of complex-valued wind

$$X(\tau, \phi, Q) = \int_{-\infty}^{+\infty} x(t) w(t-\tau, \phi, Q) e^{-2i\pi\phi t} dt.$$

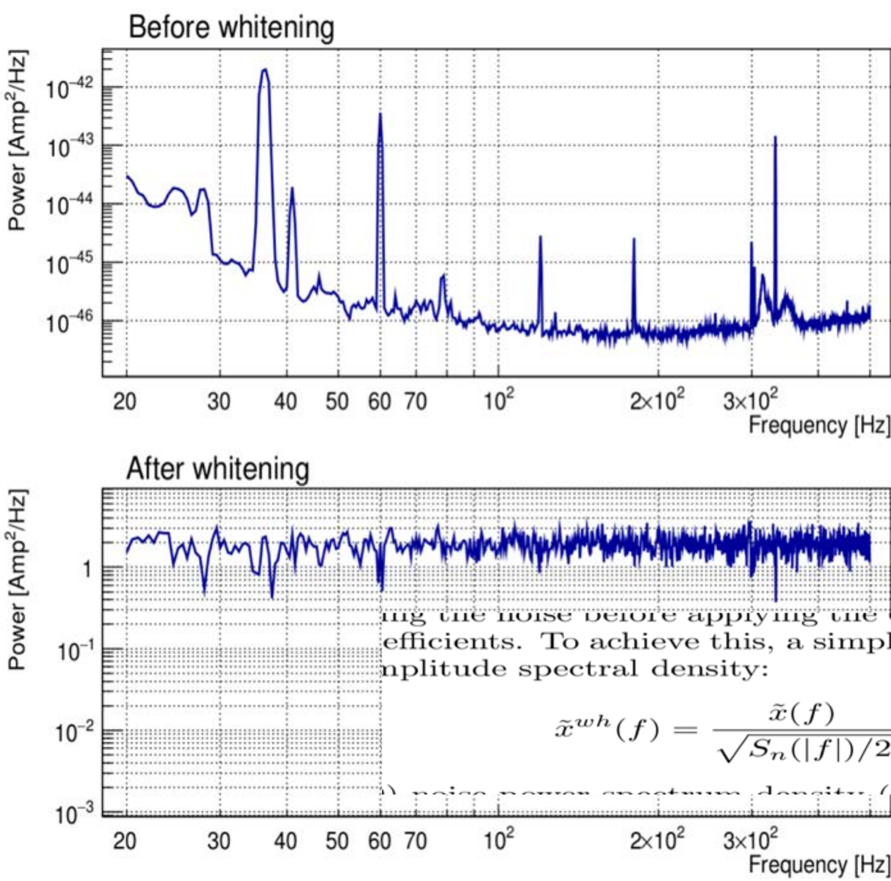
ent, X, measures the average signal amplitude and phase within a time-fr
ıe τ and frequency ϕ, whose shape and area are determined by the requ

→ Tiling: Q planes with frequency rows (log) subdivided in time tiles (linear)



The time series must be whitened. Several methods are used :
- reweighting of frequency bins
- linear prediction

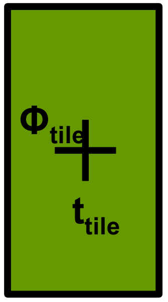
→ white noise



efficients. To achieve this, a simple meth
nplitude spectral density:

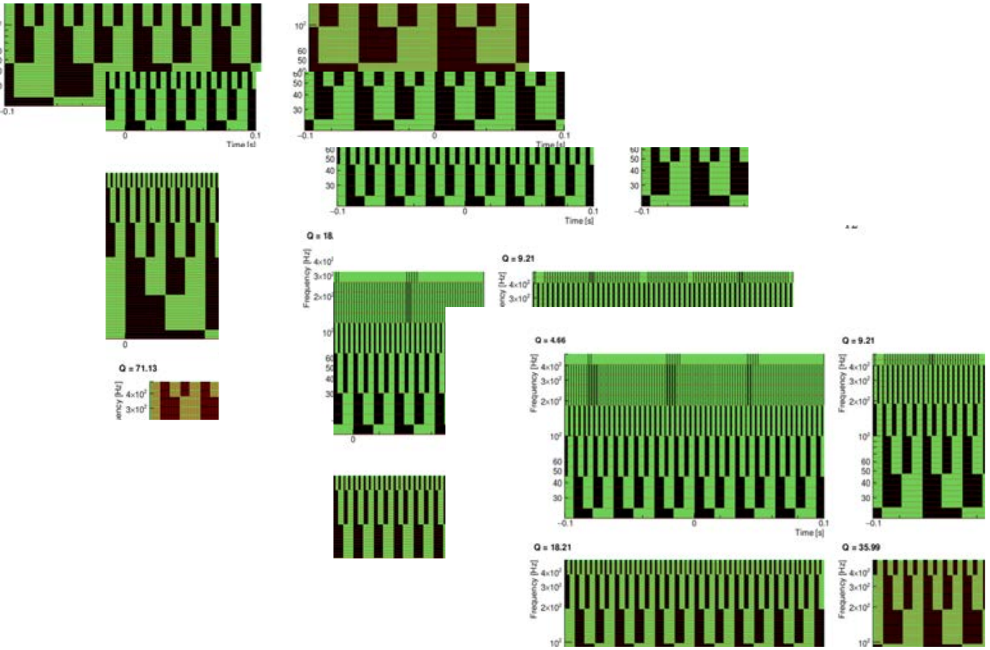
$$\tilde{x}^{wh}(f) = \frac{\tilde{x}(f)}{\sqrt{S_n(|f|)/2}},$$

The Q-transform of whitened data directly



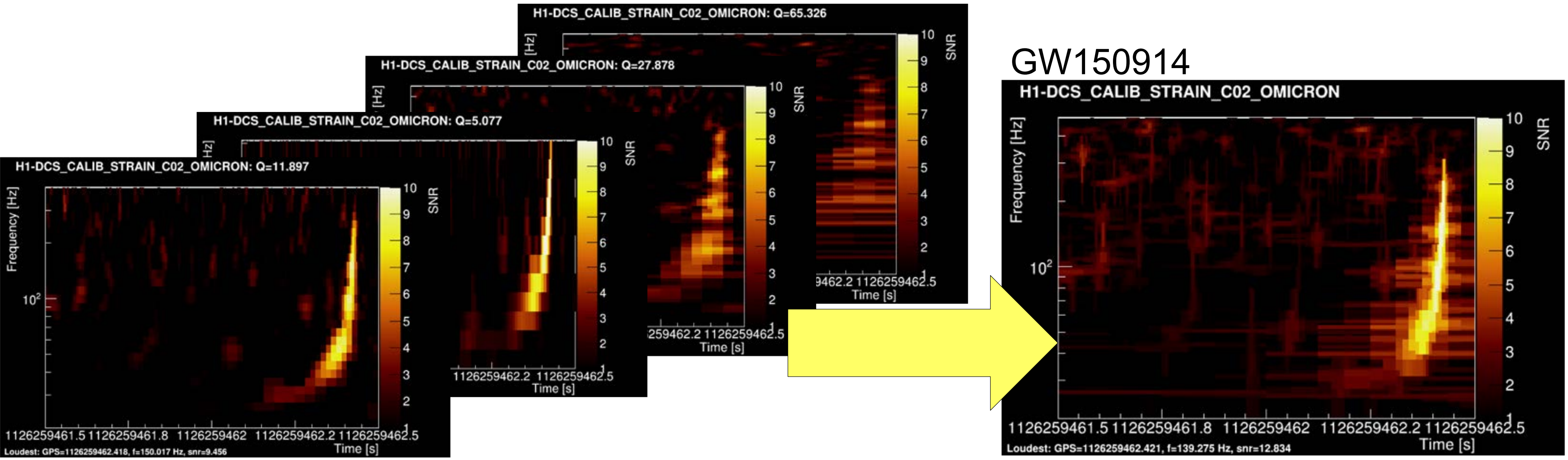
- peak time and duration
- peak frequency and bandwidth
- SNR

Time-frequency maps



The Q transform is computed for every tiles → SNR → maps

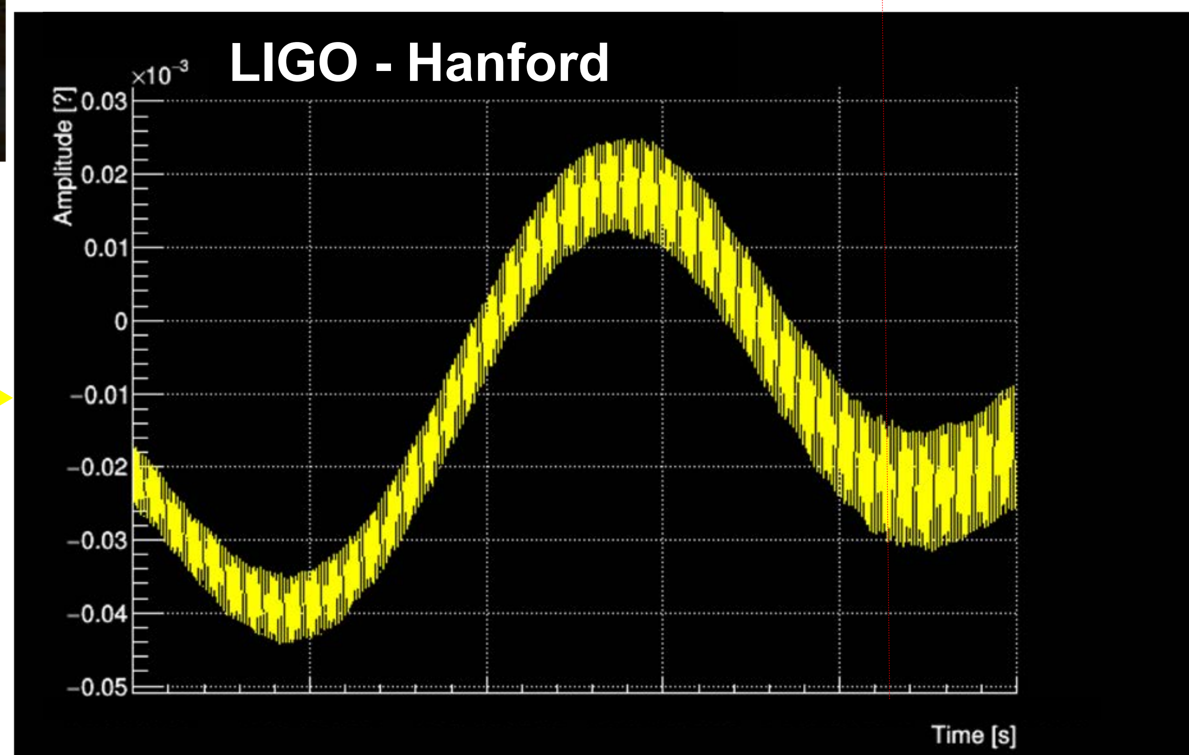
Maps are stacked up, tiles with highest SNR values are c



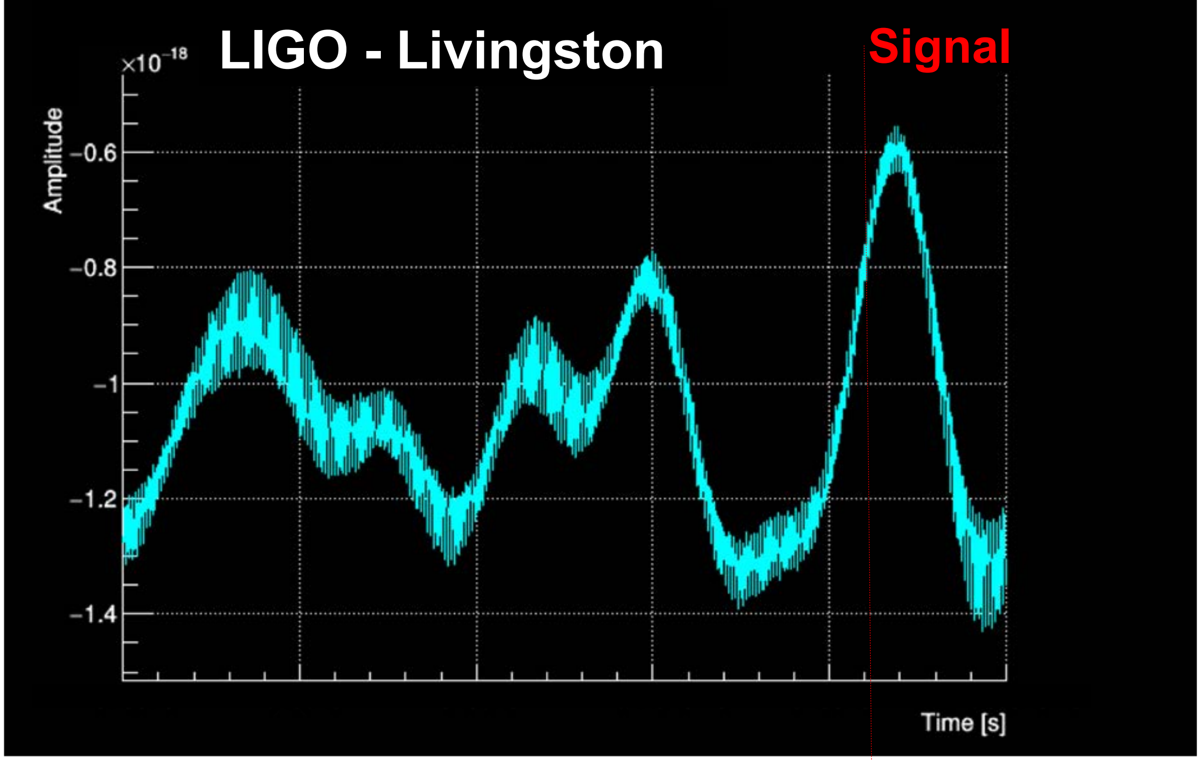
GW150914

Output power

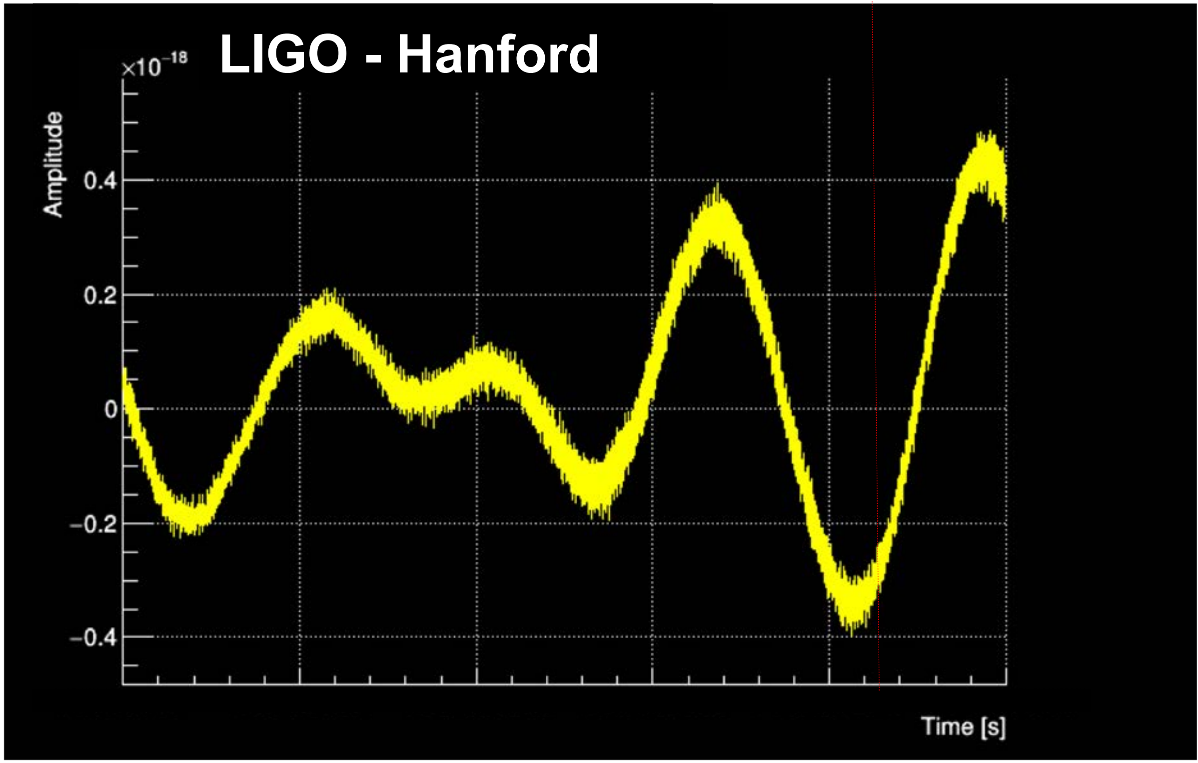
Output power



GW150914



$h(t)$

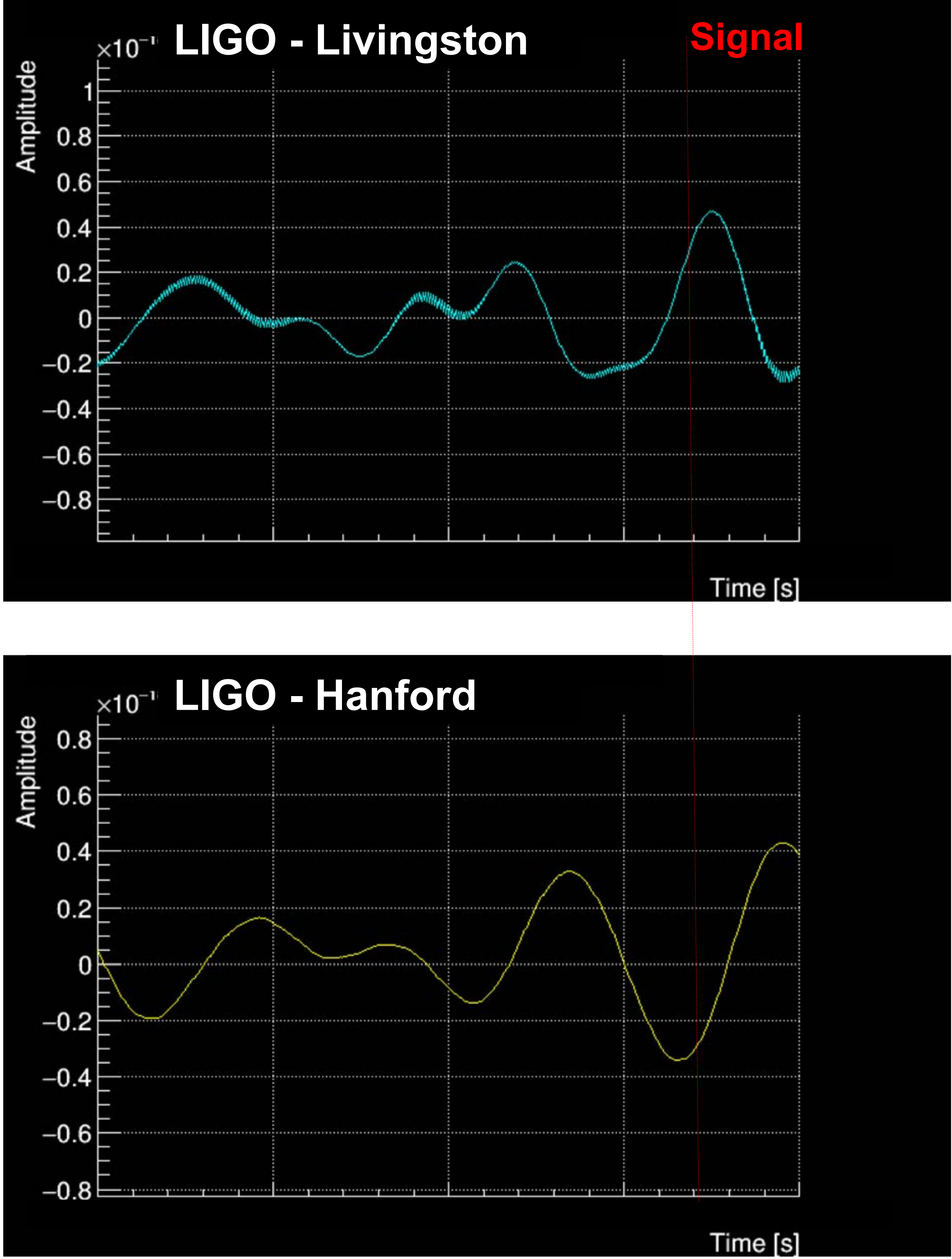


$h(t)$

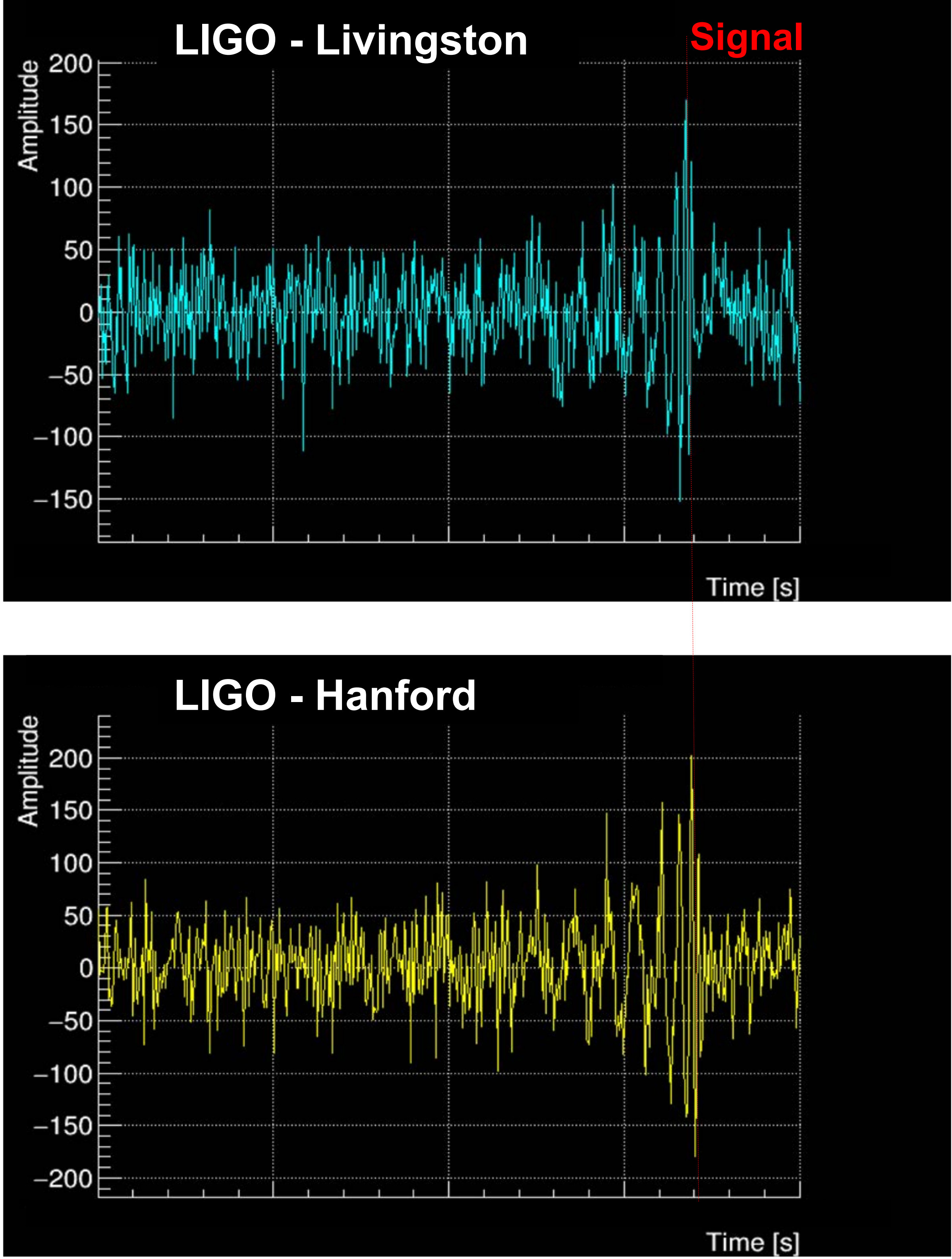
Data is calibrated
→ GW strain amplitude *h(t)*
(including high-pass filter f > 10 Hz)

GW150914

Data are low-pass filtered (here, < 500 Hz)



