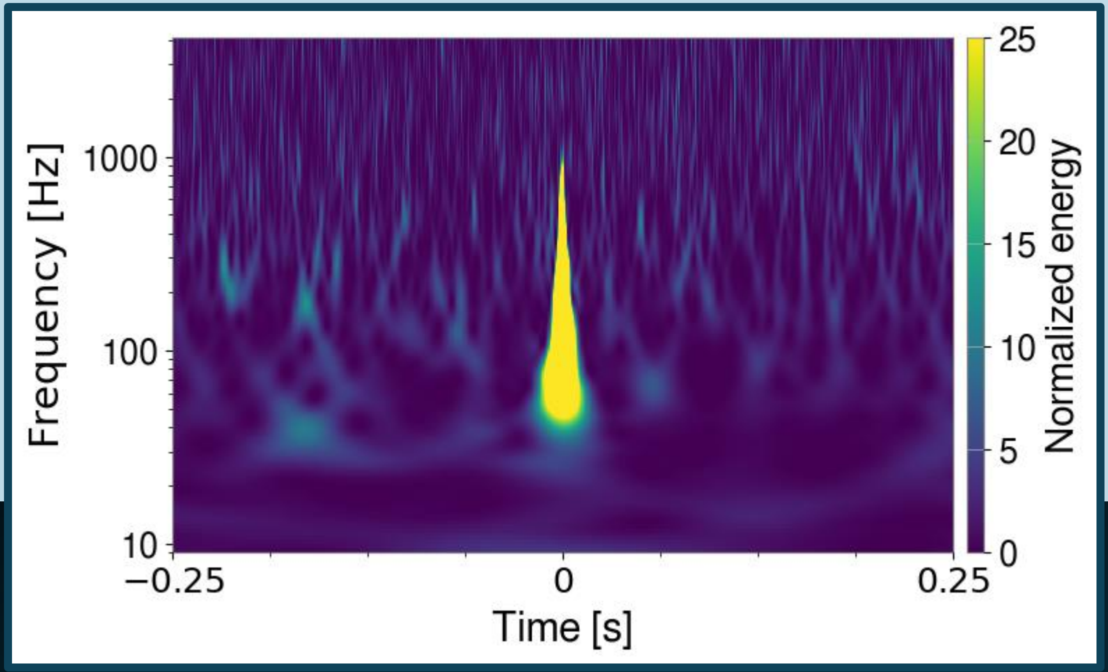
Detector Characterization



Tabata Aira Ferreira
Louisiana State University

GW Open Data Workshop
May 14, 2025

Outline

- What are the main responsibilities of the Detector Characterization group?

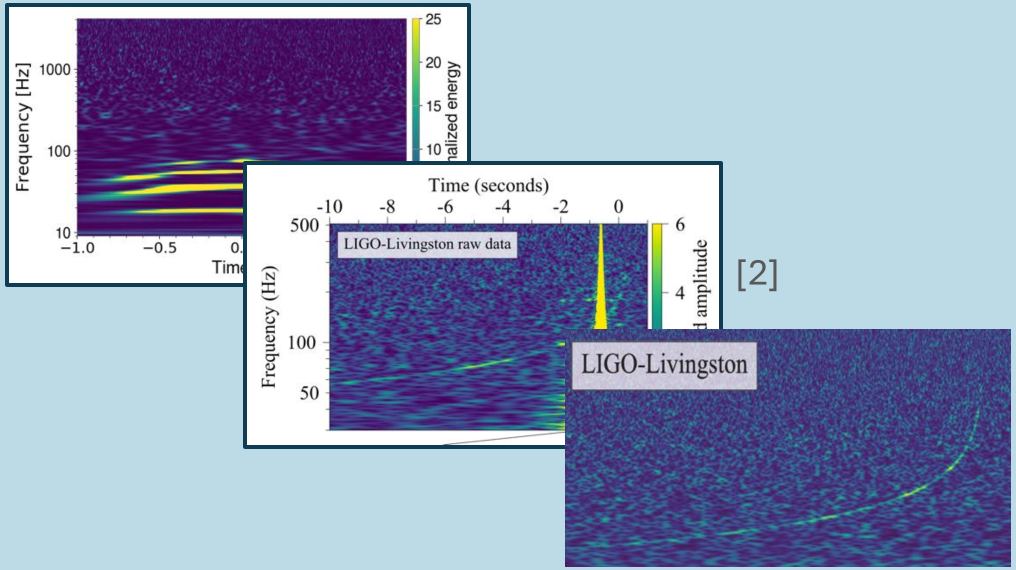
- Gravitational-wave detector strain data:
  - Time Domain
  - Frequency domain (PSD/ASD)
  - Time-Domain (Post-Processing: Whitening, Filtering)

- Gravitational-Wave Detector Noise:
  - Persistent or slowly time-varying noise signals (lines)
  - Transient noise signals (glitches)
  - Auxiliary Channels
  - Data Quality Products

- O4a Summary

What are the main responsibilities of the DetChar group?