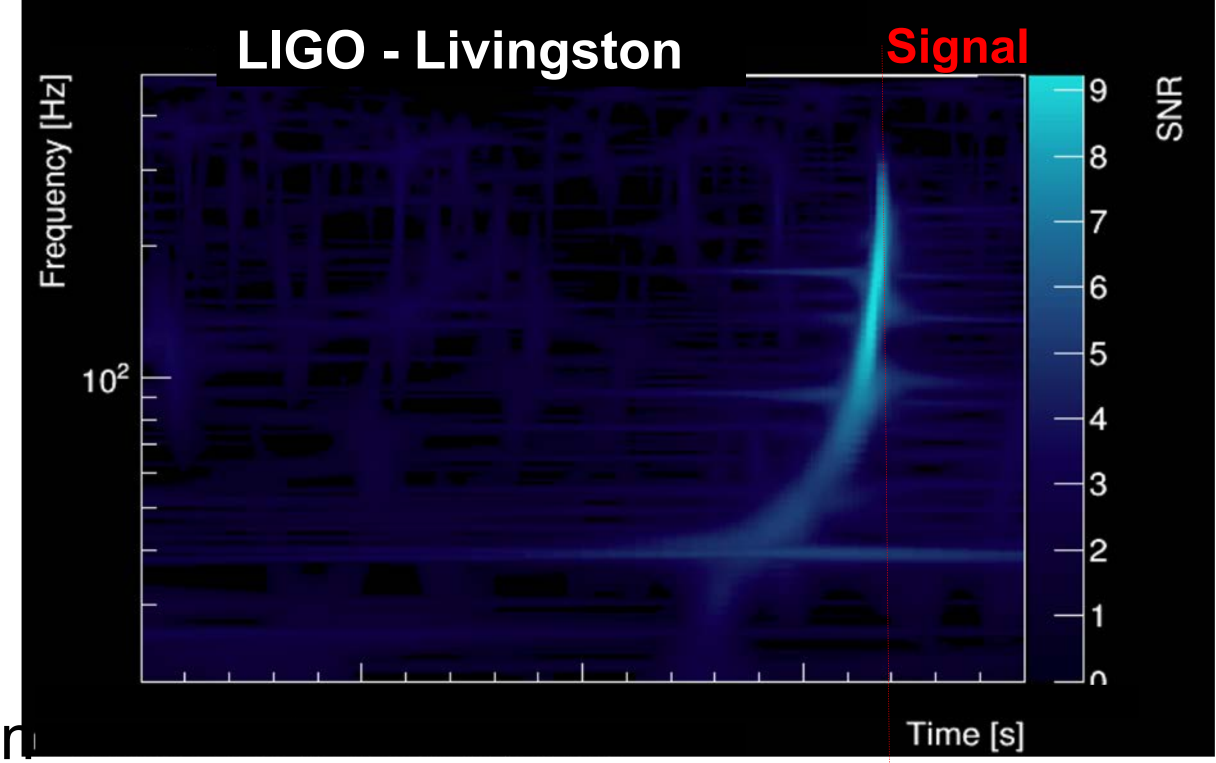
GW150914

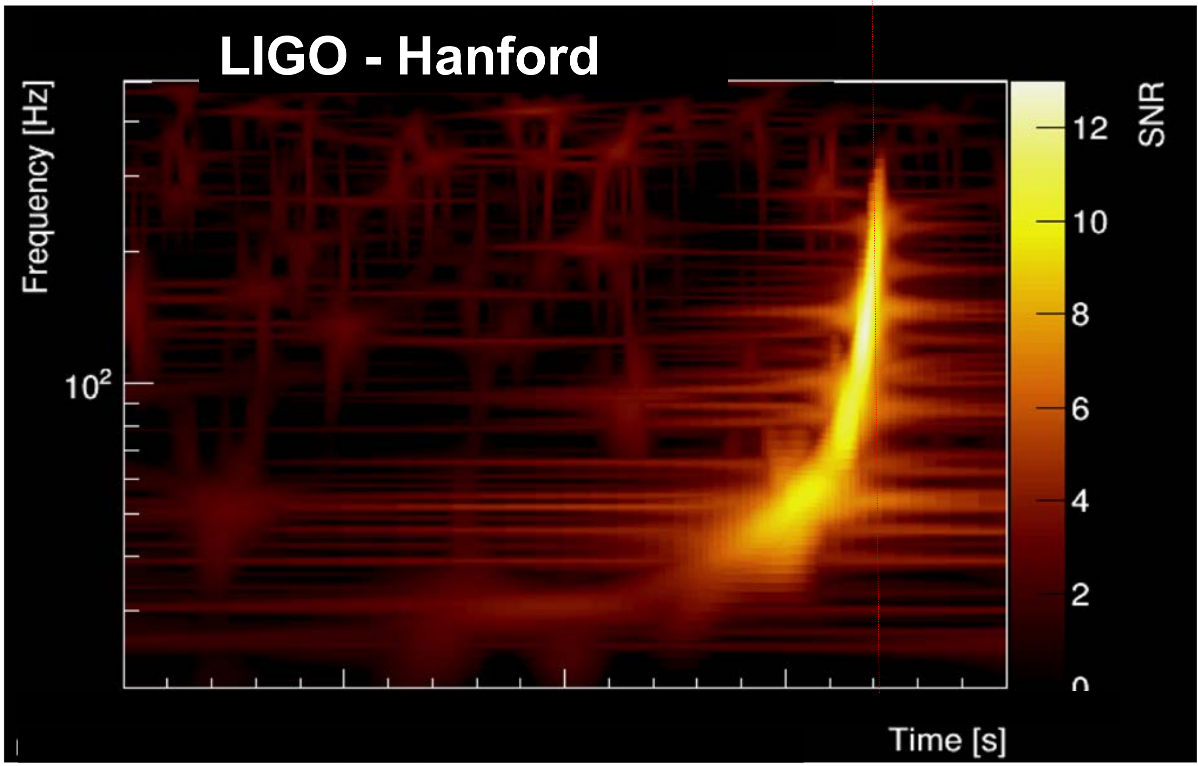


Data are whitened

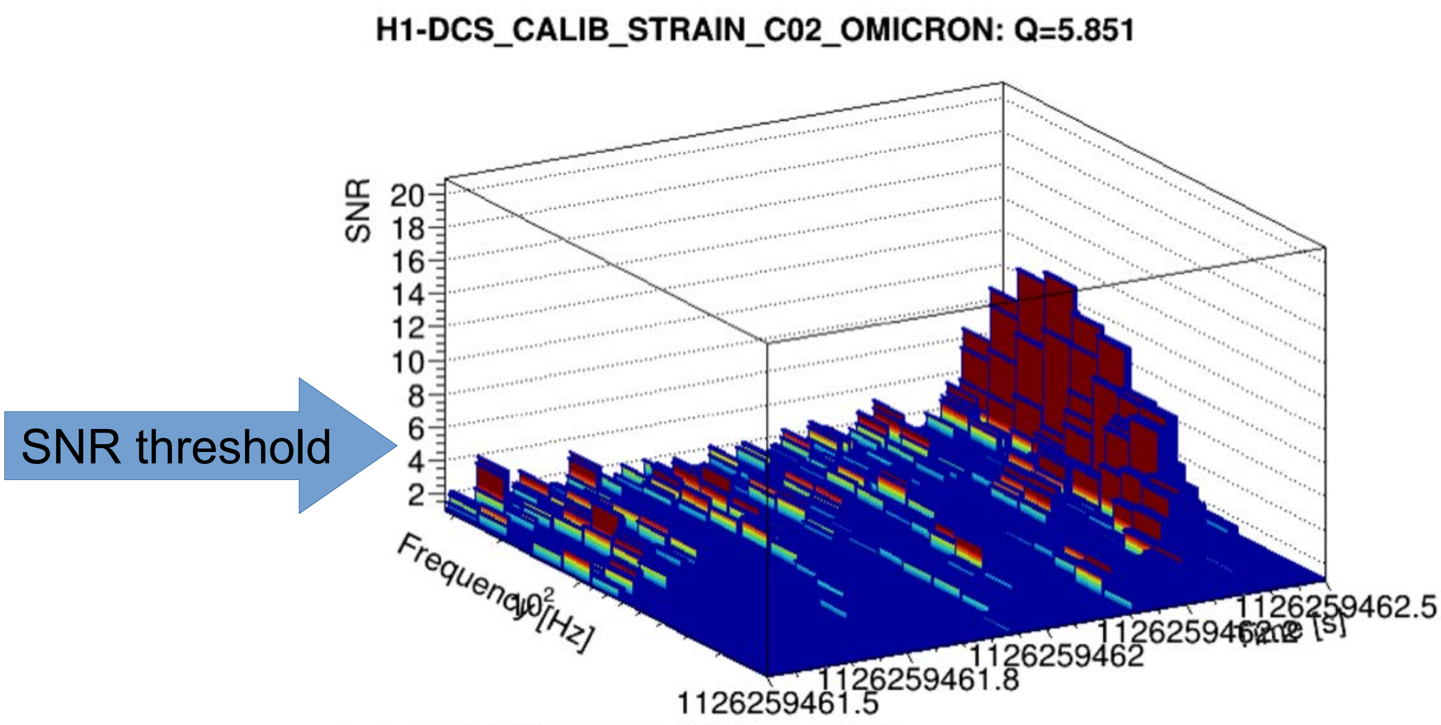
GW150914

Time-frequency decomposition
(Q transform)

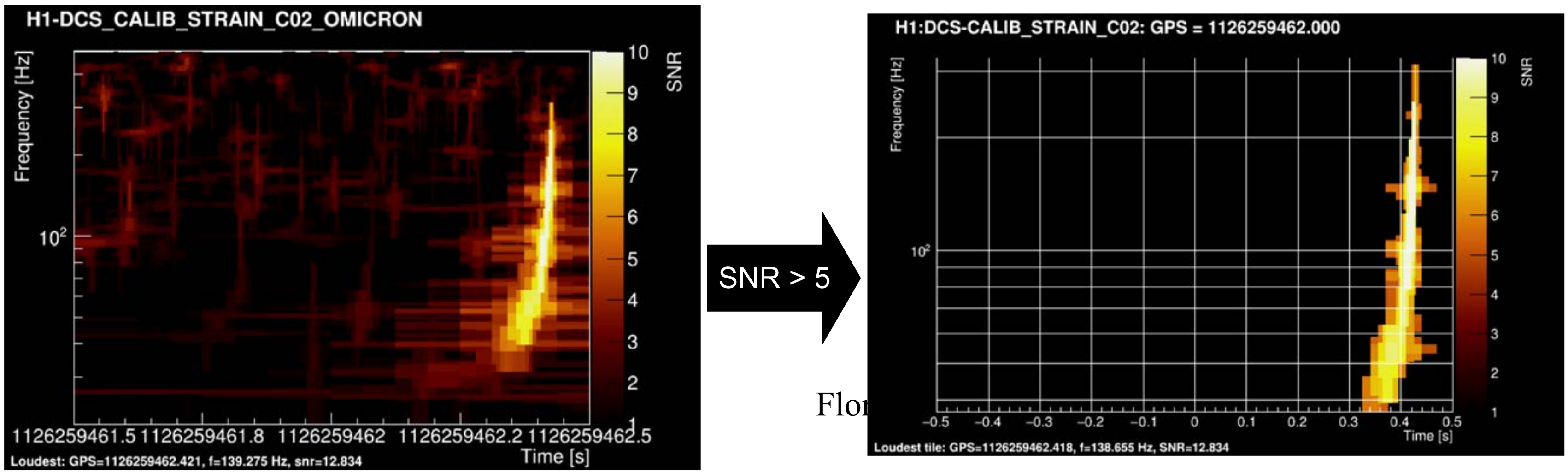


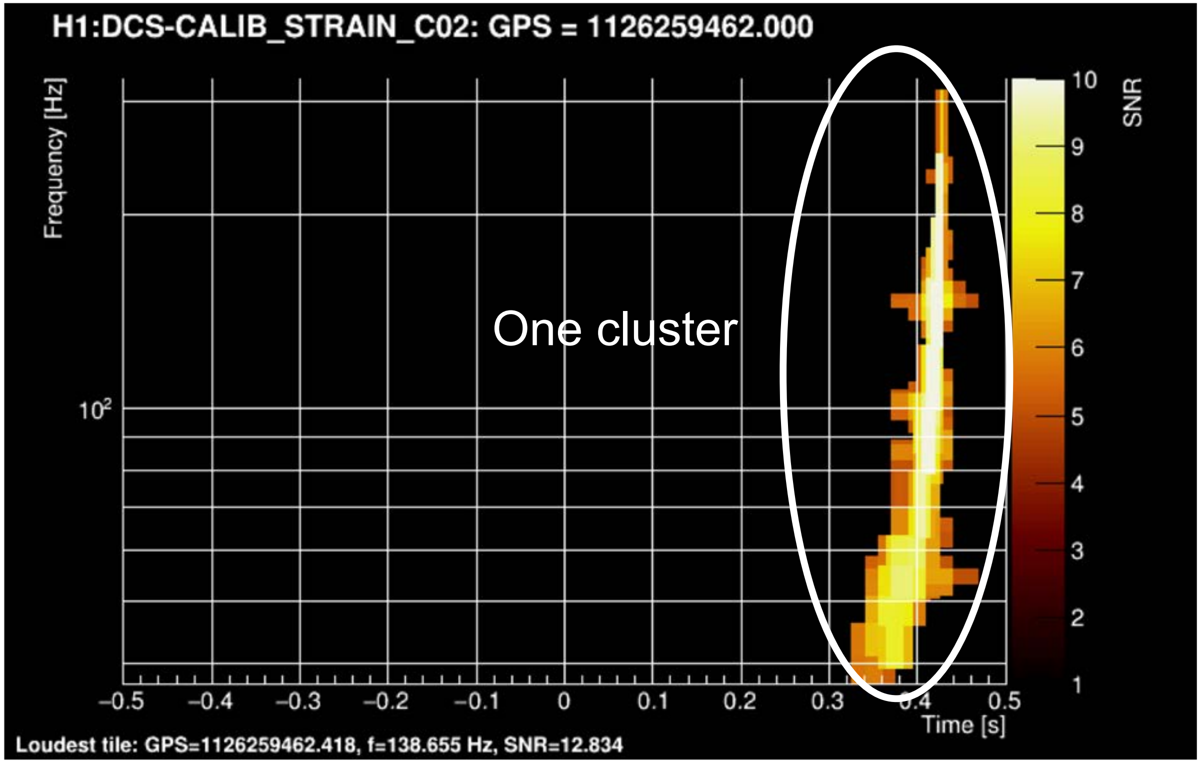


Triggers



A trigger = a tile with a SNR value above a given threshold





Triggers are clustered in time

One cluster:
- time
- frequency
- Q value
- SNR

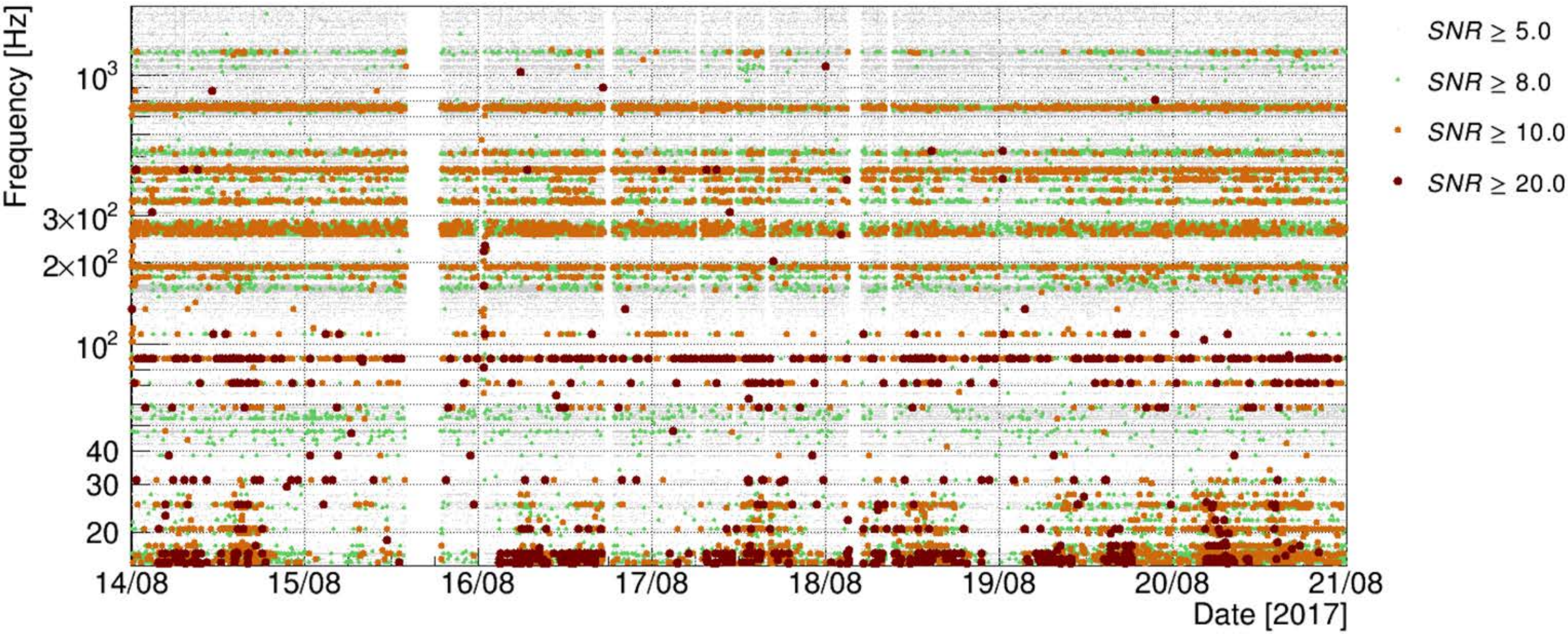
→ given by the tile with the highest SNR

+ duration, bandwidth...

For noise investigation we will always work with clusters

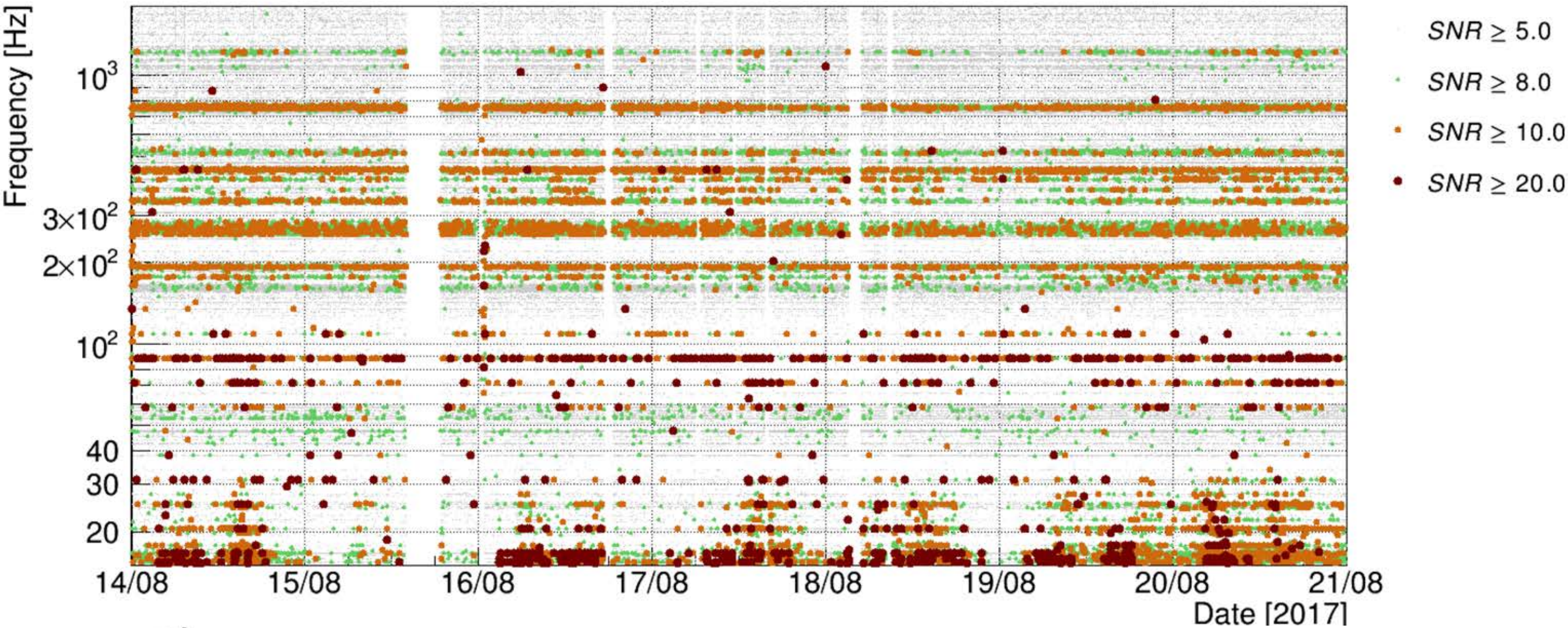
Clusters will be called « triggers » for simplicity.

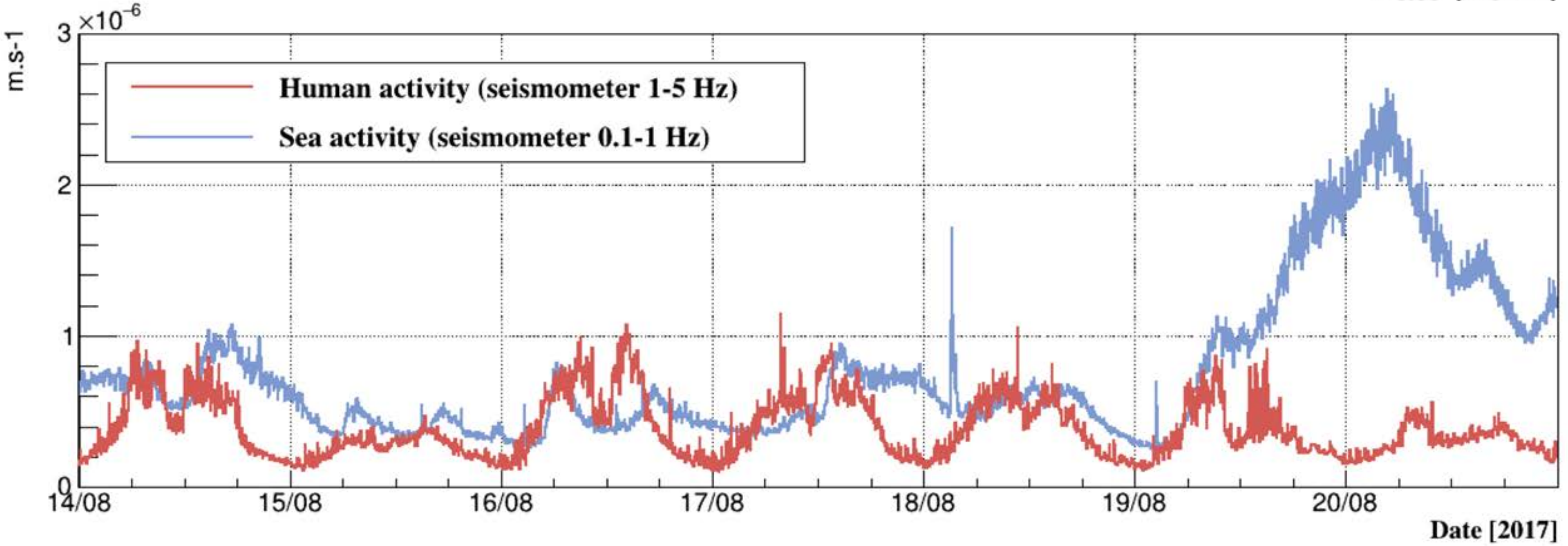
One typical week of glitches in Virgo data (O2)



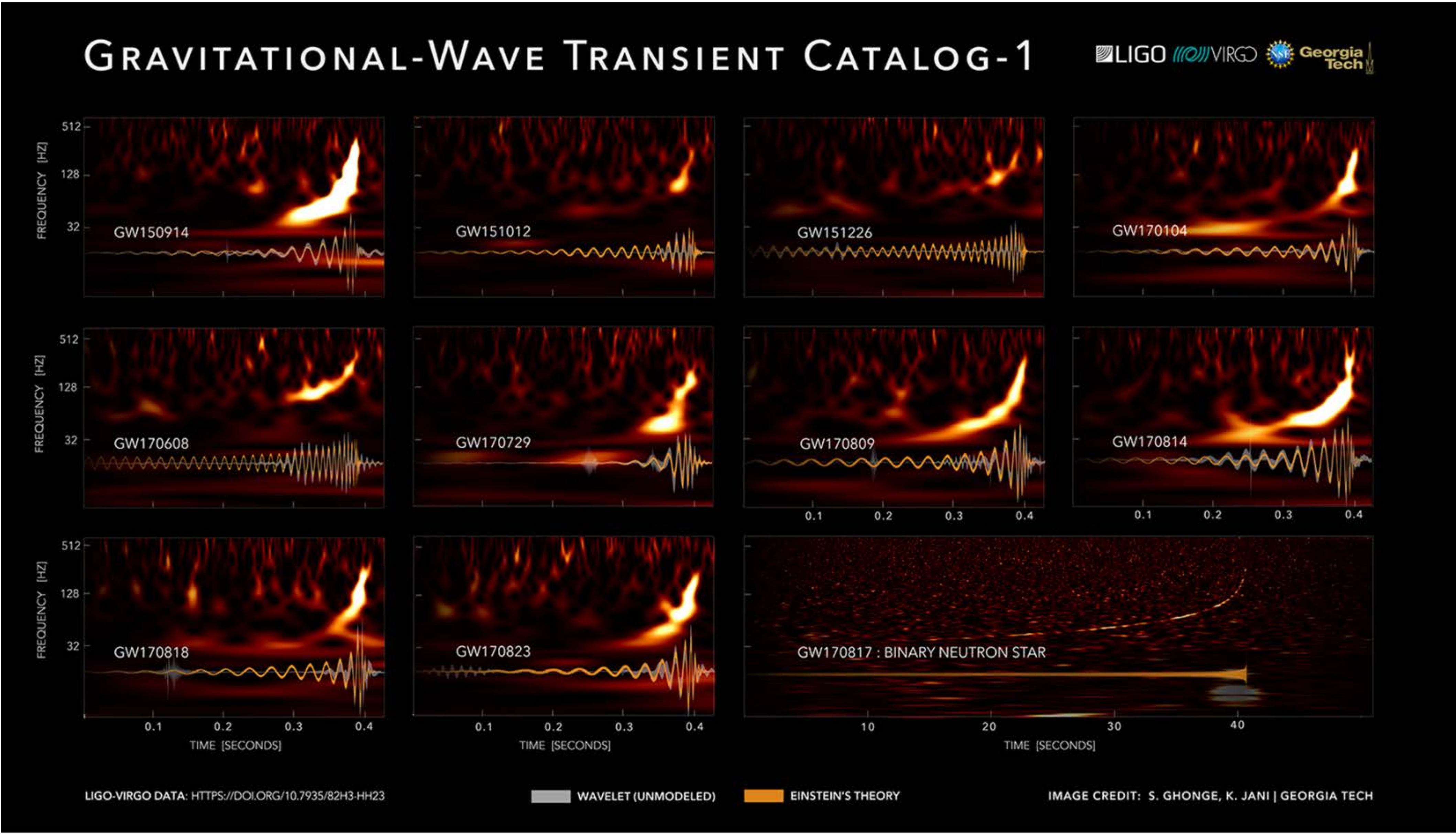
→ High rate of glitches
→ Specific distribution in time/frequency/SNR → we will exploit this for investigation
→ Use glitch population for characterization studies

One typical week of glitches in Virgo data (O2)

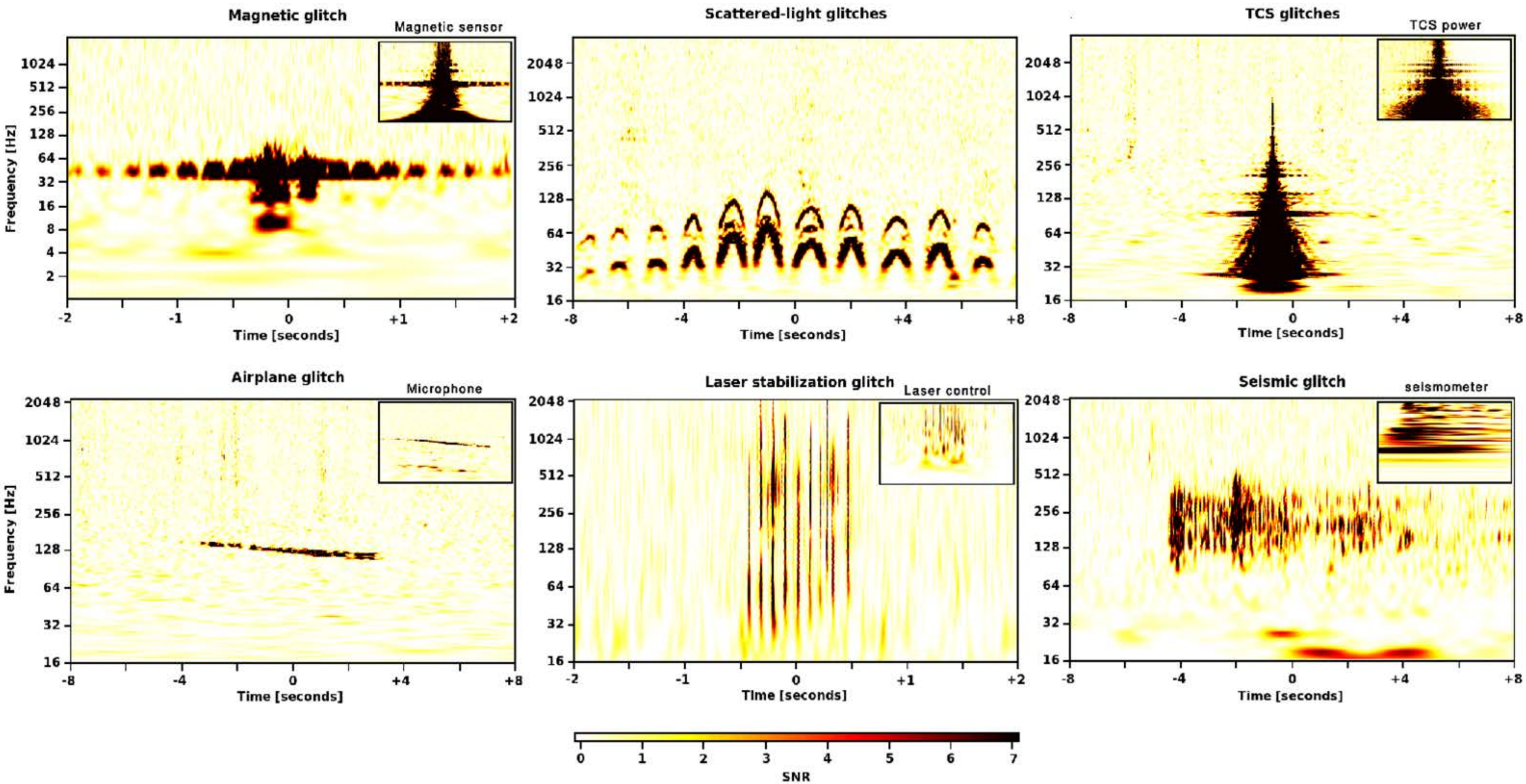




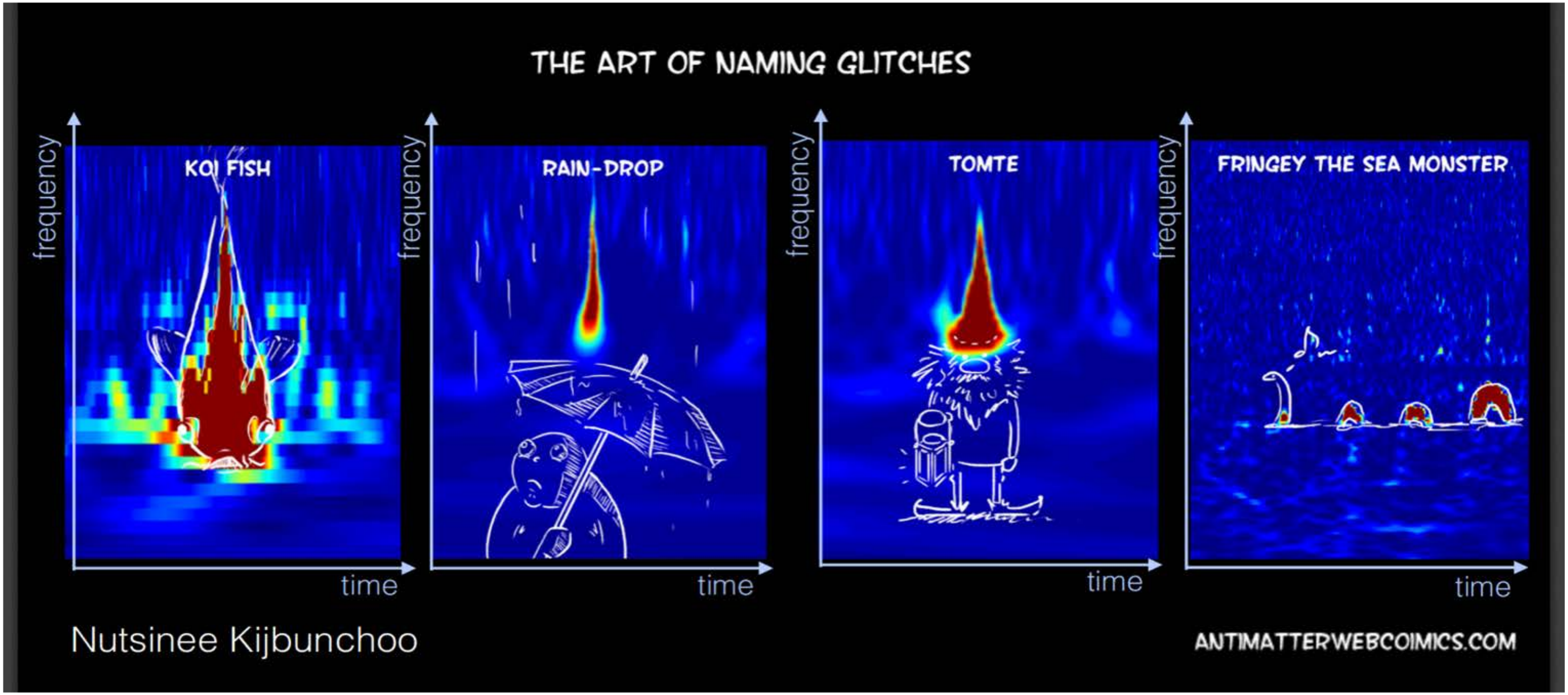
Signal spectrograms



Glitch spectrograms



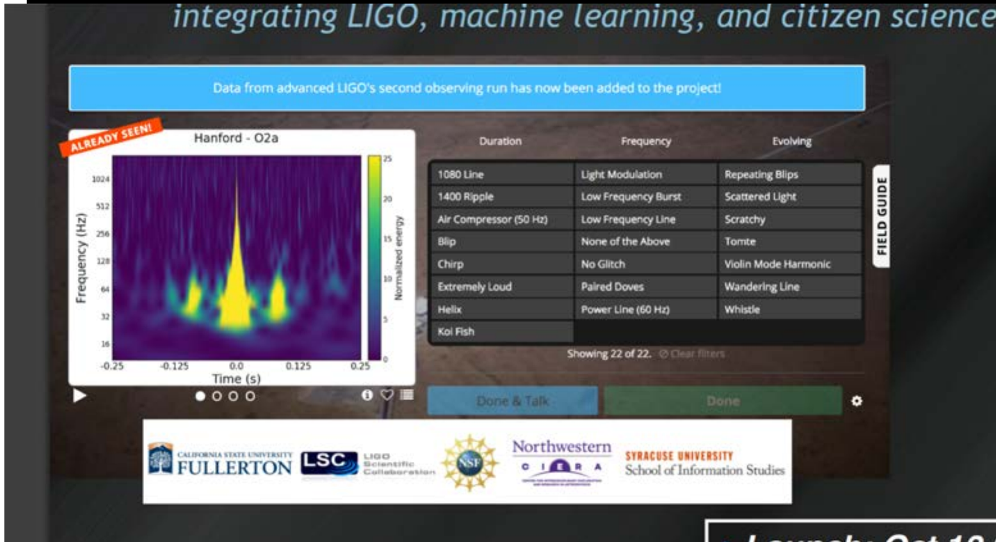
→ Glitch time-frequency distribution can be very specific
→ With experience, the noise source can identified when looking at time-frequency plots

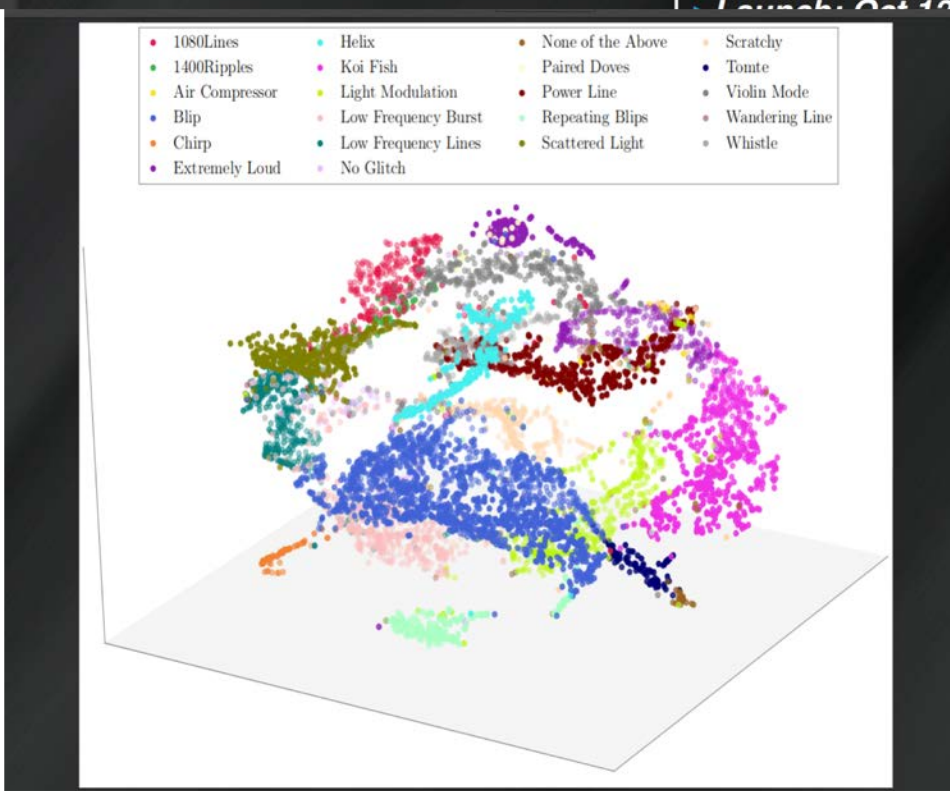


→ Glitch time-frequency distribution can be very specific

→ With experience, the noise source can identified when looking at time-frequency plots

Glitch classification





Glitch classification projects

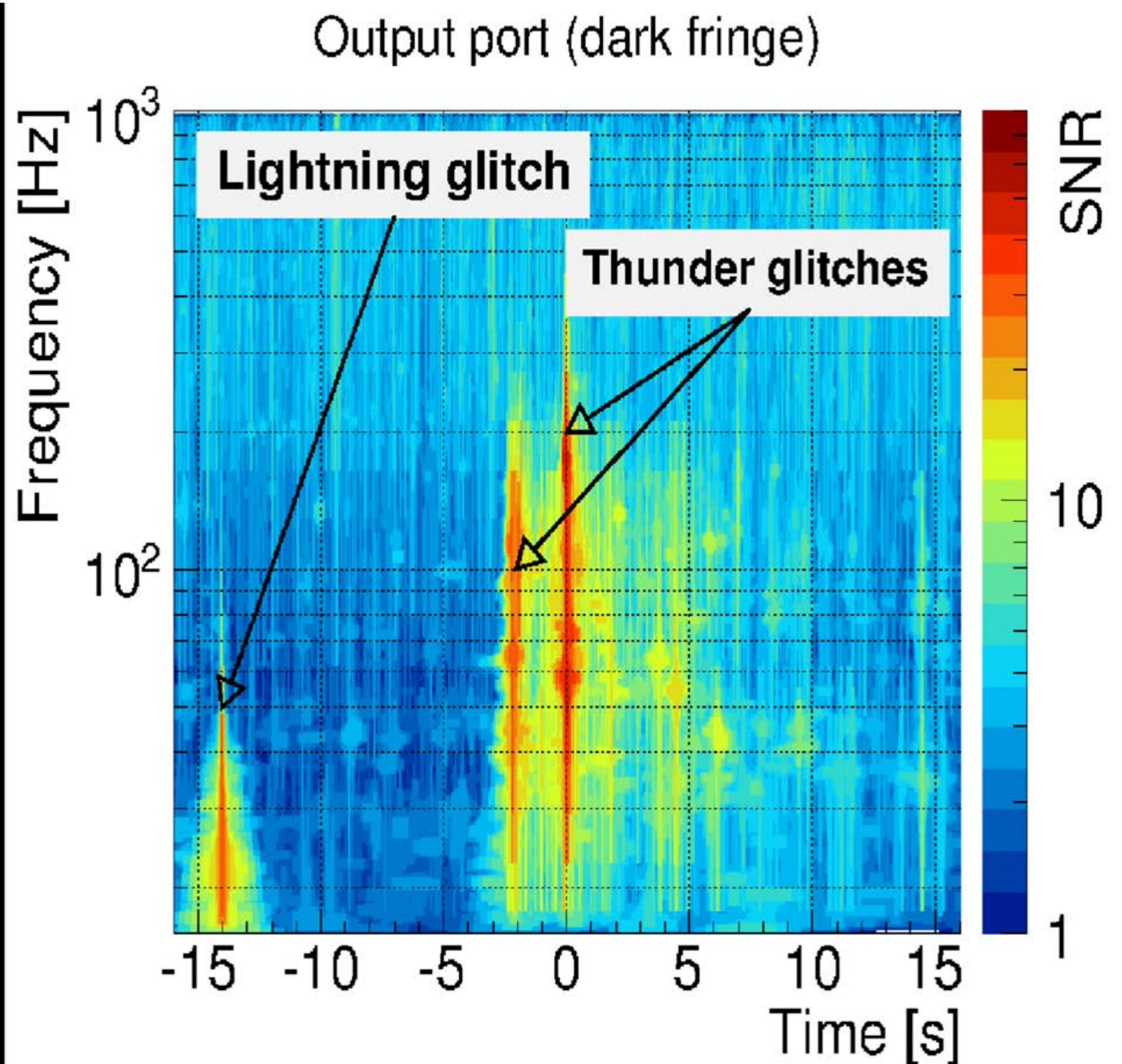
ex. citizen science ”gravity spy”

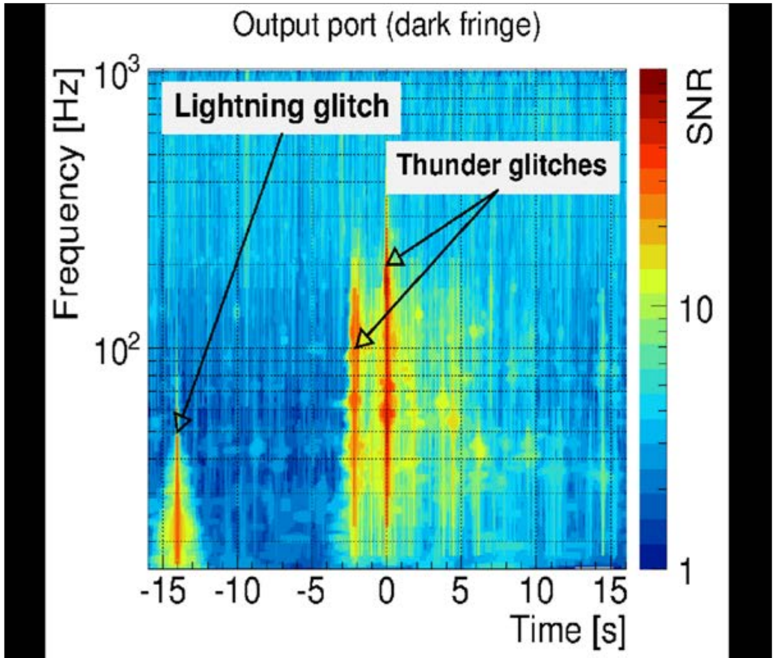
Machine learning algorithms

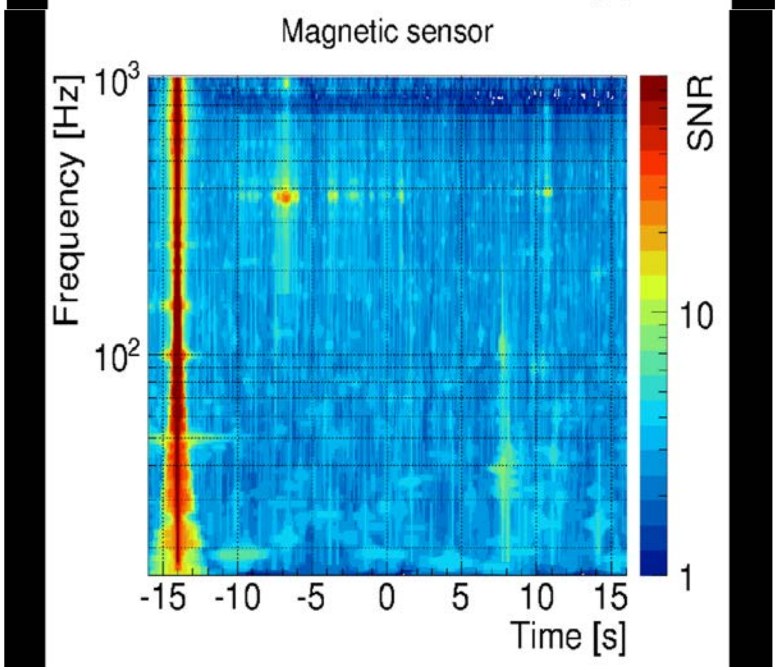
→ classify glitches for noise investigations

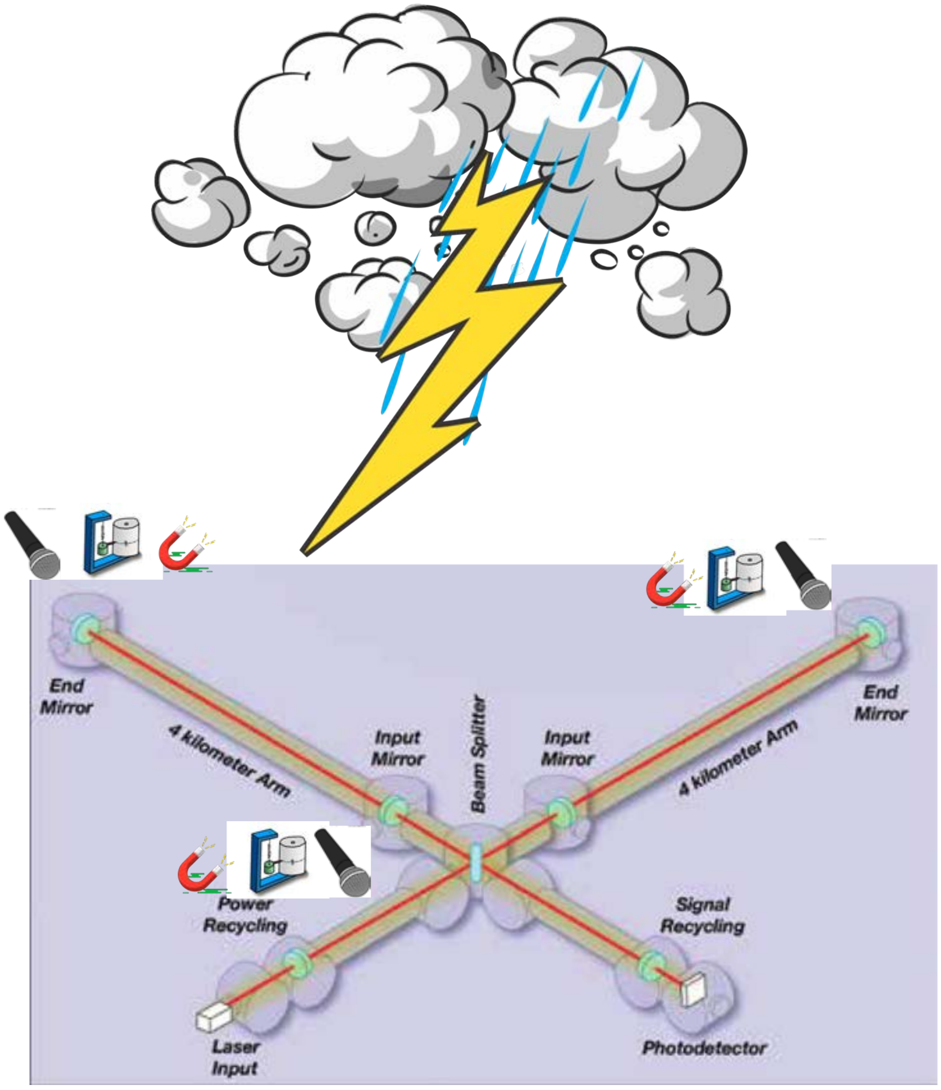
→ Test similarity of GW detections with glitch

→ *Detect GWs (?!)*

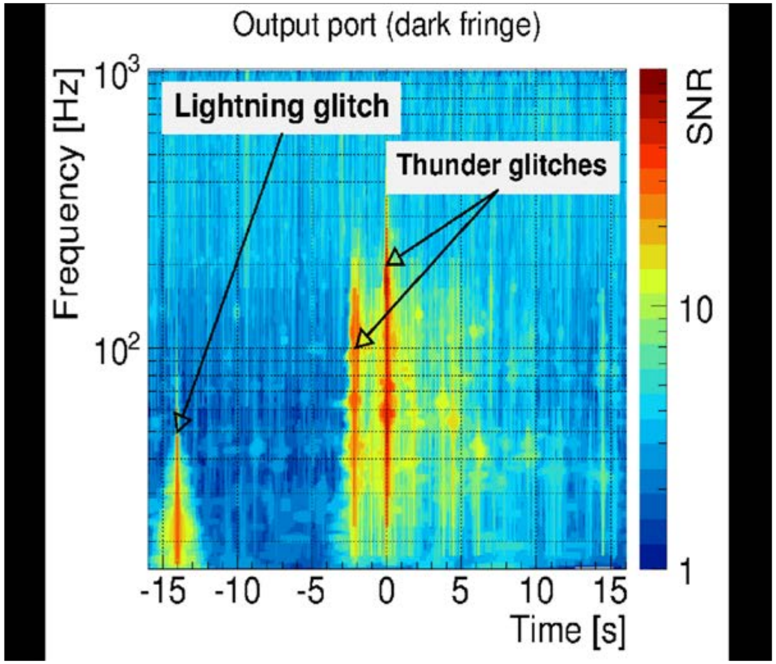

Output port (dark fringe)
Lightning glitch
Thunder glitches
Frequency [Hz]
10^3
10^2
SNR
10
1
-15 -10 -5 0 5 10 15
Time [s]