The Detector Characterization (DetChar) group focuses on both instrumentation and data quality - investigating the detectors to identify and mitigate noise sources, and providing data-quality information to support gravitational-wave searches and the validation of candidate events.



[2]

[1]

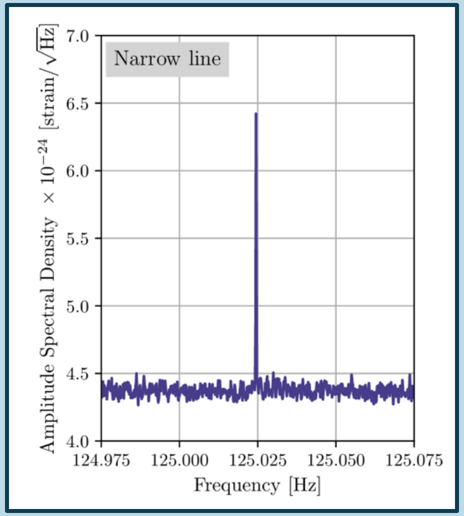
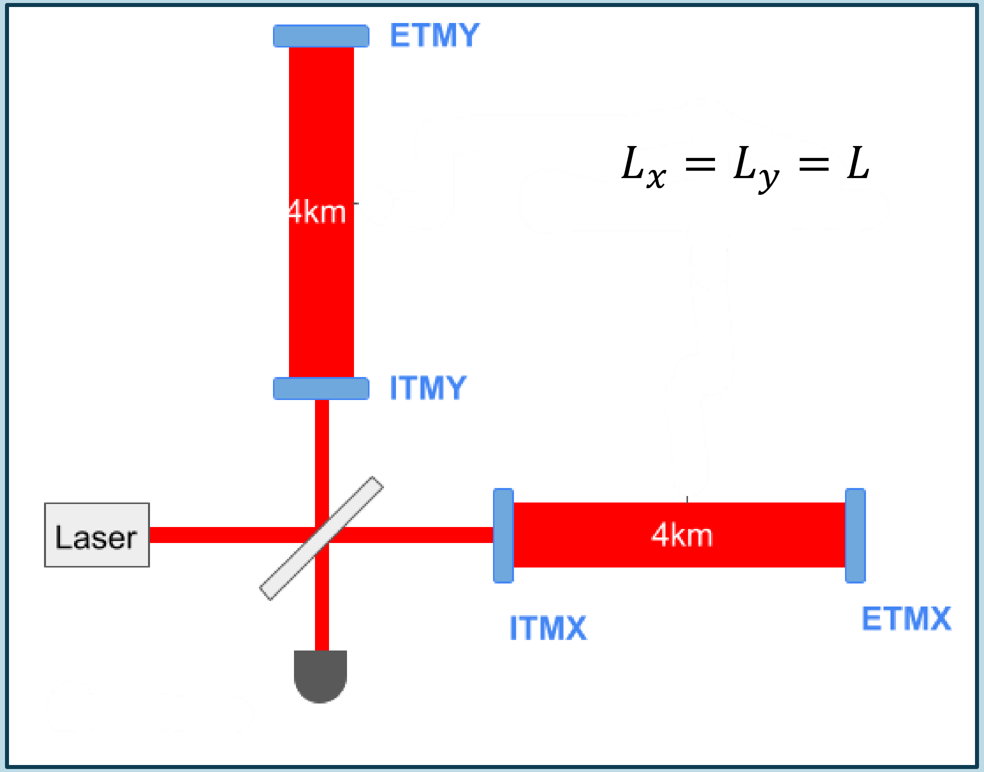


Image credit: Generated by AI

[1] and [2] are adapted from Soni et al. (2025) and Abbott et al. (2017), respectively.