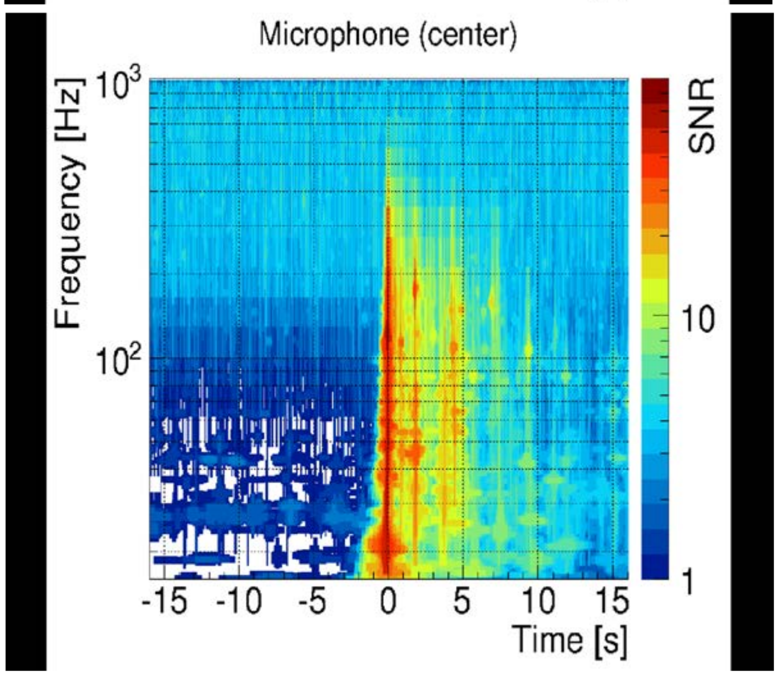

Output port (dark fringe)
Lightning glitch
Thunder glitches
Frequency [Hz]
SNR
Time [s]

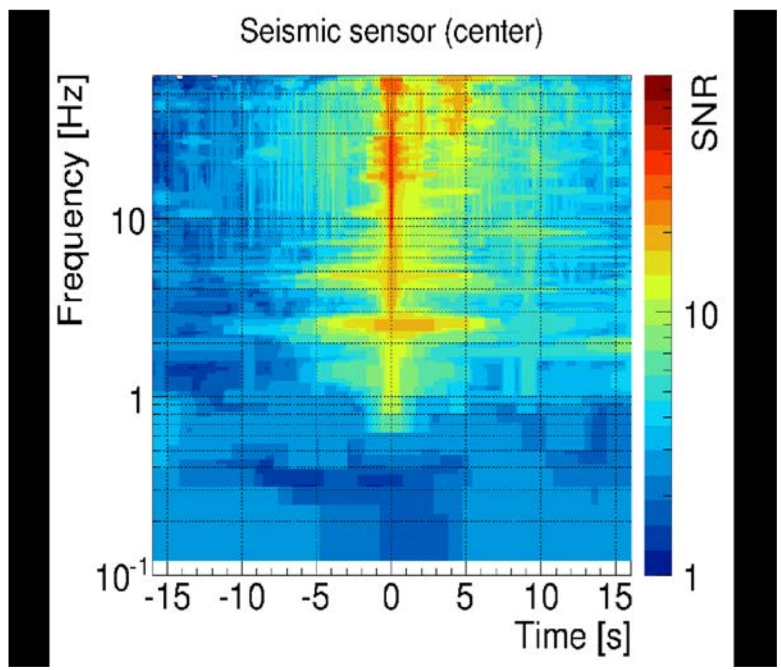

Magnetic sensor
Frequency [Hz]
SNR
Time [s]


End Mirror
4 kilometer Arm
Input Mirror
Beam Splitter
Input Mirror
4 kilometer Arm
End Mirror
Power Recycling
Signal Recycling
Laser Input
Photodetector

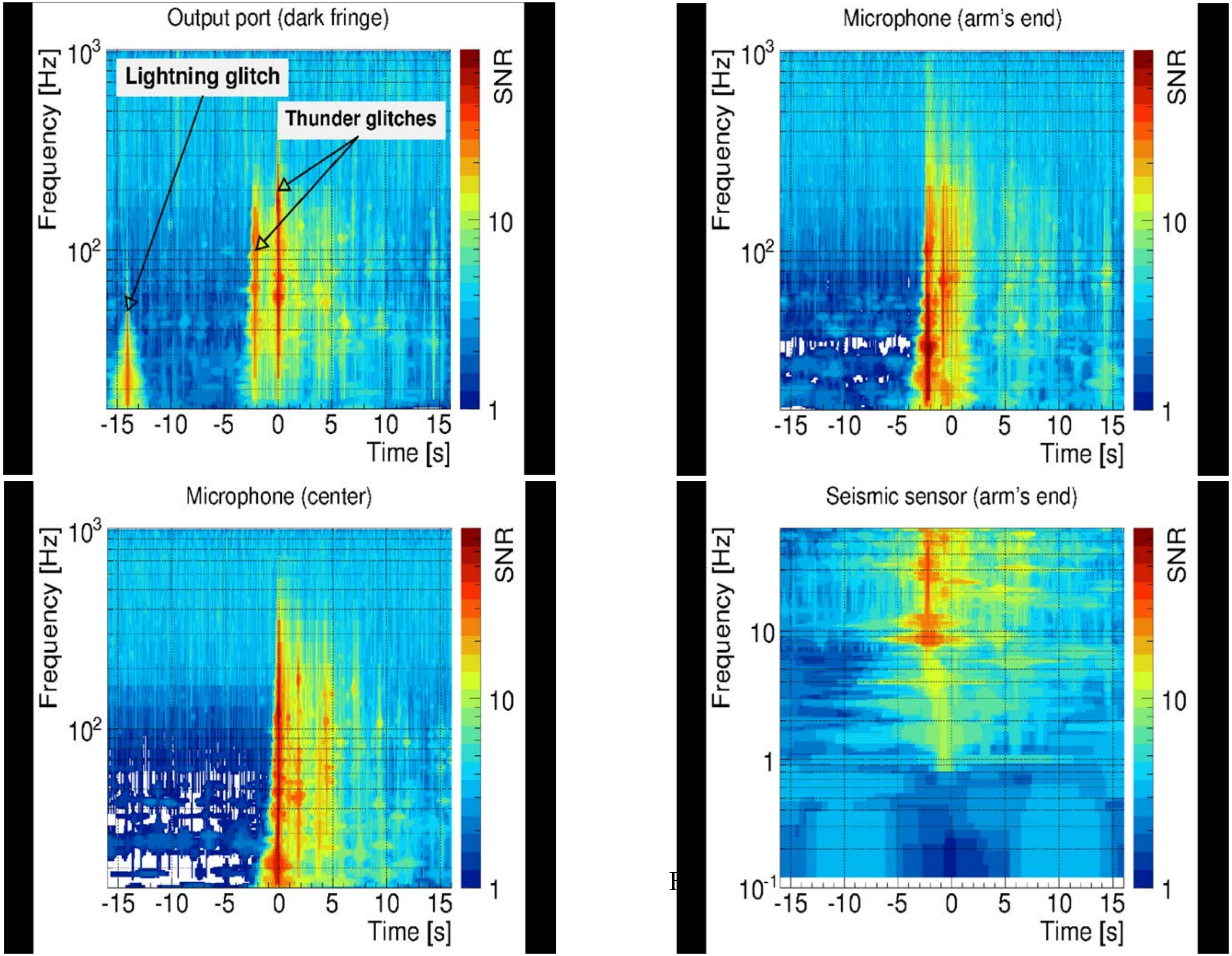
Glitch-to-glitch example







Glitch-to-glitch example



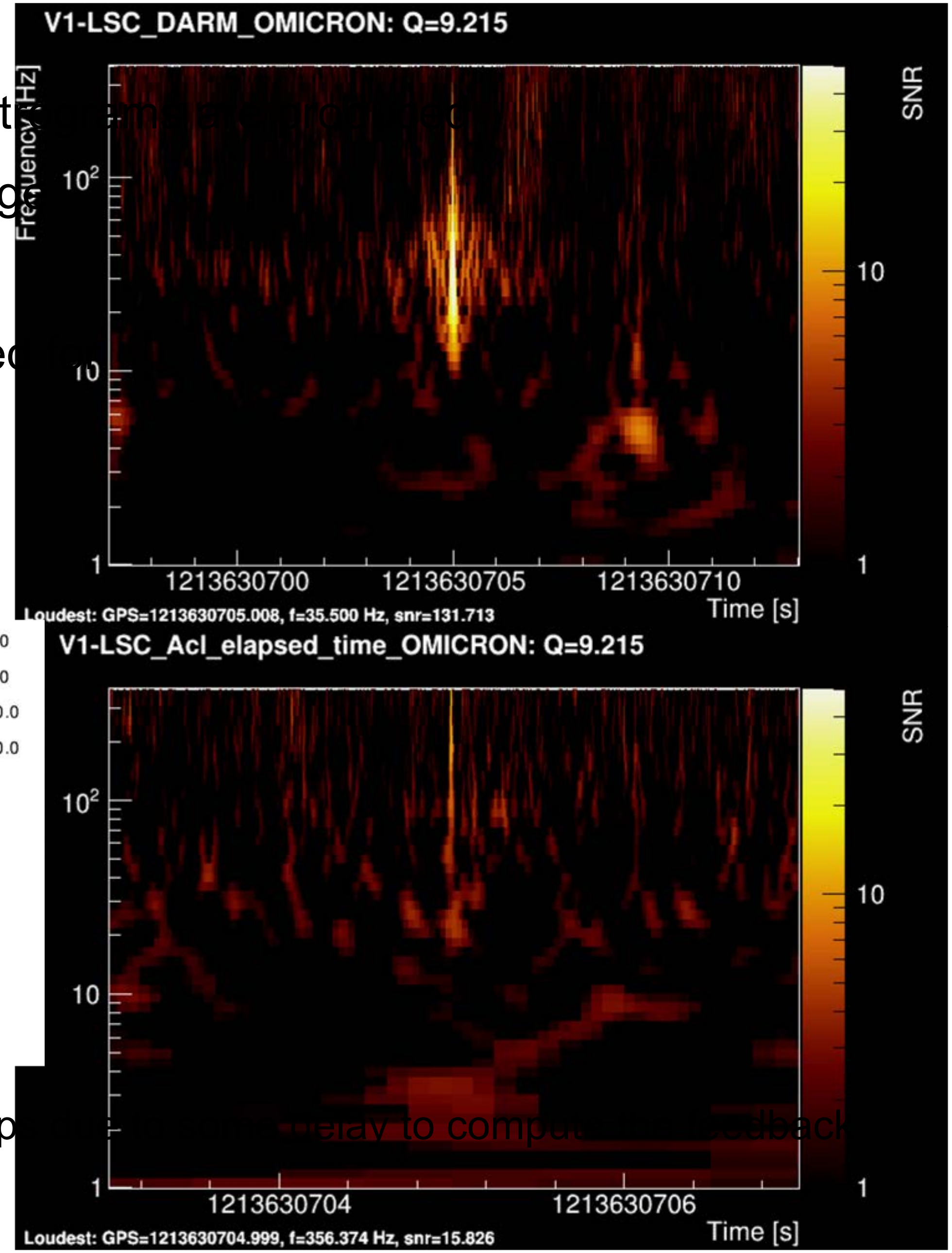
Glitches can be investigated "by hand"

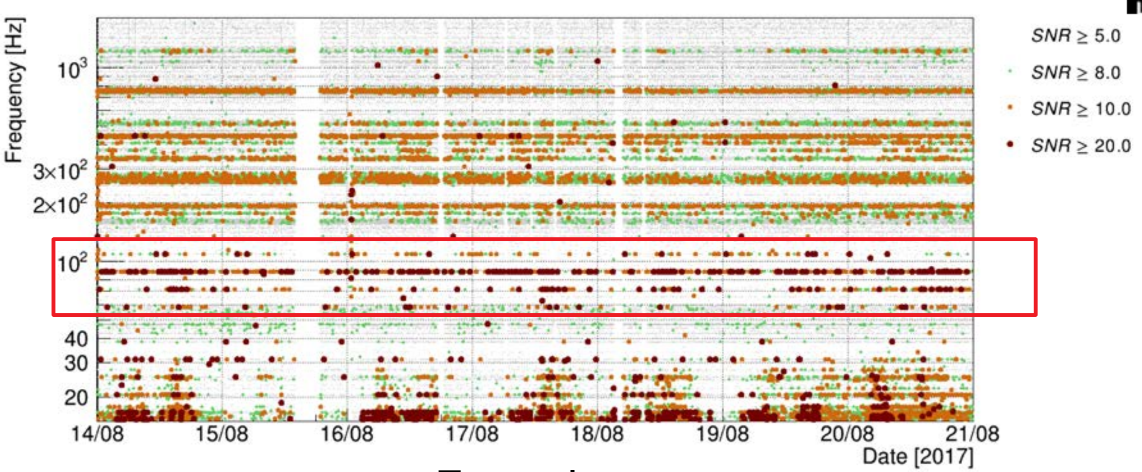
→ All auxiliary channels are scanned and spect

→ Plots and results are displayed on a web pag

→ Plots are visually inspected

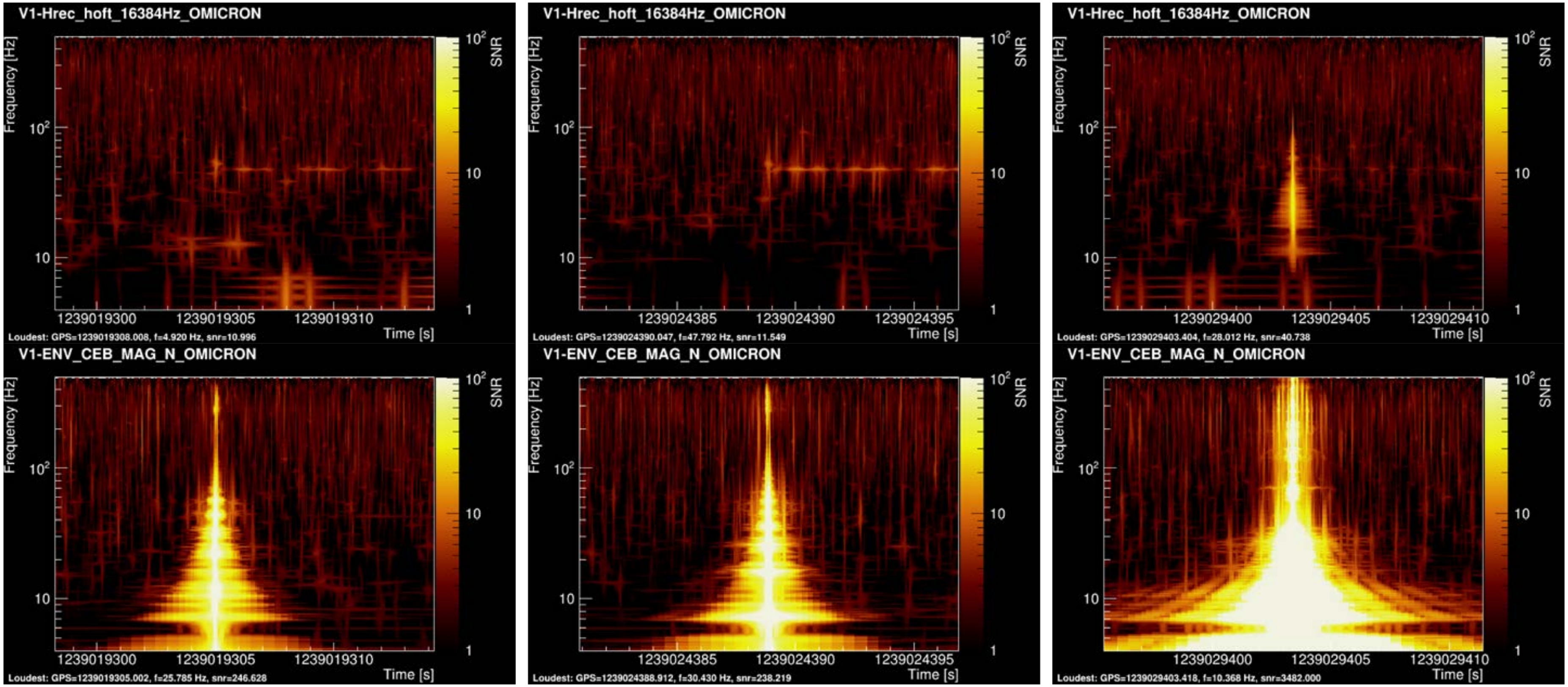
→ Correlations between channels are searched





Example:
Missing sample in mirror control loop
→ kick in the mirror

Glitch-to-glitch example



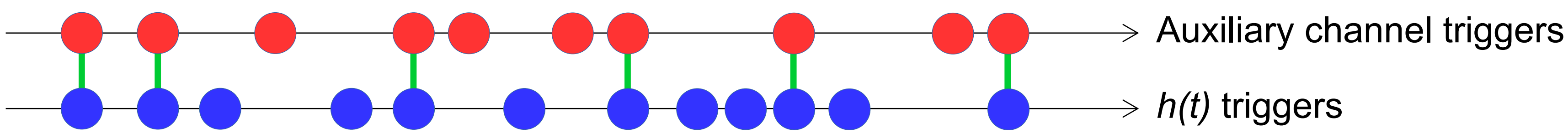
Occasional loud magnetic glitches → lightning strikes

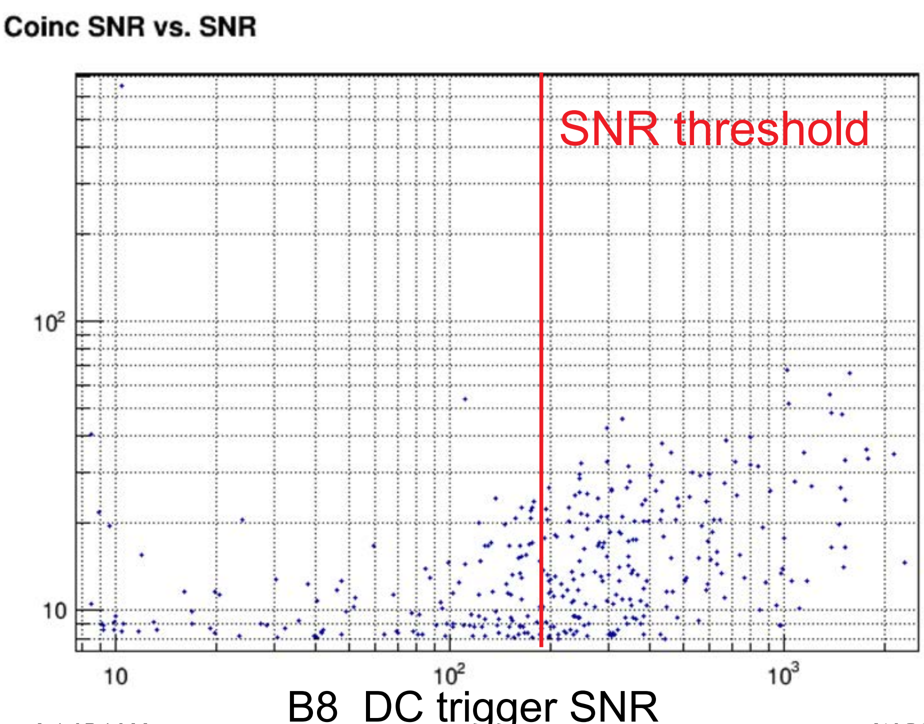
Good witness channels: magnetometers

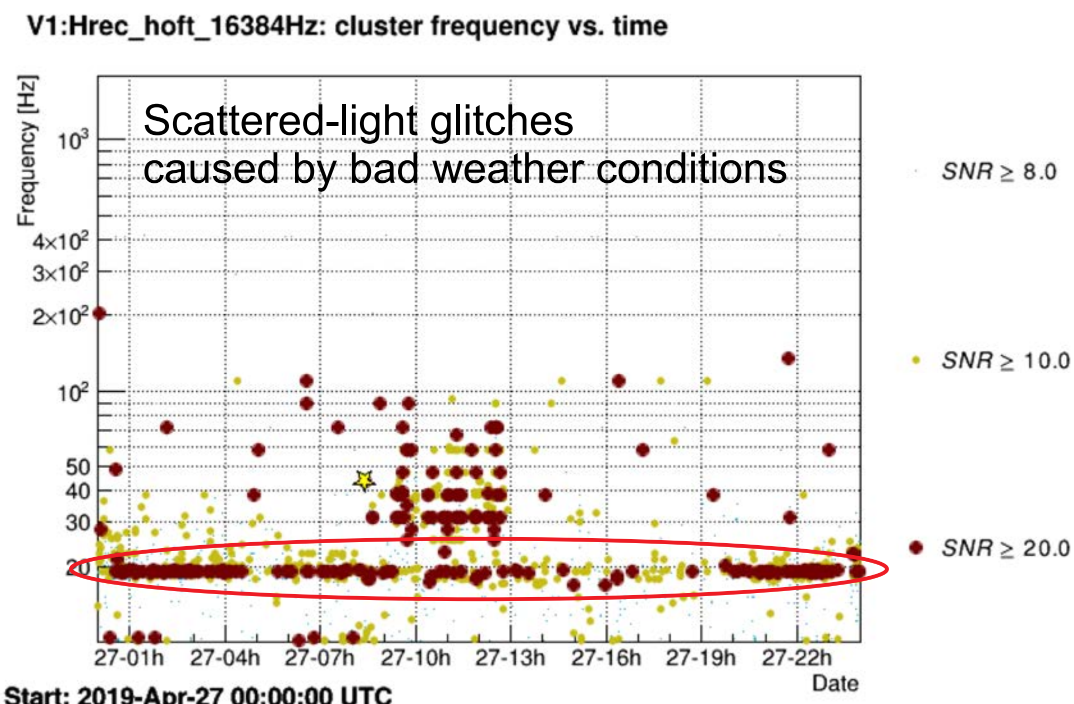
We developed tools to study glitch-to-glitch coupling with auxiliary channels

UPV algorithm

→ Scan triggers of hundreds of auxiliary channels
→ Perform time coincidence
→ The coupling is "real" if the fraction of coincidences is important





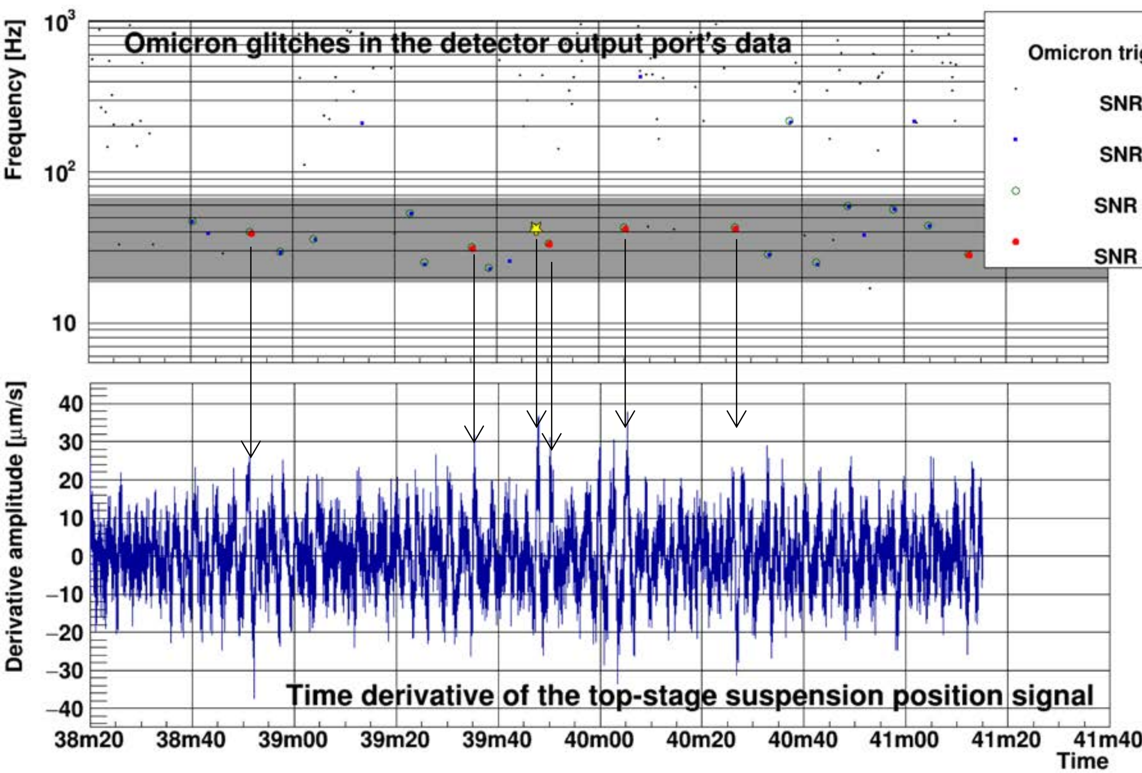


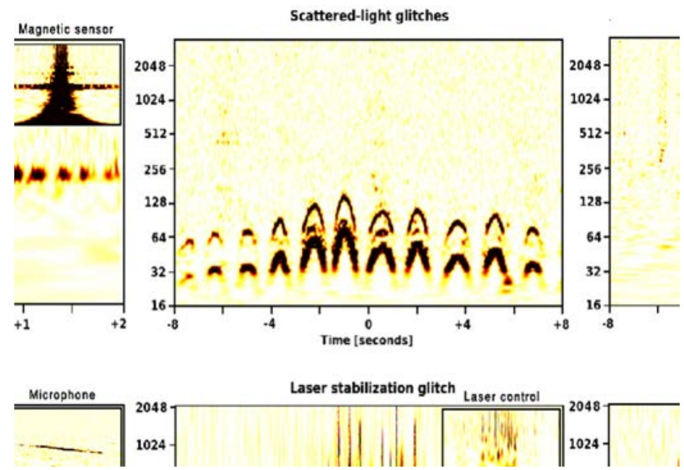
EXCAVATor

→ Isolate a list of glitches

→ Scan auxiliary channel values (or derivative) at the time of the glitches

→ The coupling is “real” if the distribution of values differs from a distribution taken at random ti



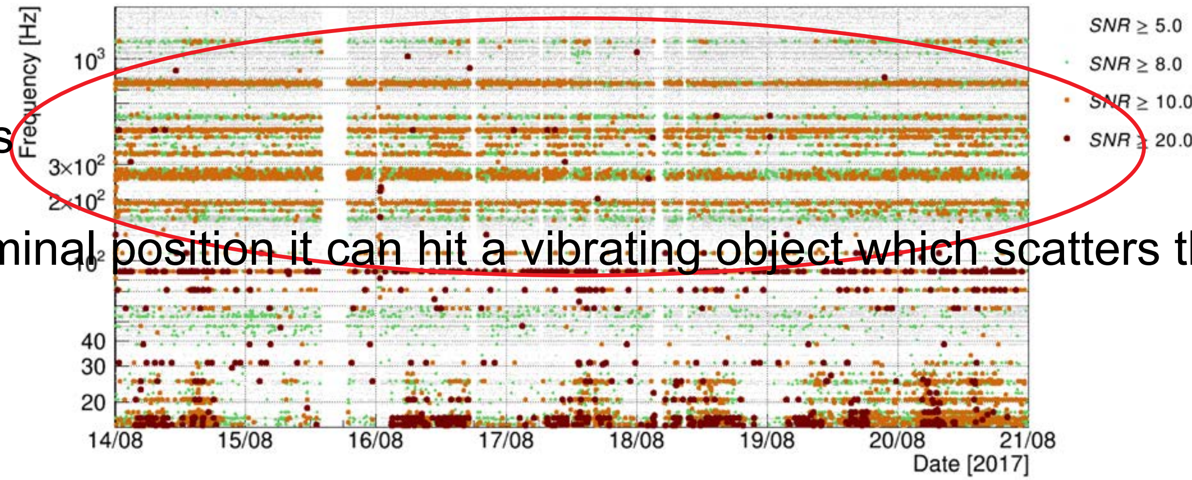


Glitches caused by light scattered by vibratin

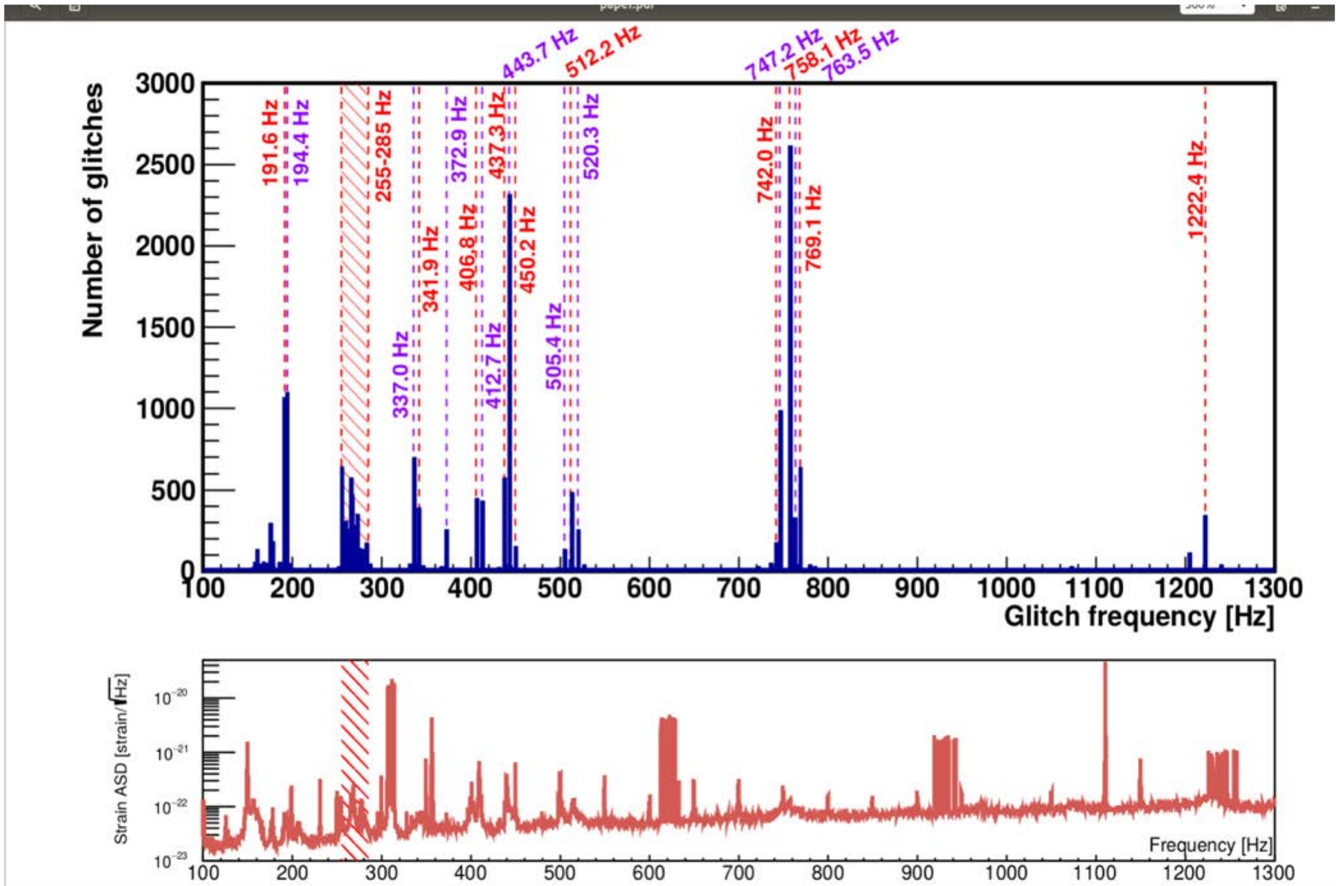
The frequency of the arches is proportional to

Alignment glitches

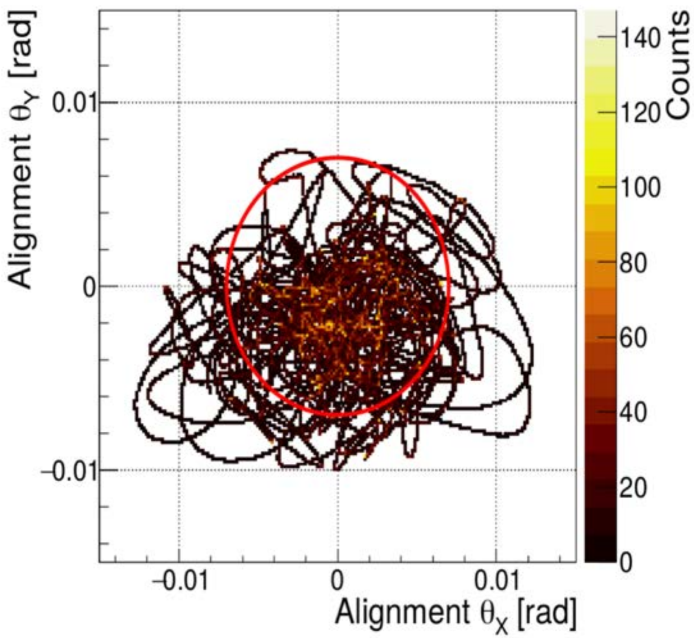
Caused by beam pointing fluctuations

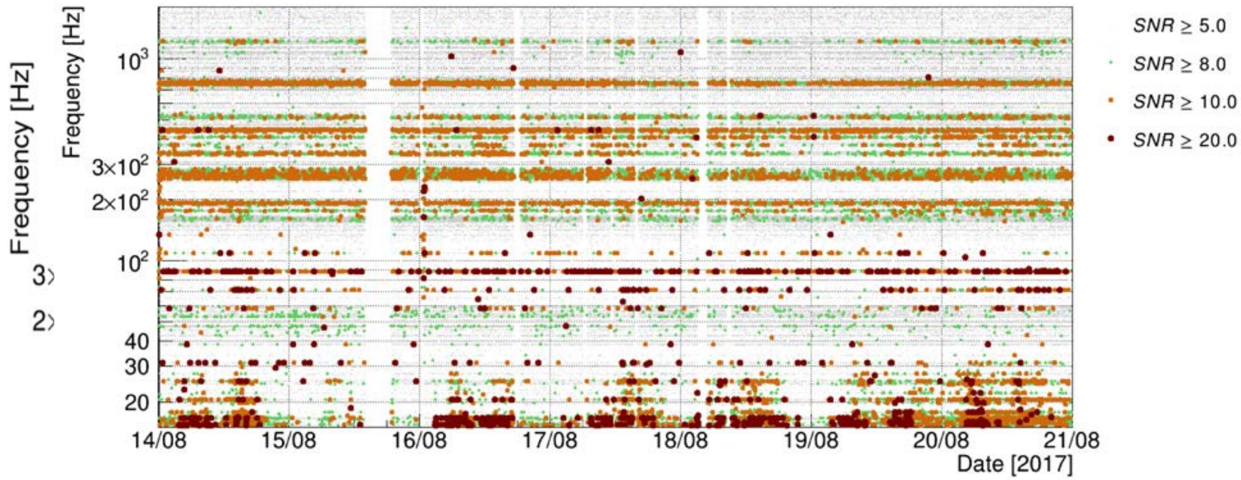


When the beam deviates from its nominal position it can hit a vibrating object which scatters the



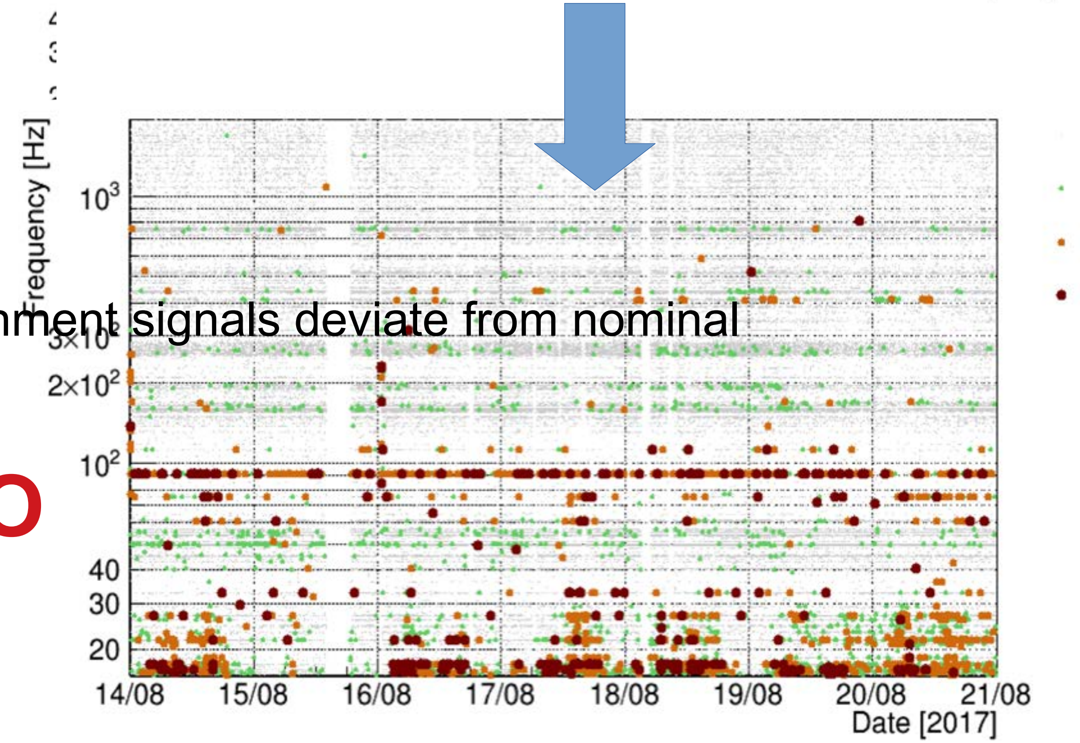
Alignment glitches



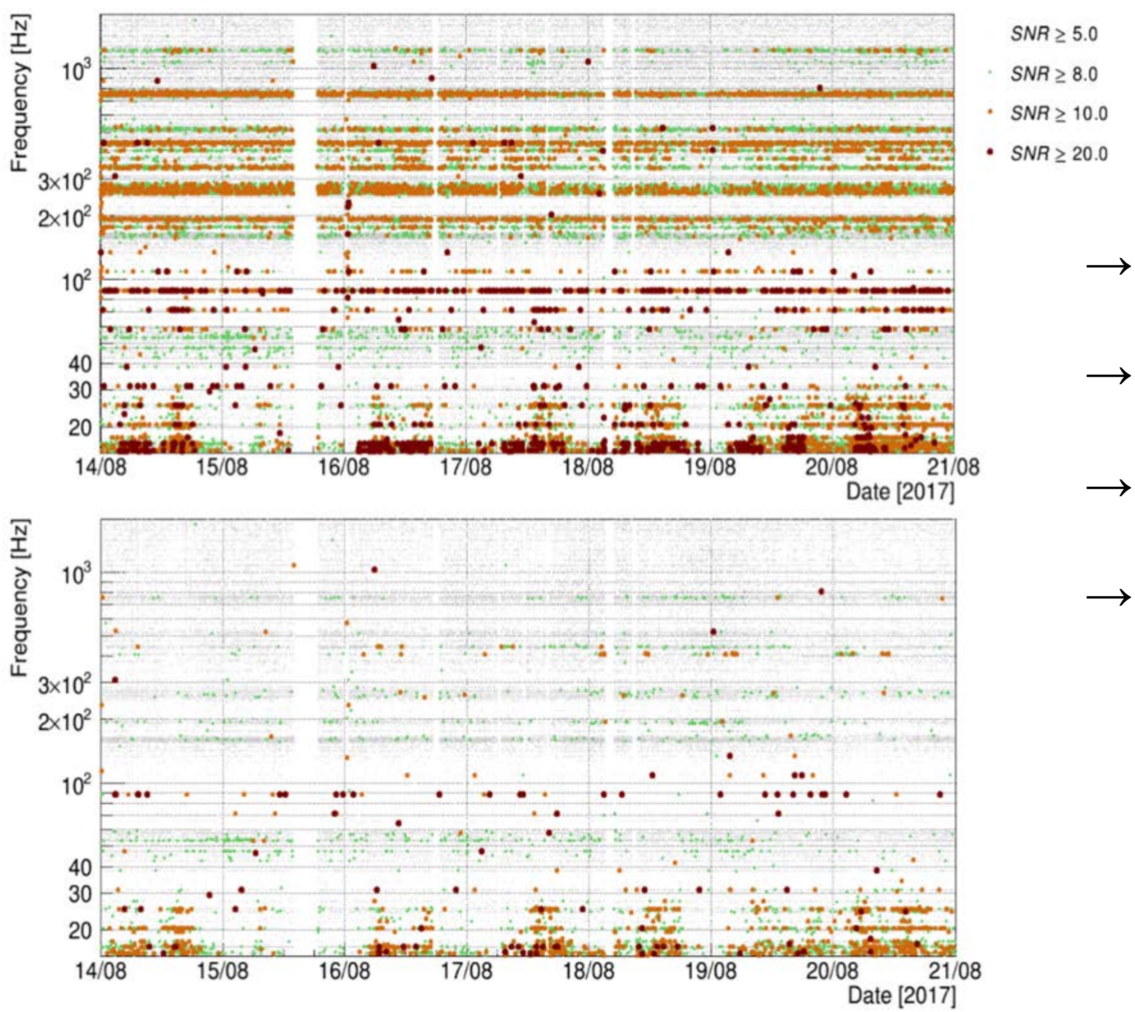


Glitches can be removed when alignment signals deviate from nominal

VETO



Glitch vetoes



Before/after applying O2 Virgo vetoes

→ Lists of time segments are produced

→ When conducting a GW search, glitc

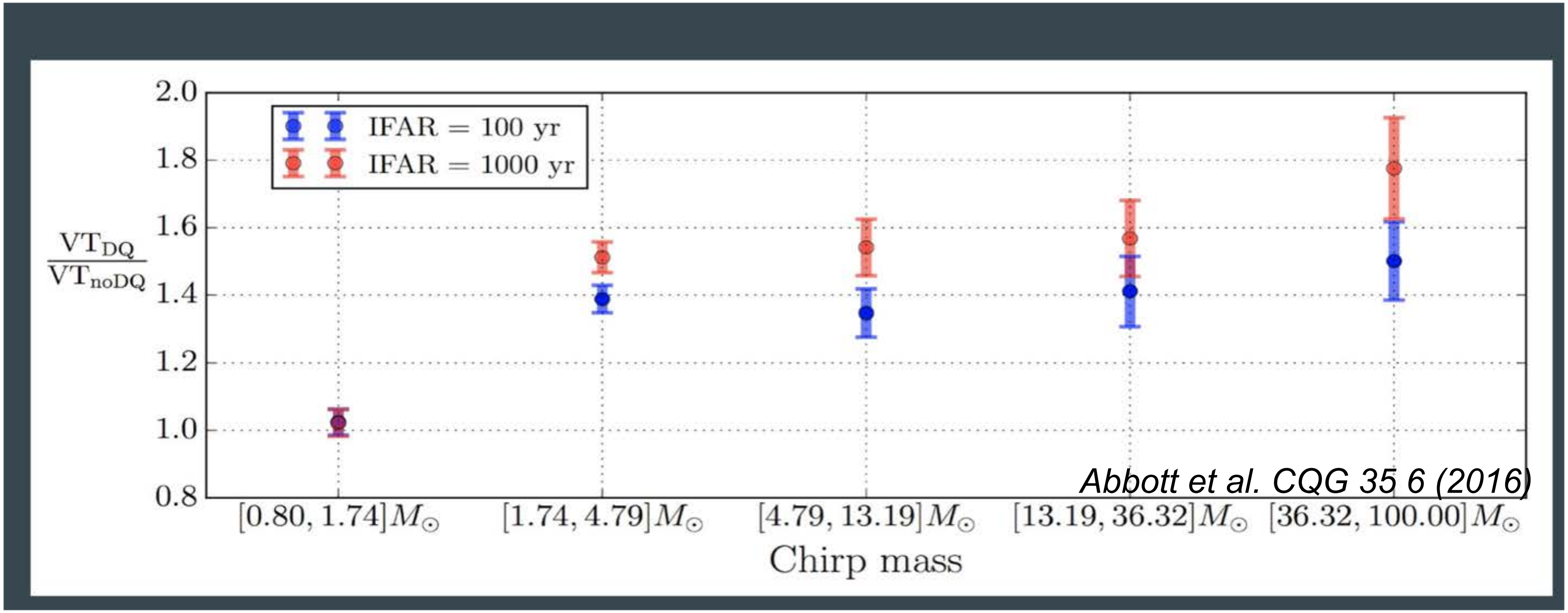
→ Specific vetoes are selected for a giv

→ When designing a veto, care is taken

– to limit the rejected time

– to check that vetoes are not coupled to GW signals!

Impact of O1 vetoes (LIGO) on CBC searches



Abbott et al. CQG 35 6 (2016)

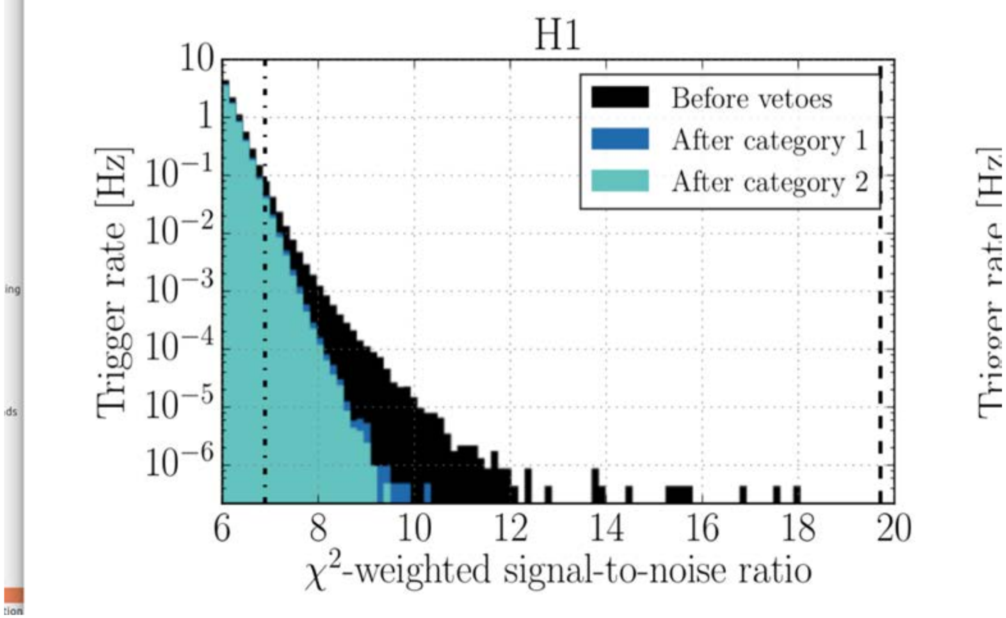
Motivation: transient searches

→ Transient searches are contaminated by spurious noise events mimicking GW signals

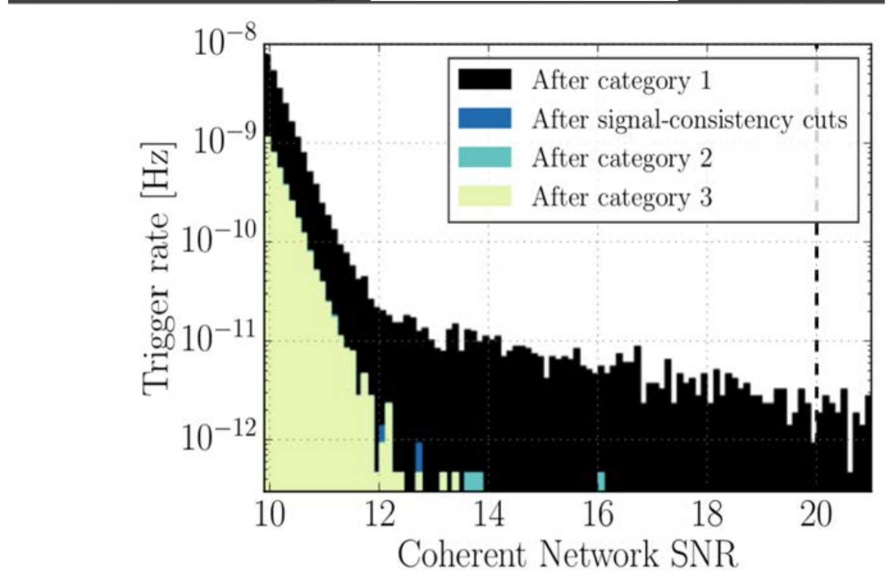
→ Background distribution is highly non-Gaussian

→ The detector characterization group studies the events in the tails and designs vetoes

CBC search



Burst search



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→ Background distribution is highly non-Gaussian

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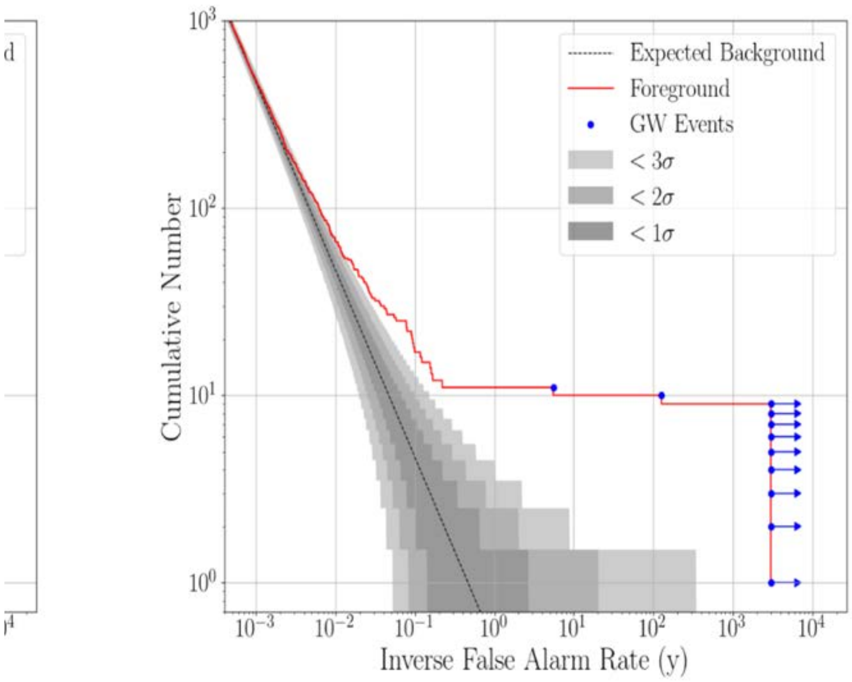

→ The background of transient searches is composed of random coincidences

→ **What about correlated noise?**

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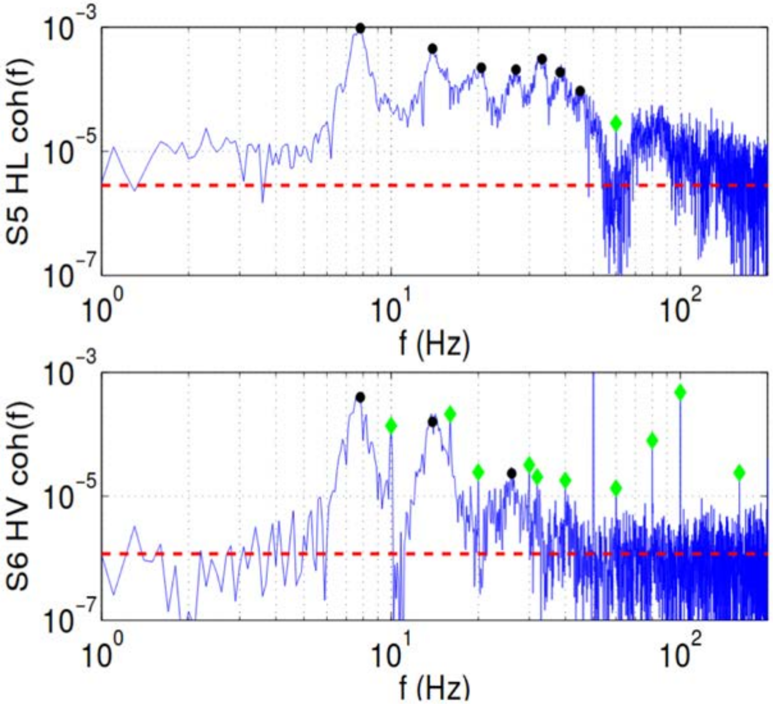
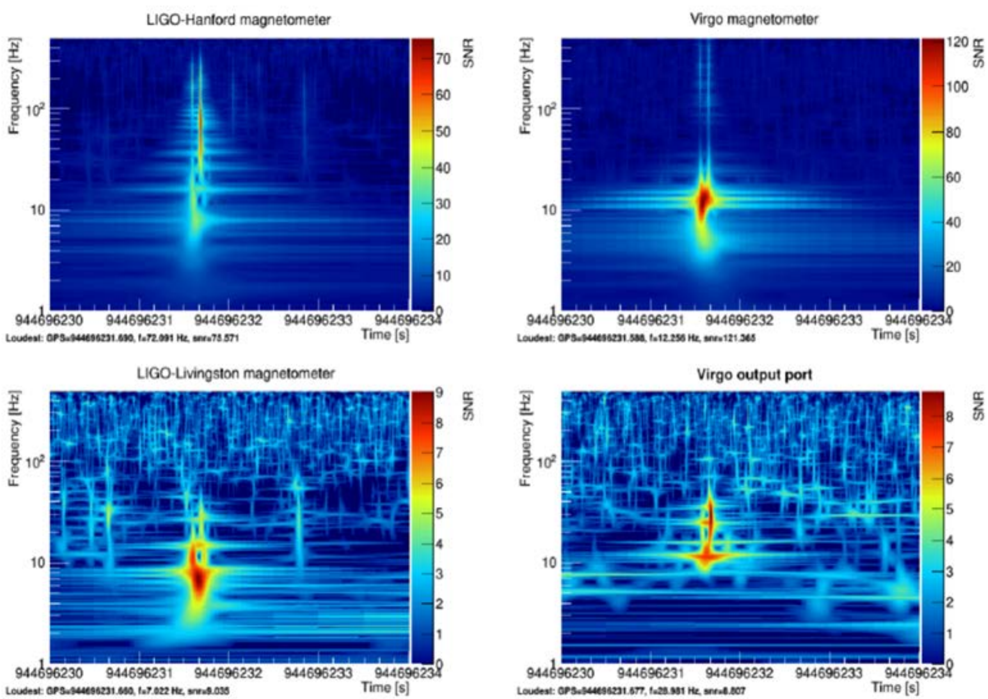
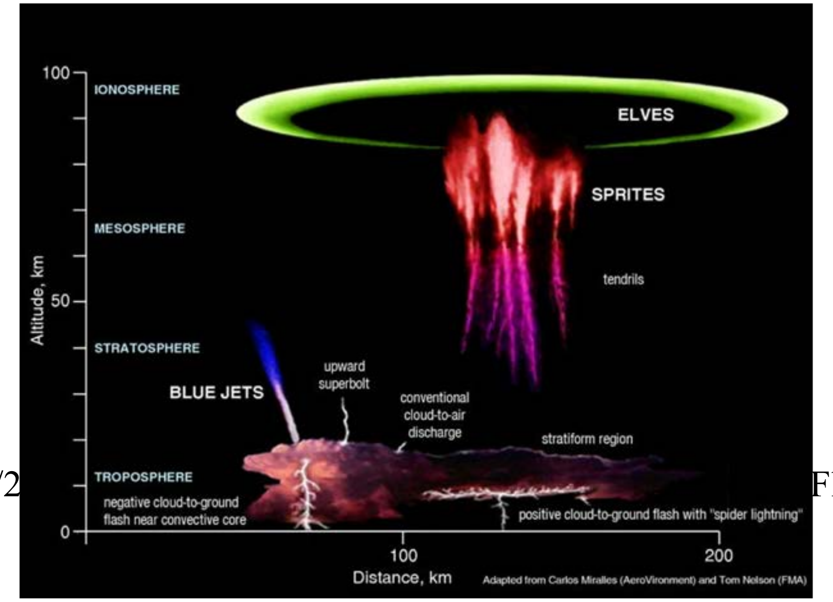
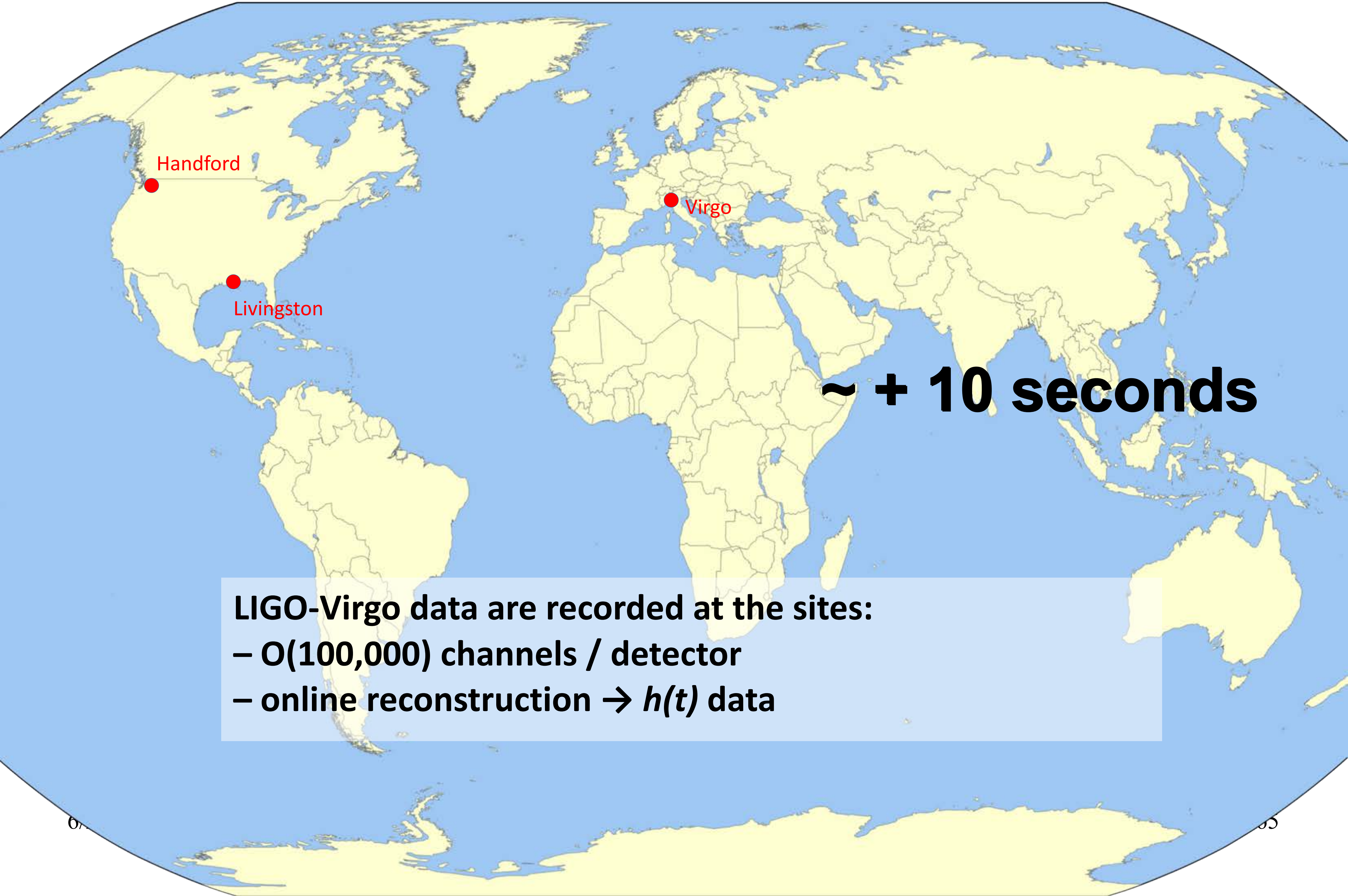


Schumann resonance





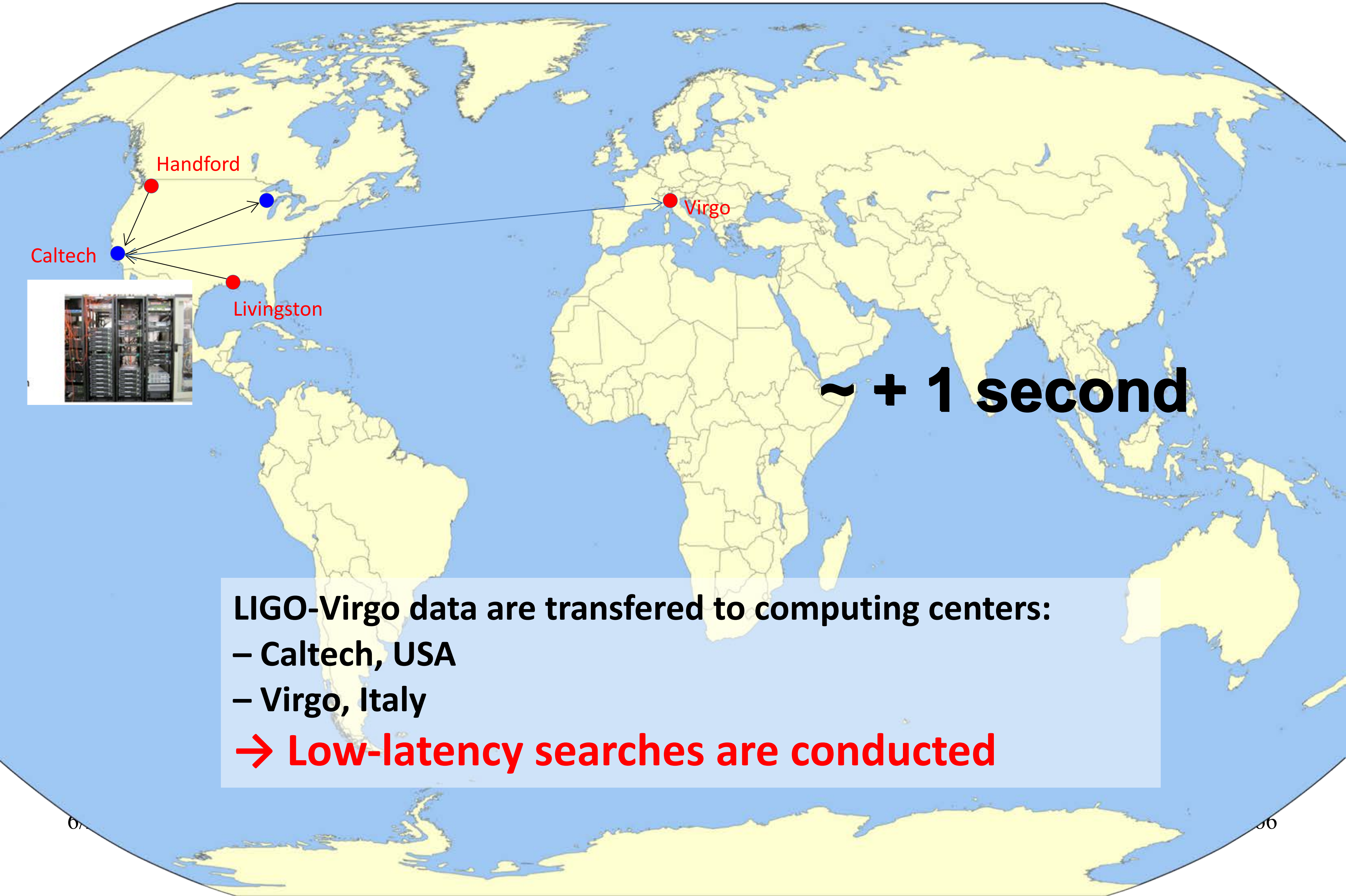
Low-latency searches



~ + 10 seconds

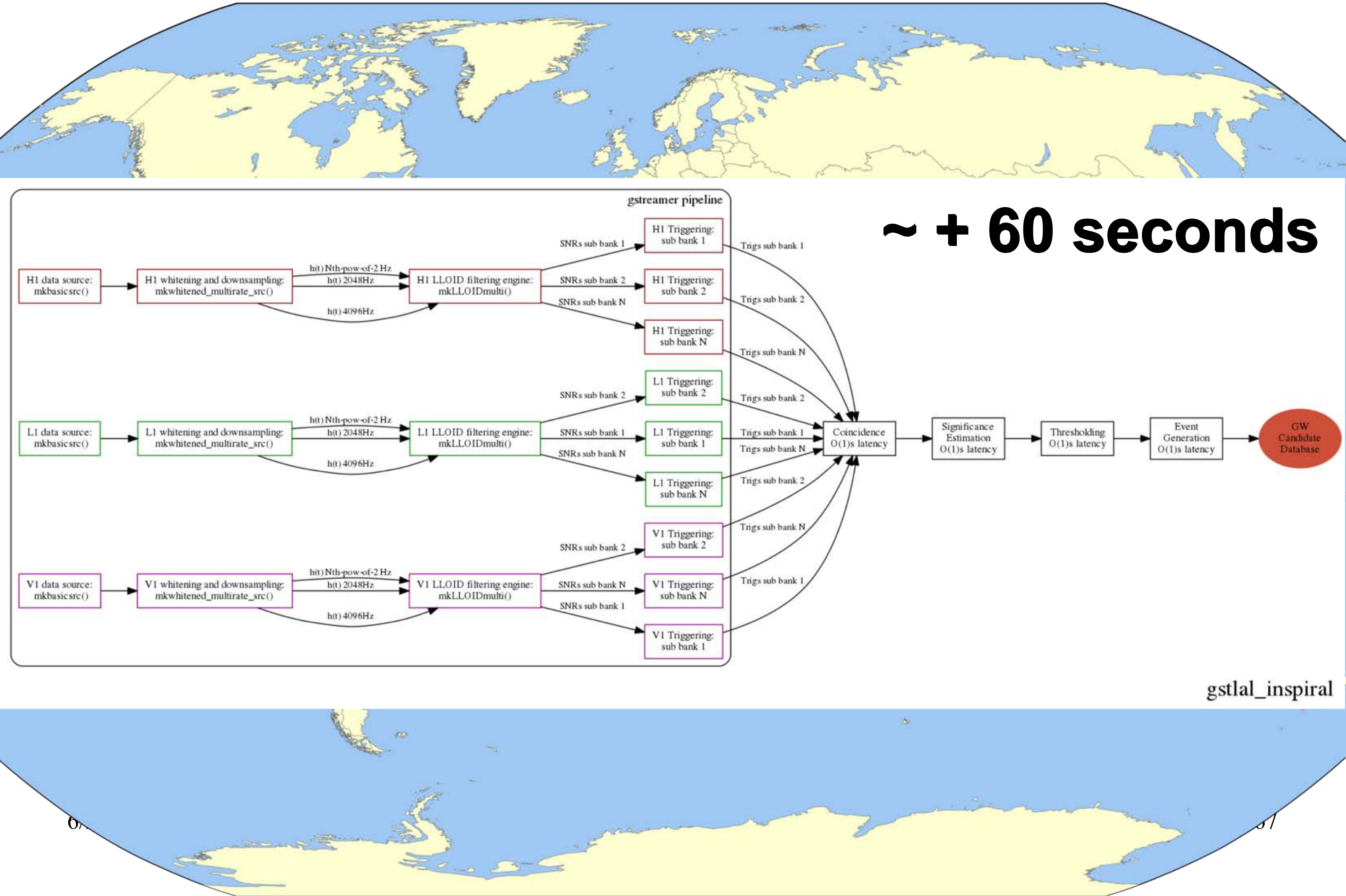
LIGO-Virgo data are recorded at the sites:
– O(100,000) channels / detector
– online reconstruction → *h(t)* data

Low-latency searches



LIGO-Virgo data are transfered to computing centers:
– Caltech, USA
– Virgo, Italy
→ Low-latency searches are conducted

Low-latency searches



GW candidate database

GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | CREATE | REPORTS | RSS | LATEST | OPTIONS | DOCUMENTATION | AUTHENTICATED AS: FLORENT ROBINET

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	UTC Event Time	FAR (Hz)	Links	UTC Submitted
G211117	H1OK L1OK ADVOK EM_READY	CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	3.333e-11	Data	2015-12-26 03:40:00 UTC

Coinc Tables

End Time (GPS)	1135136350.6478 s
Total Mass	26.3501 $M_\odot$
Chirp Mass	9.5548 $M_\odot$
SNR	11.7103
False Alarm Probability	1.120e-04
Log Likelihood Ratio	22.5996

W151226

Single Inspiral Tables

IFO	L1	H1
Channel	GDS-CALIB_STRAIN	GDS-CALIB_STRAIN
End Time (GPS)	1135136350.646883043 s	1135136350.647757924 s
Template Duration	2.25322770554 s	2.25322770554 s
Effective Distance	472.93436 Mpc	461.88879 Mpc
COA Phase	2.7356486 rad	0.13969257 rad
Mass 1	19.924686 $M_\odot$	19.924686 $M_\odot$
Mass 2	6.4254546 $M_\odot$	6.4254546 $M_\odot$
η	0.18438664	0.18438664
F Final	1024.0 Hz	1024.0 Hz
SNR	7.3947201	9.0802174
χ^2	1.0857431	1.0069774
χ^2 DOF	1	1
spin1z	0.33962944	0.33962944
spin2z	-0.1238557	-0.1238557

Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	Δgpstime	FAR (Hz)	Links	UTC Submitted
G211182		Burst	CWB2G	AllSky	H1,L1	1135136350.6291	-0.018658		Data	2015-12-26 09:44:37 UTC
G211115		CBC	gstlal	HighMass	H1,L1	1135136350.6405	-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
G211118		CBC	gstlal	HighMass	H1,L1	1135136350.6477	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
G216856		CBC	gstlal	HighMass	H1,L1	1135136350.6480	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
G211116		CBC	gstlal	HighMass	H1,L1	1135136350.6485	0.000780	4.507e-09	Data	2015-12-26 03:40:00 UTC

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modeled search

+1 min

W151226

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physical parameters
(preliminary)

Neighbors [-5,+5]

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G211115		CBC	gstlal	HighMass	H1,L1	1135136350.6405	-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
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G216856		CBC	gstlal	HighMass	H1,L1	1135136350.6480	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
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GW candidate database

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Basic Info

FAR ~ 950 yr-1

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modeled search

+1 min

W151226

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GW candidate database

GW151226

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FAR ~ 950 yr-1

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Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	Δgpstime	FAR (Hz)	Links	UTC Submitted
G211182		Burst	CWB2G	AllSky	H1,L1	1135136350.6291	-0.018658		Data	2015-12-26 09:44:37 UTC
G211115		CBC	gstlal	HighMass	H1,L1	1135136350.6405	-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
G211118		CBC	gstlal	HighMass	H1,L1	1135136350.6477	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
G216856		CBC	gstlal	HighMass	H1,L1	1135136350.6480	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
G211116		CBC	gstlal	HighMass	H1,L1	1135136350.6485	0.000780	4.507e-09	Data	2015-12-26 03:40:00 UTC

multiple detections over time

GW candidate database

In O3, significant events uploaded in the database are publicly available (immediately!)

GraceDB — Gravitational Wave Candidate Event Database

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Superevent Info

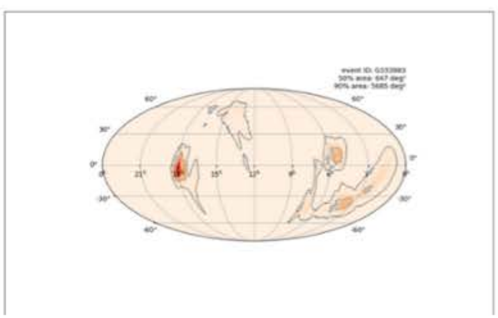
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC Submission time	Links
S190524q	Production	DQOK ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	6.971e-09	1 per 4.5458 years	1242708743.678669	1242708744.678669	1242708746.133301	2019-05-24 04:52:30 UTC	Data

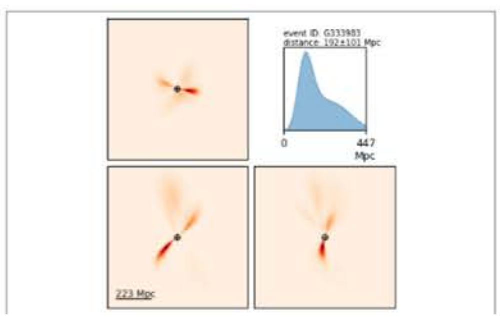
Preferred Event Info

Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	gstlal	AllSky	H1,L1,V1	1242708744.6787	2019-05-24 04:52:28 UTC

Superevent Log Messages

Sky Localization





Since O3, GCN notices are issued publicly and automatically


```
//////////////////////////////////////////////////////////////////////////////
TITLE:            GCN/LVC NOTICE
NOTICE_DATE:      Fri 24 May 19 04:58:33 UT
NOTICE_TYPE:      LVC Preliminary
TRIGGER_NUM:      S190524q
TRIGGER_DATE:     18627 TJD;    144 DOY;    2019/05/24 (yyyy/mm/dd)
TRIGGER_TIME:     17526.678669 SOD {04:52:06.678669} UT
SEQUENCE_NUM:     1
GROUP_TYPE:       1 = CBC
SEARCH_TYPE:      1 = AllSky
PIPELINE_TYPE:    4 = GSTLAL
FAR:              6.971e-09 [Hz]  (one per 1660.3 days)  (one per 4.55 years)
PROB_NS:          1.00 [range is 0.0-1.0]
PROB_REMNANT:     1.00 [range is 0.0-1.0]
PROB_BNS:         0.29 [range is 0.0-1.0]
PROB_NSBH:        0.00 [range is 0.0-1.0]
PROB_BBH:         0.00 [range is 0.0-1.0]
PROB_MassGap:     0.00 [range is 0.0-1.0]
PROB_TERRES:      0.70 [range is 0.0-1.0]
TRIGGER_ID:       0x10
MISC:             0x189C407
SKYMAP_FITS_URL:  https://gracedb.ligo.org/api/superevents/S190524q/files/bayestar.fits.gz
EVENTPAGE_URL:    https://gracedb.ligo.org/superevents/S190524q/view/
COMMENTS:         LVC Preliminary Trigger Alert.
COMMENTS:         This event is an OpenAlert.
COMMENTS:         LIGO-Hanford Observatory contributed to this candidate event.
COMMENTS:         LIGO-Livingston Observatory contributed to this candidate event.
COMMENTS:         VIRGO Observatory contributed to this candidate event.
```

+ 6 min

Human vetting

GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | CREATE | REPORTS | RSS | LATEST | OPTIONS | DOCUMENTATION | AUTHENTICATED AS: FLORENT ROBINET

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	UTC Event Time	FAR (Hz)	Links	UTC Submitted
G211117	H1OK L1OK ADVOK EM_READY	CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	3.333e-11	Data	2015-12-26 03:40:00 UTC

Coinc Tables

End Time (GPS)	1135136350.6478 s
Total Mass	26.3501 $M_\odot$
Chirp Mass	9.5548 $M_\odot$
SNR	11.7103
False Alarm Probability	1.120e-04
Log Likelihood Ratio	22.5996

Single Inspiral Tables

IFO	L1	H1
Channel	GDS-CALIB_STRAIN	GDS-CALIB_STRAIN
End Time (GPS)	1135136350.646883043 s	1135136350.647757924 s
Template Duration	2.25322770554 s	2.25322770554 s
Effective Distance	472.93436 Mpc	461.88879 Mpc
COA Phase	2.7356486 rad	0.13969257 rad
Mass 1	19.924686 $M_\odot$	19.924686 $M_\odot$
Mass 2	6.4254546 $M_\odot$	6.4254546 $M_\odot$
η	0.18438664	0.18438664
F Final	1024.0 Hz	1024.0 Hz
SNR	7.3947201	9.0802174
χ^2	1.0857431	1.0069774
χ^2 DOF	1	1
spin1z	0.33962944	0.33962944
spin2z	-0.1238557	-0.1238557

Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	Δgpstime	FAR (Hz)	Links	UTC Submitted
G211182		Burst	CWB2G	AllSky	H1,L1	1135136350.6291	-0.018658		Data	2015-12-26 09:44:37 UTC
G211115		CBC	gstlal	HighMass	H1,L1	1135136350.6405	-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
G211118		CBC	gstlal	HighMass	H1,L1	1135136350.6477	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
G216856		CBC	gstlal	HighMass	H1,L1	1135136350.6480	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
G211116		CBC	gstlal	HighMass	H1,L1	1135136350.6485	0.000780	4.507e-09	Data	2015-12-26 03:40:00 UTC

→ Preliminary GCN notice is issued

→ Electronic alerts (emails, texts, phone calls) are sent to LIGO-Virgo people

→ Virtual meeting with many people
- detector control rooms
- detector experts
- run coordinators
- detector characterization experts
- search pipeline managers
- calibration experts

→ The gravitational-wave candidate is scrutinized:
- data quality
- detector status
- event preliminary parameters
- first sky map

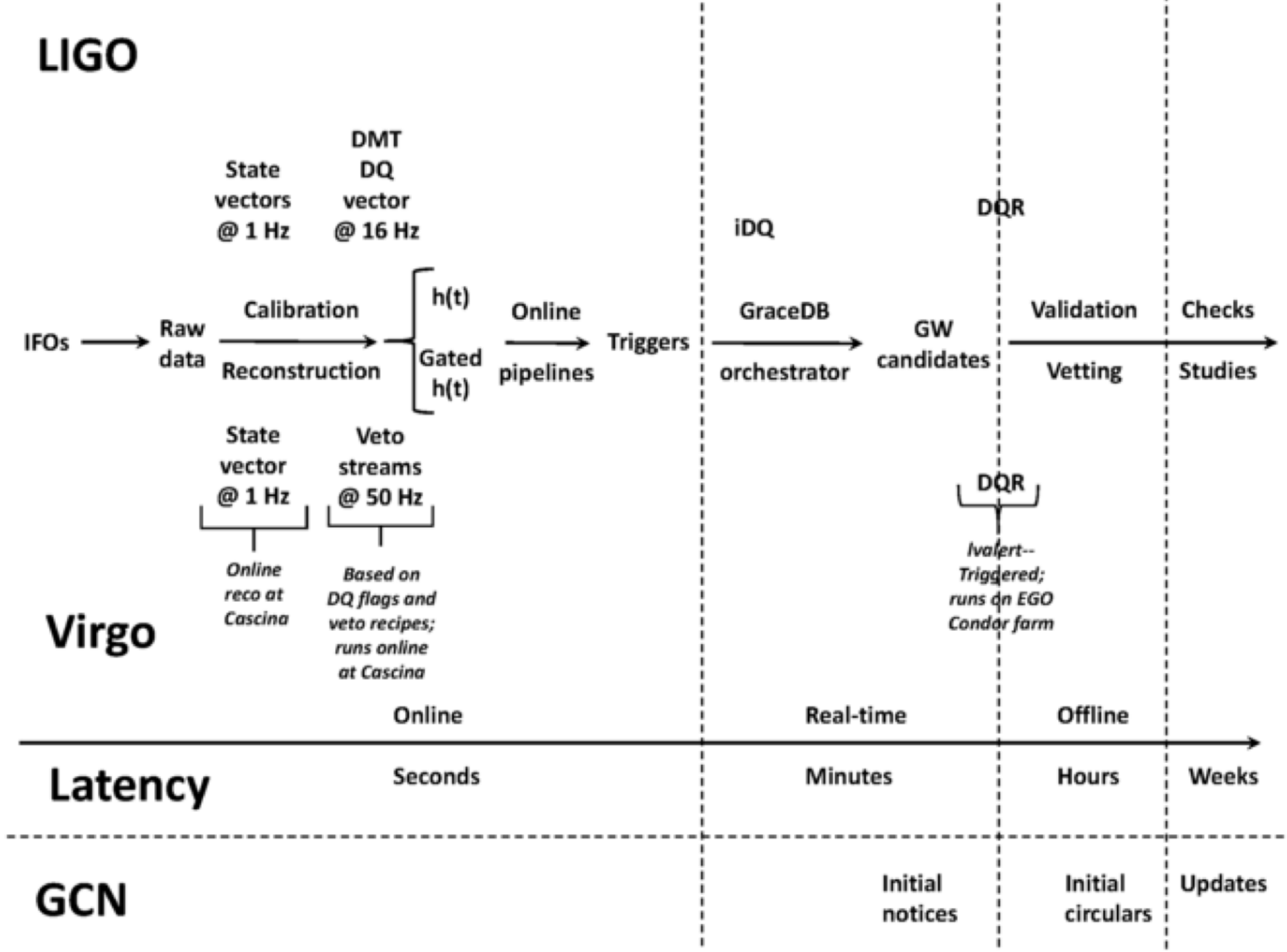
→ GCN notice is updated

GCN circular updates

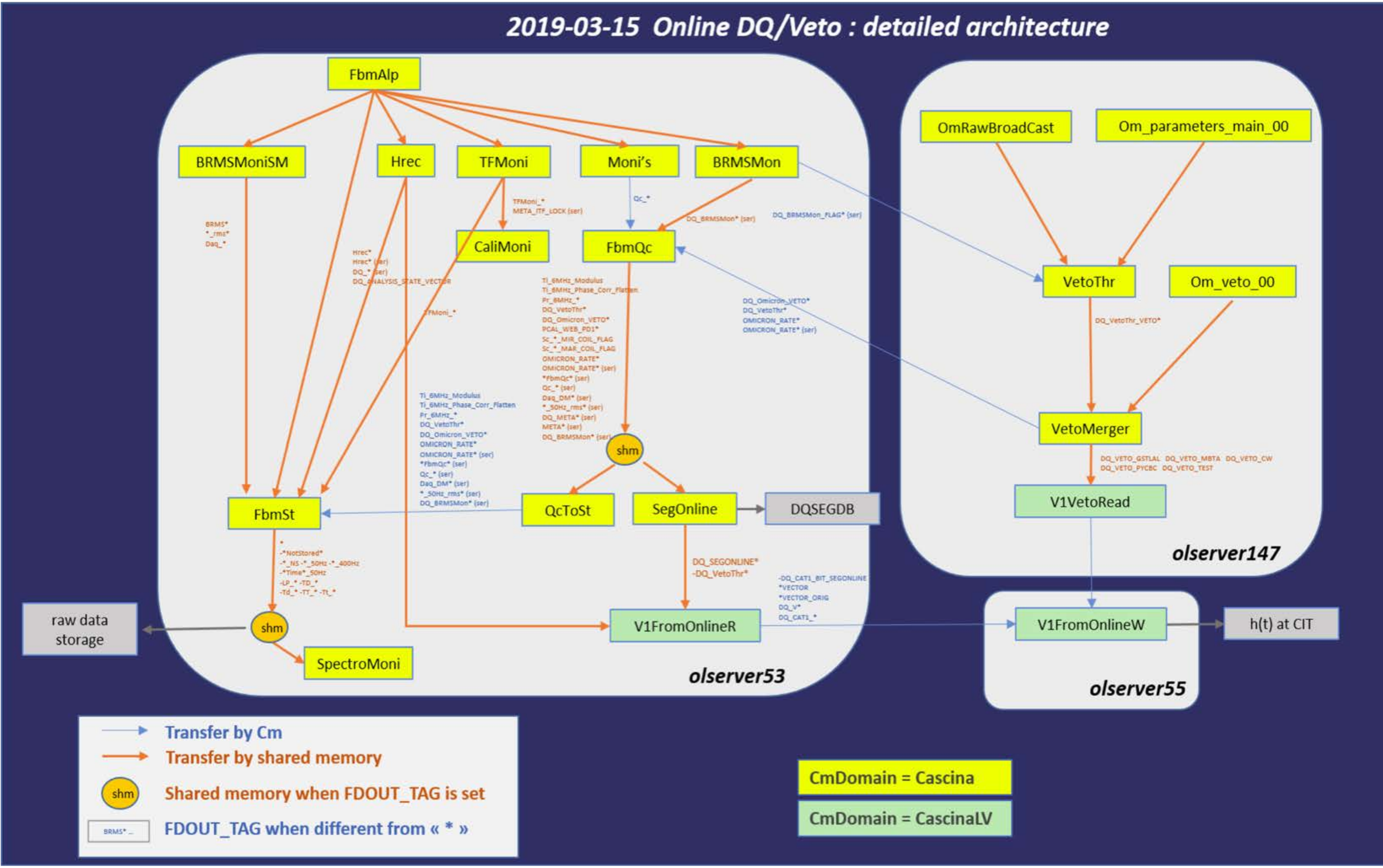
GWOLLUM doc Analysis DetChar wiki PCE - MXT SatAndLight Scientific partition LAL webmail International Institute...

```
TITLE:   GCN CIRCULAR
NUMBER:  24656
SUBJECT: SUBJECT: LIGO/Virgo S190524q: Retraction of GW compact binary merger candidate
DATE:    19/05/24 05:20:40 GMT
FROM:    Brandon Piotrzkowski at U of Wisconsin-Milwaukee  <piotrzk3@uwm.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:


The trigger S190524q is no longer considered to be a gravitational

wave signal.


The data in LIGO-Livingston were highly non-stationary leading up to

the reported trigger time.
```

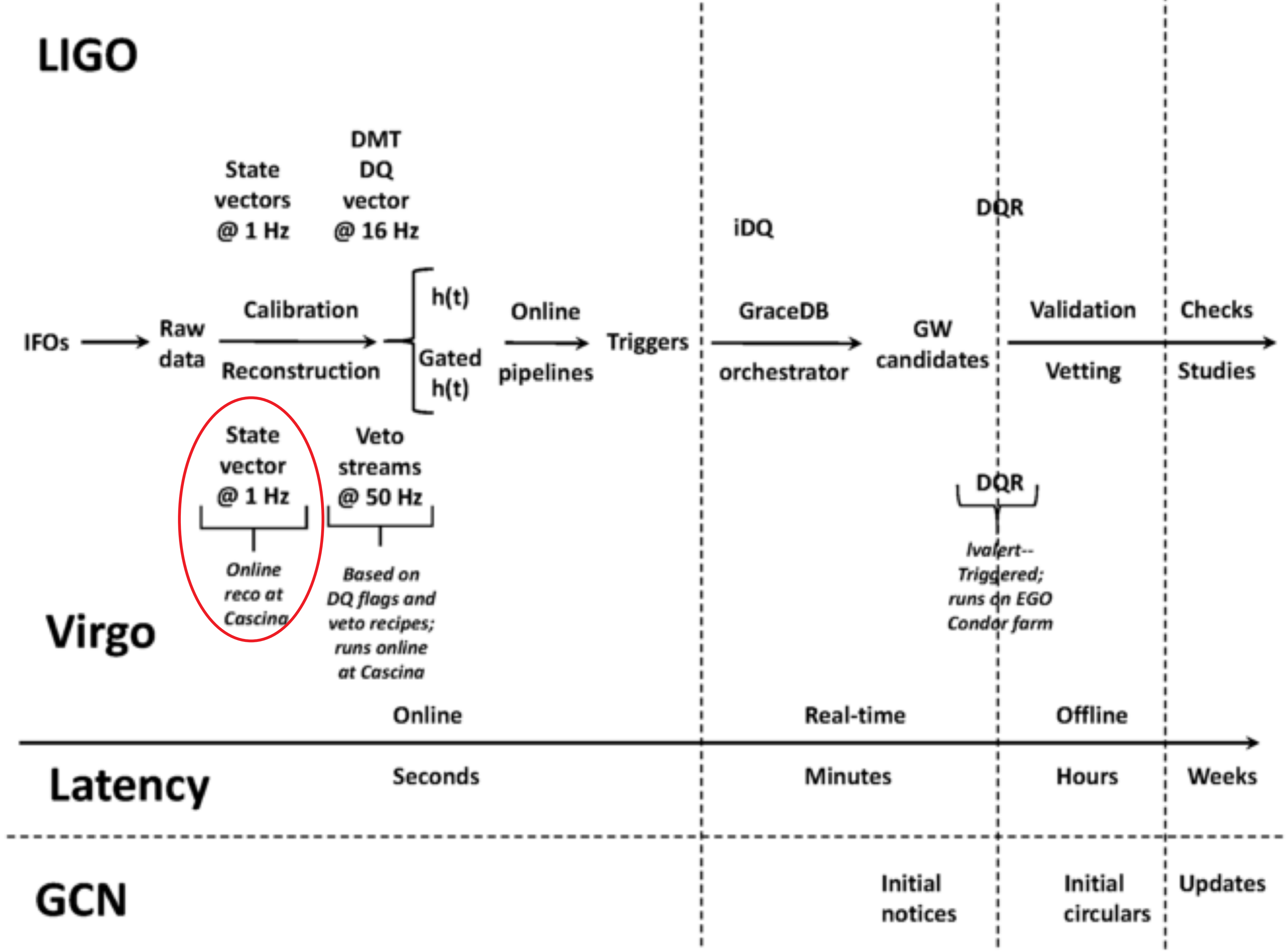
Detector characterization online pipeline

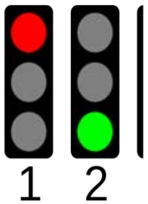


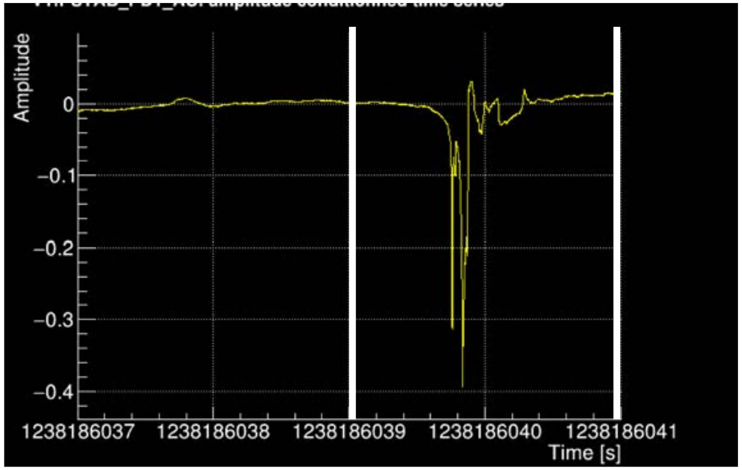
Detector characterization online pipeline



Detector characterization online pipeline







The state vector is used to tell the online pipelin

State vector bit definition:

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)

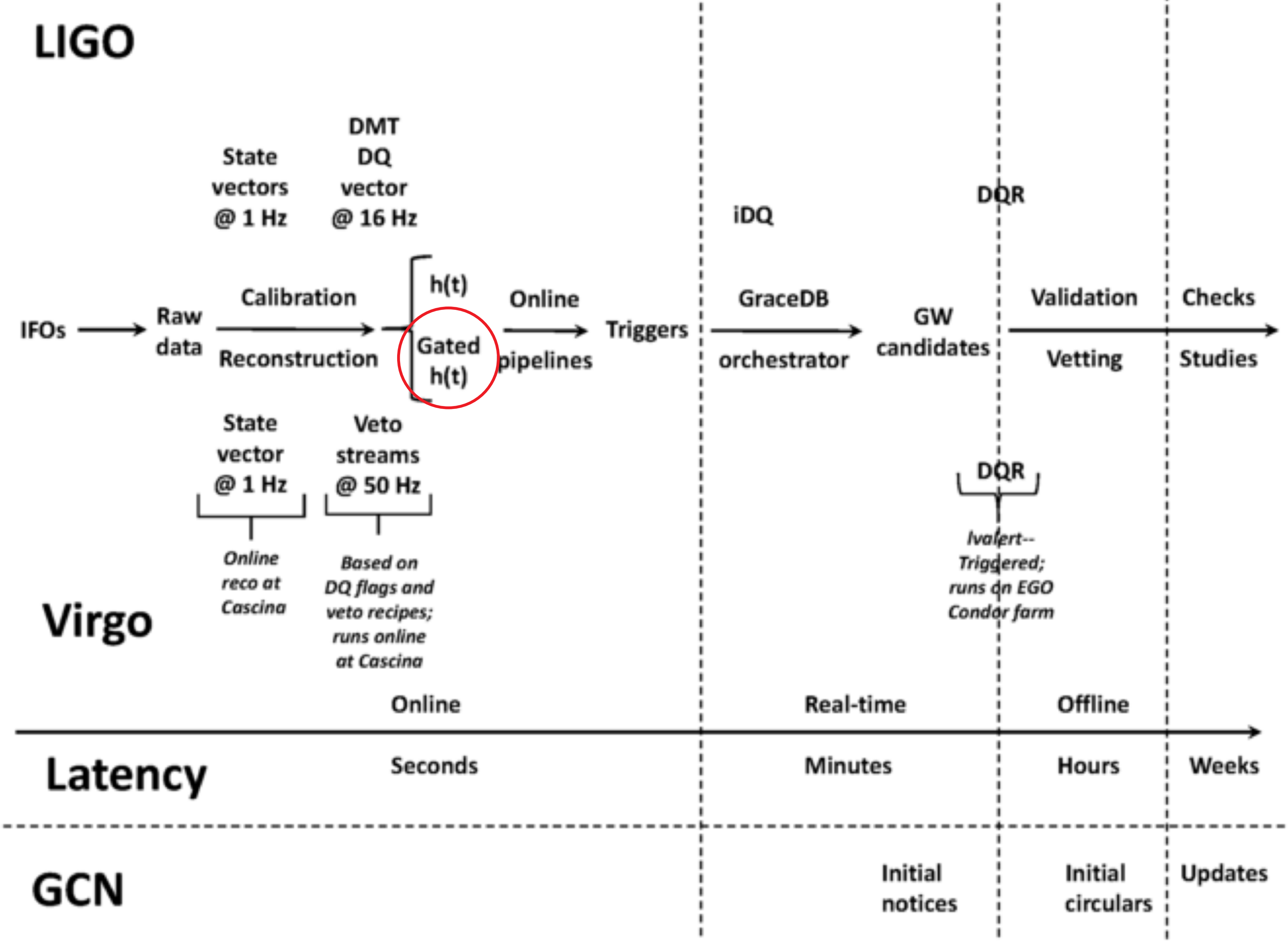
11: interferometer is locked

This bit (@1Hz) flags serious detector malfuncti

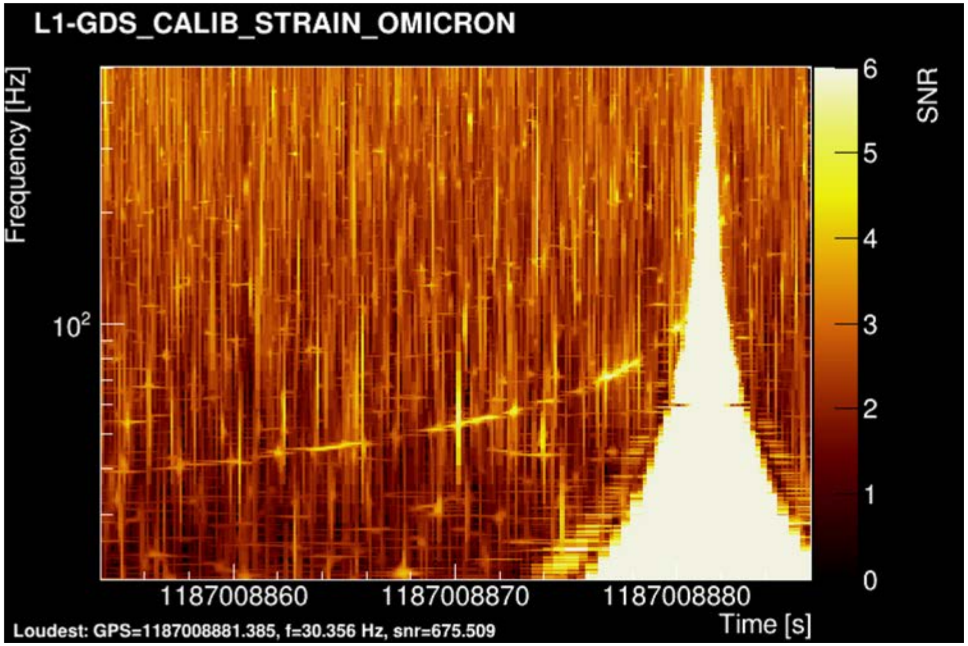
Current definition :

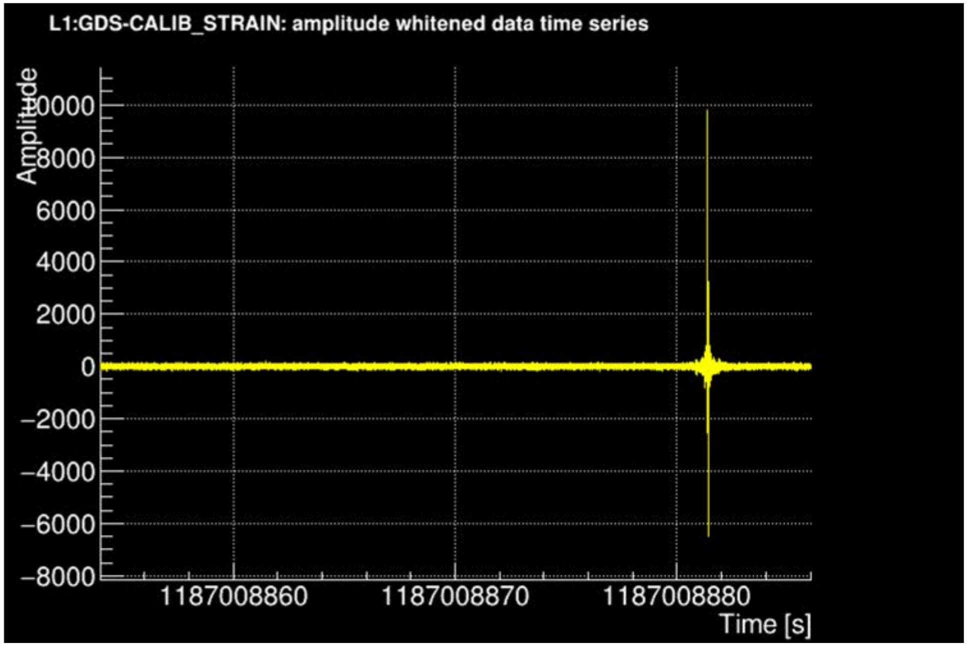
- Saturation of output port photodiodes
- Saturation of suspension coil drivers
- *Saturation of omicron glitch rate (DARM)*

Detector characterization online pipeline

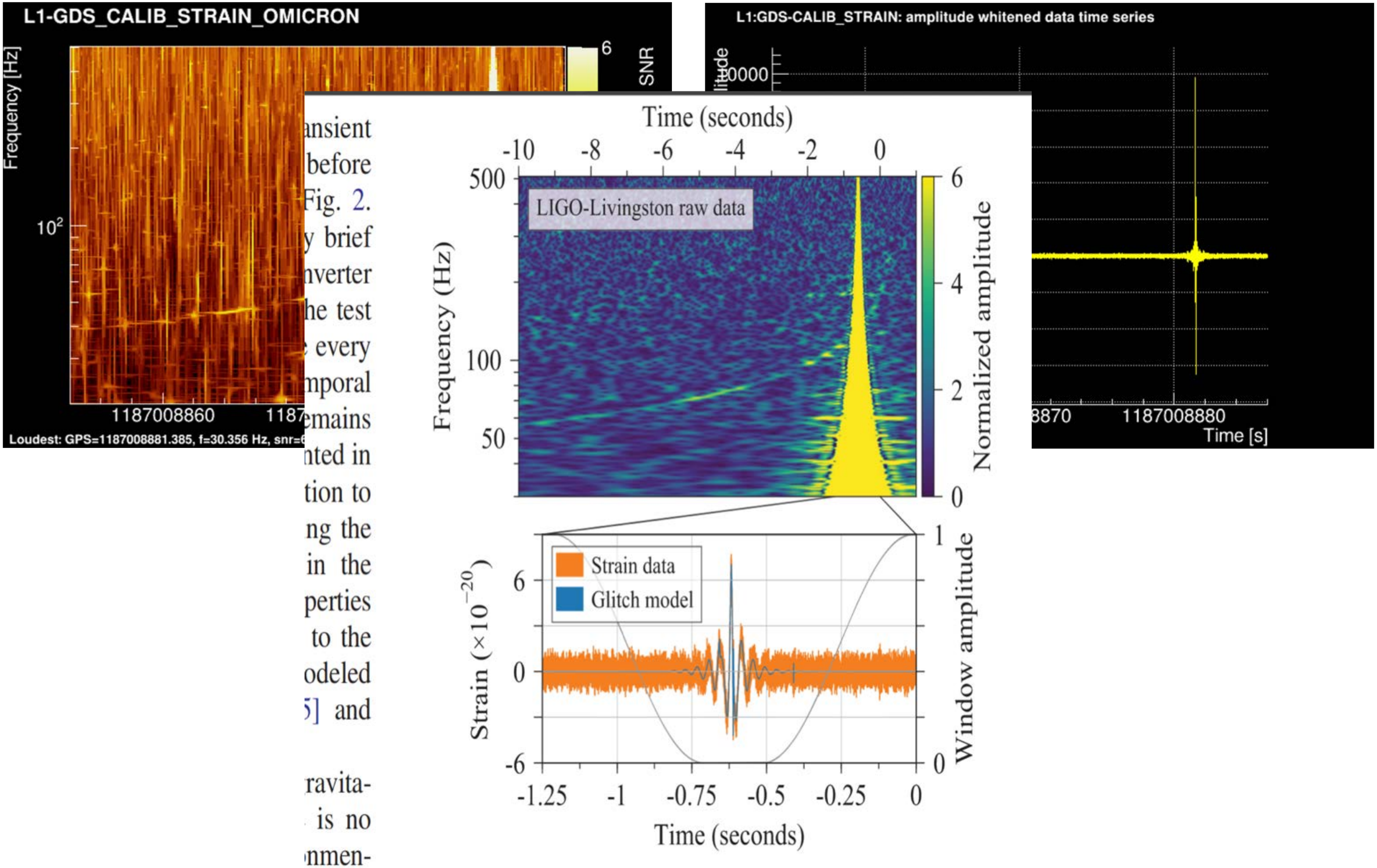


h(t) gating

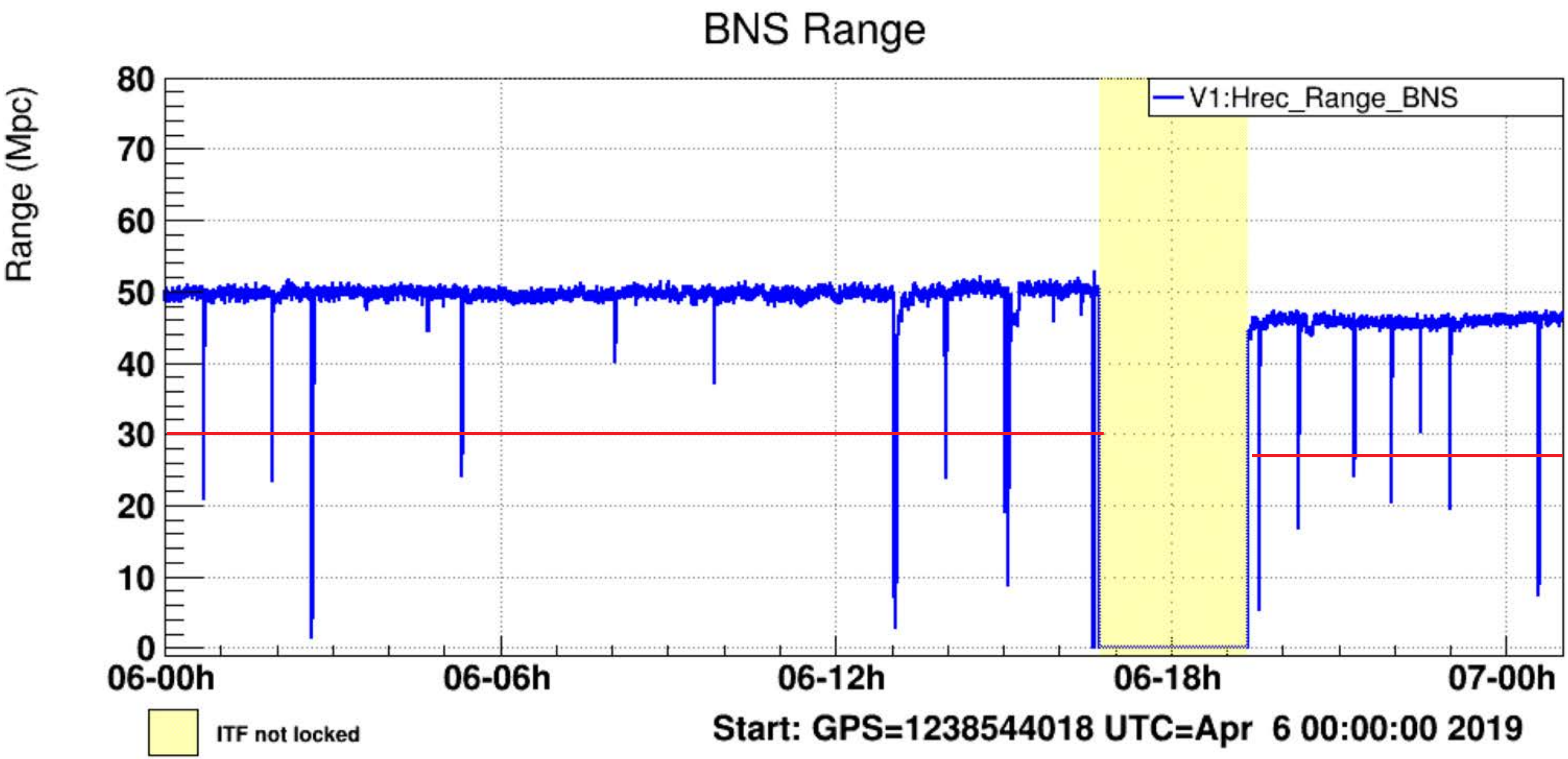

L1-GDS_CALIB_STRAIN_OMICRON
Frequency [Hz]
10^2
1187008860
1187008870
1187008880
Time [s]
SNR
0
1
2
3
4
5
6
Loudest: GPS=1187008881.385, f=30.356 Hz, snr=675.509


L1:GDS-CALIB_STRAIN: amplitude whitened data time series
Amplitude
10000
8000
6000
4000
2000
0
−2000
−4000
−6000
−8000
1187008860
1187008870
1187008880
Time [s]

h(t) gating



L1-GDS_CALIB_STRAIN_OMICRON
Frequency [Hz]
SNR
1187008860
Loudest: GPS=1187008881.385, f=30.356 Hz, snr=
L1:GDS-CALIB_STRAIN: amplitude whitened data time series
1187008880
Time [s]
Time (seconds)
LIGO-Livingston raw data
Frequency (Hz)
Normalized amplitude
Strain data
Glitch model
Strain (×10^−20)
Window amplitude
Time (seconds)

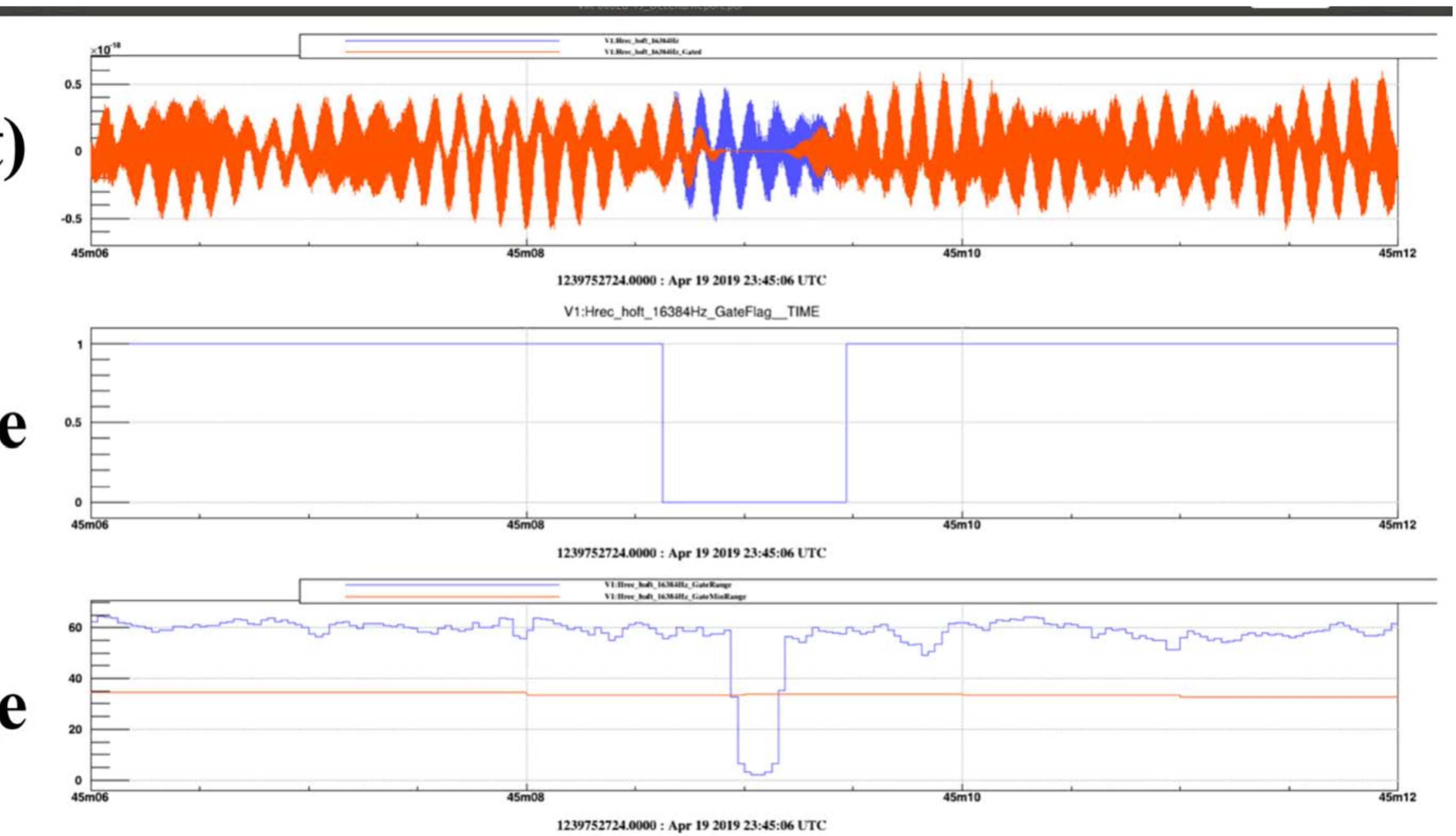


Virgo implementation:
Open a gate whenever the BNS range drops below 60% of its nominal value (+ < 1s)

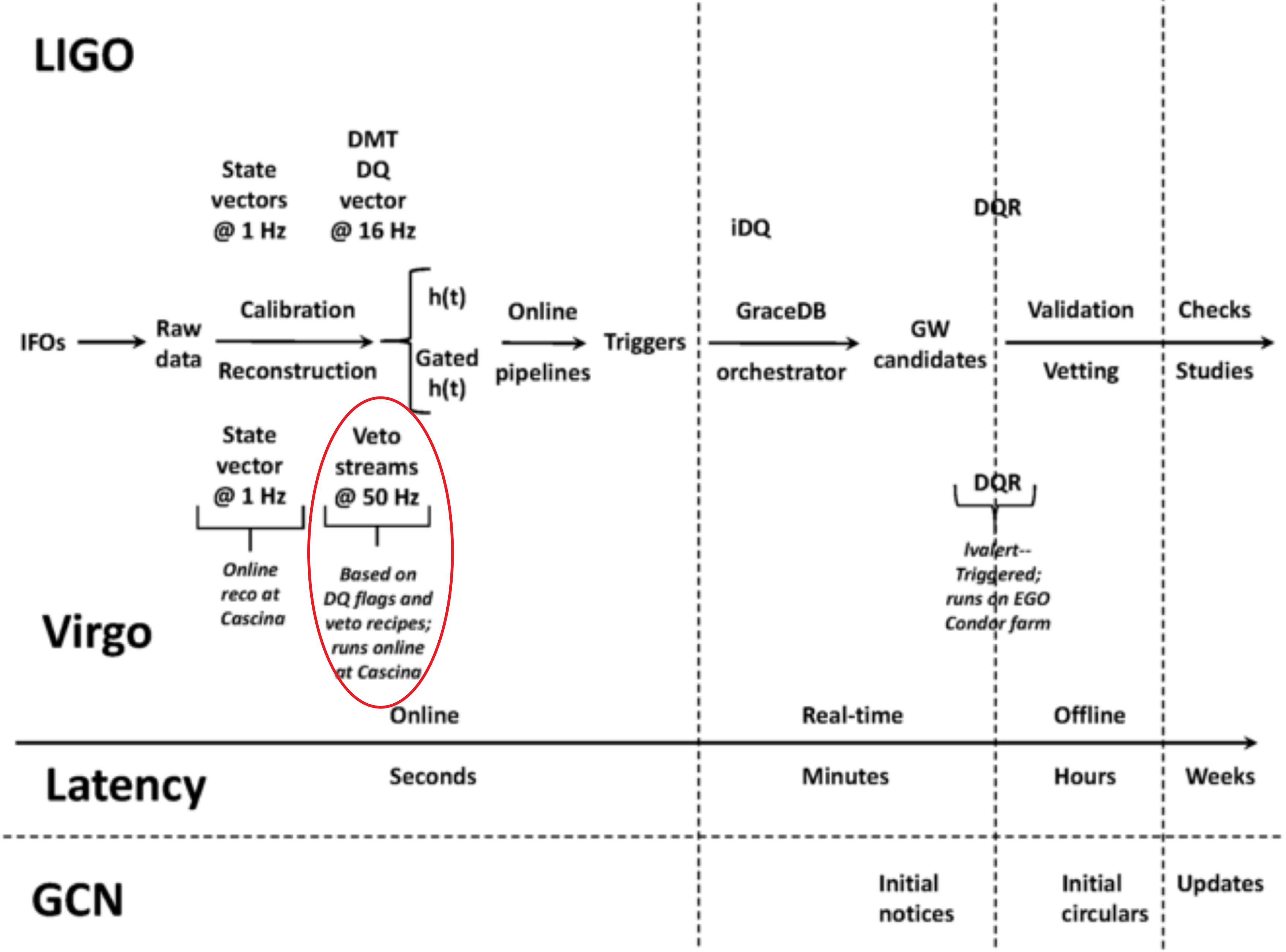
h(t)

GATE

BNS RANGE

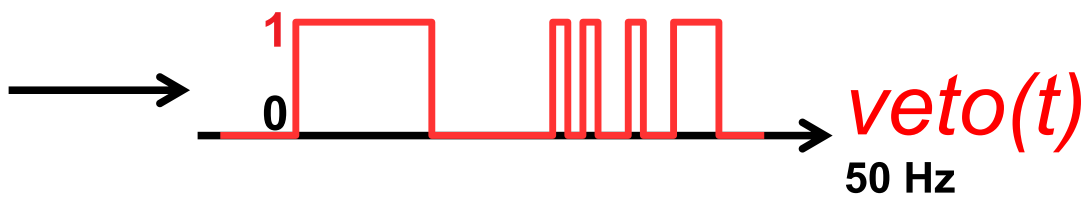


Detector characterization online pipeline



Veto streams

Auxiliary channels input



Goal:

→ produce a veto channel informing the searches when the data is contaminated wit

What:

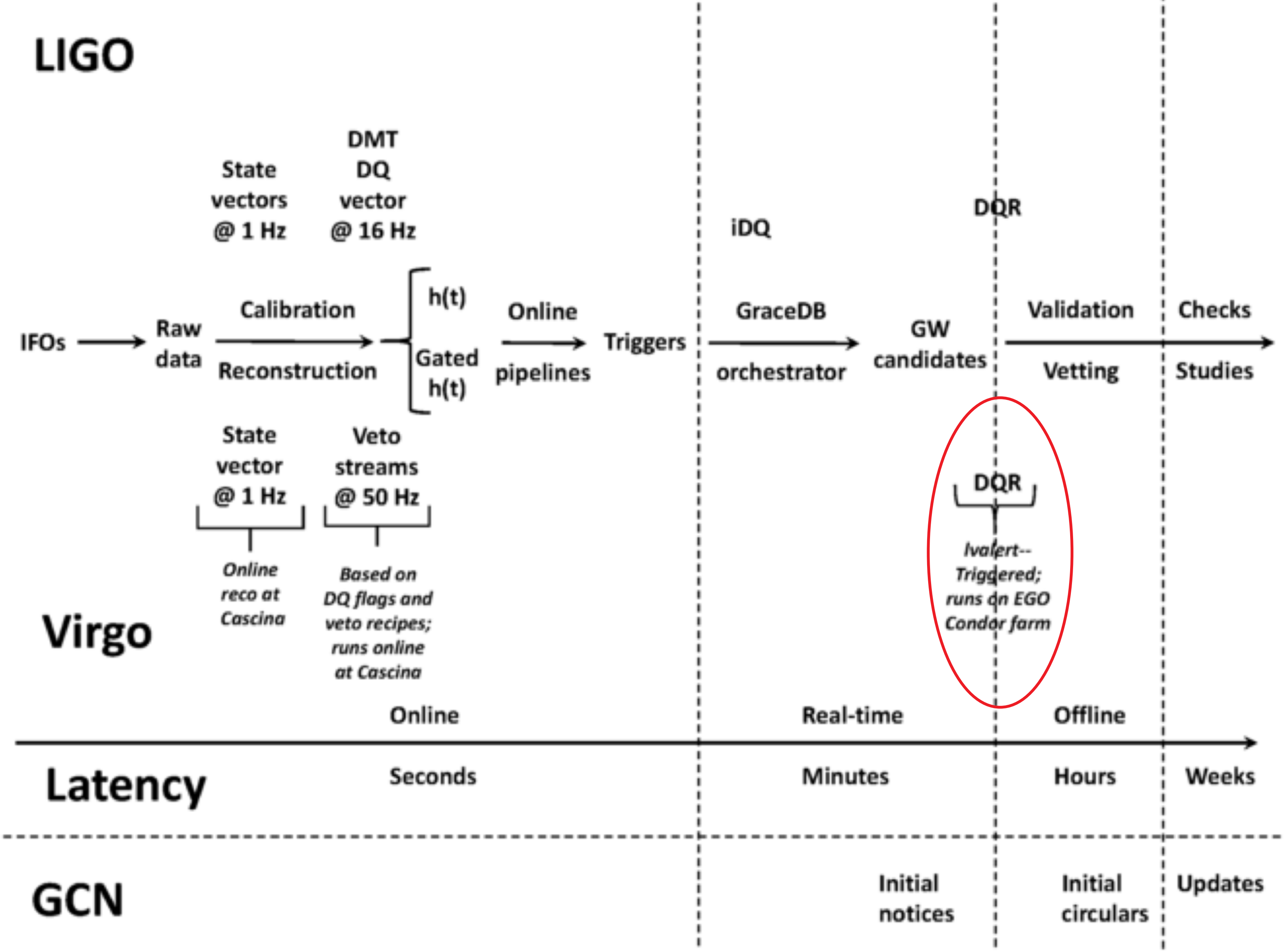
→ a channel taking 1/0 values: 1= “BAD”, 0=“GOOD”

How:

→ online monitors are flagging the data when the quality is bad (~250 channels)
→ select the relevant flags for a given search
→ combine the flags into a single channel
→ revisit the flag selection as often as possible

LIGO equivalent: iDQ, Reed Essick et al. CQG (2013)

Detector characterization online pipeline



GraceDB — Gravitational Wave Candidate Event Database

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Superevent Info

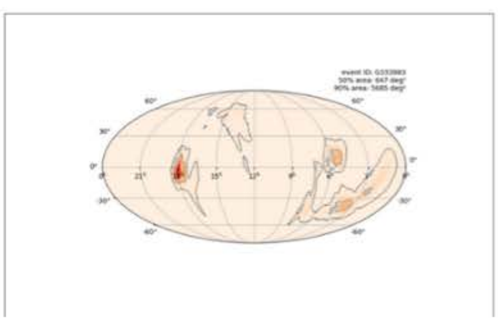
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC Submission time	Links
S190524q	Production	DQOK ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	6.971e-09	1 per 4.5458 years	1242708743.678669	1242708744.678669	1242708746.133301	2019-05-24 04:52:30 UTC	Data

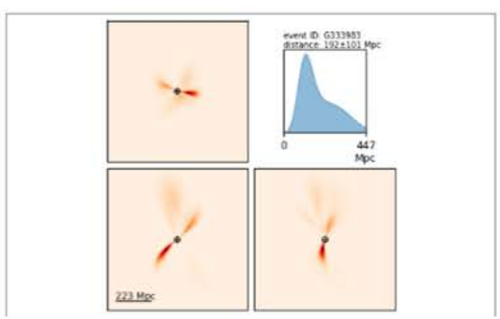
Preferred Event Info

Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	gstlal	AllSky	H1,L1,V1	6787	2019-05-24 04:52:28 UTC

Superevent Log Messages

Sky Localization





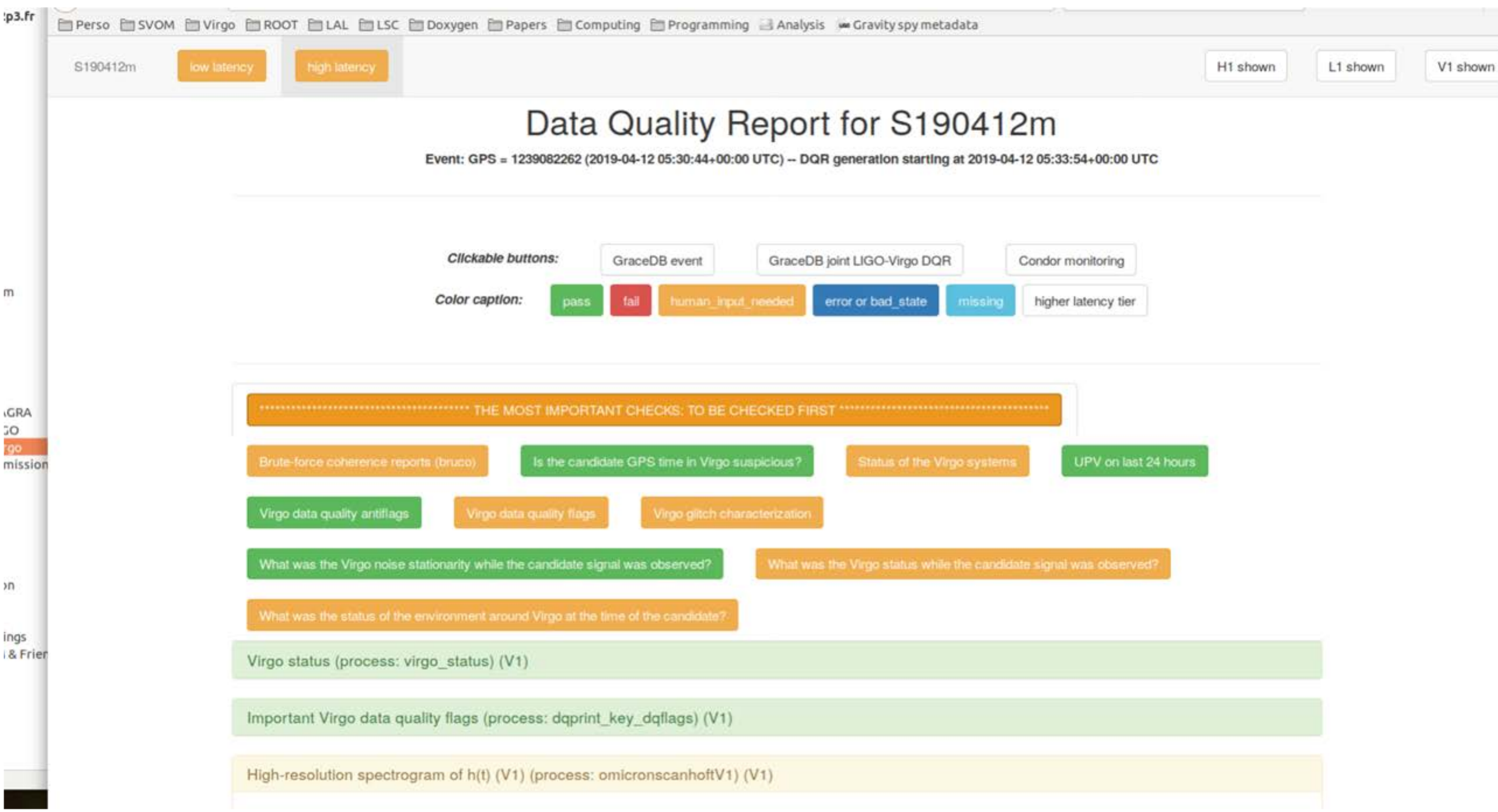
A DQR analysis is triggered

Data quality report (DQR)

→ A DQR web page is automatically generated whenever an event is uploaded to graceDB

→ Tens of checks are performed to characterize the data quality around the time of the event

→ The results of the checks are uploaded to graceDB



Data quality report (DQR)

Data quality checks

→ detector status

→ h(t) spectrograms + full scans of aux. channels

→ check online data quality flags

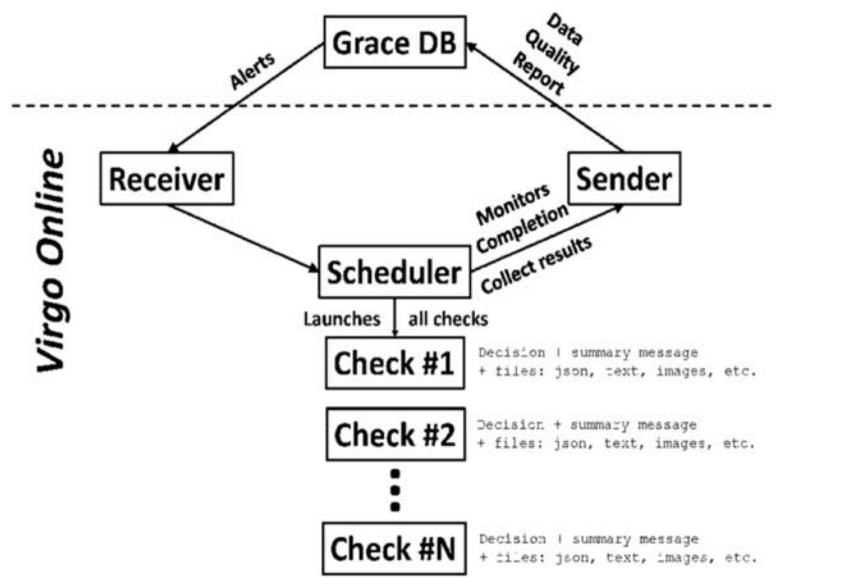
→ check noise stationary

→ check environment
– earthquakes around the globe
– weather, sea activity

→ detchar analyses
– brute force coherence
– glitch-to-glitch coupling

→ scan all online process log files

→ sub-system data quality



Results are checked by humans

Detector characterization (future) challenges

→ Transient noise modeling based on auxiliary signals

→ Transient noise subtraction

→ Automatic data quality validation of GW detection (take the human out of the loop)

→ Completely integrate detector characterization in the search pipelines
- ranking statistics including auxiliary channels
- technical challenge: transfer raw data at a single location

→ Use machine-learning techniques in main stream analyses