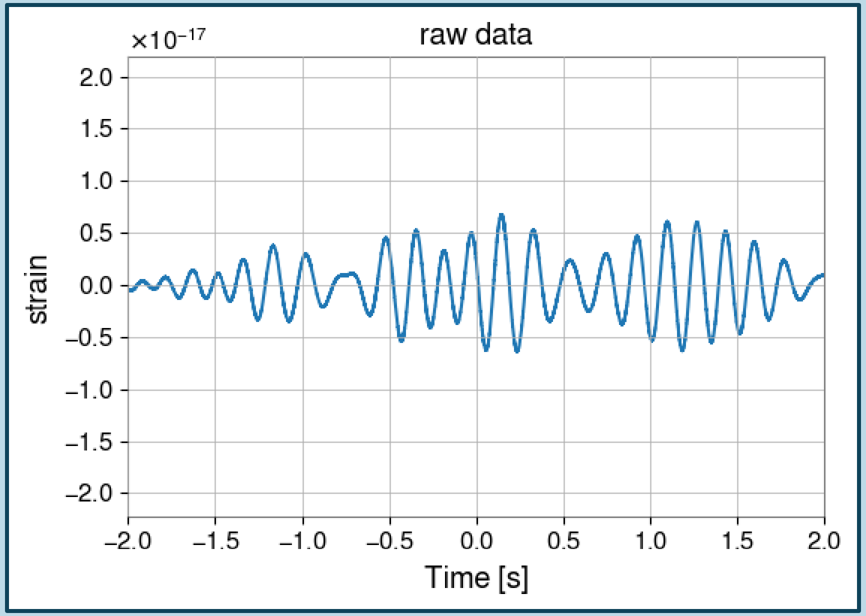
Gravitational-Wave Detector Data: Strain (Time Domain)



$$L_x = L_y = L$$

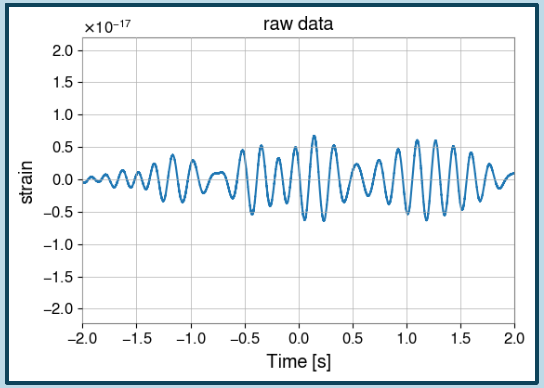
Gravitational-wave strain amplitude :

$$h(t) = \frac{\Delta L(t)}{L} = \frac{\delta L_x - \delta L_y}{L}$$

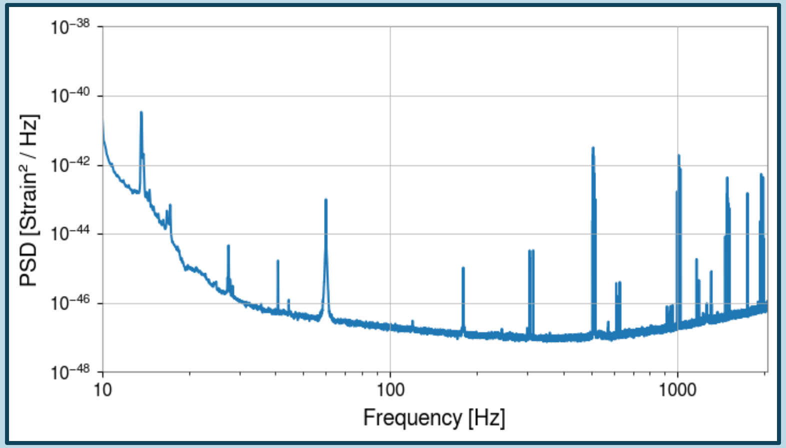


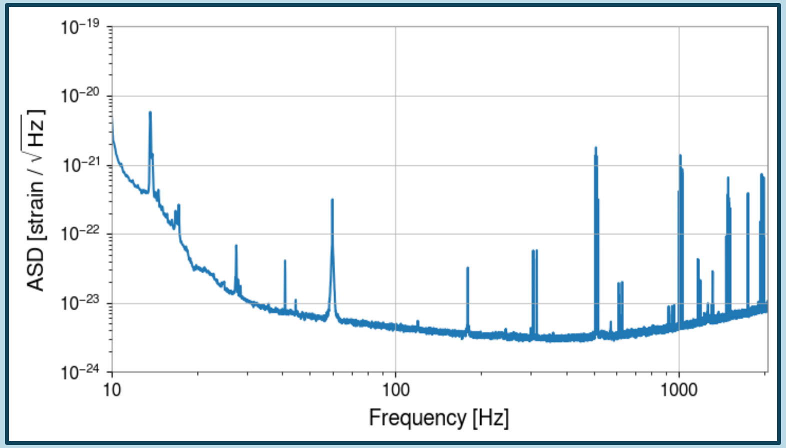
Gravitational-Wave Detector Data: Strain (Frequency Domain)

Data in time domain:



Data in the frequency domain:





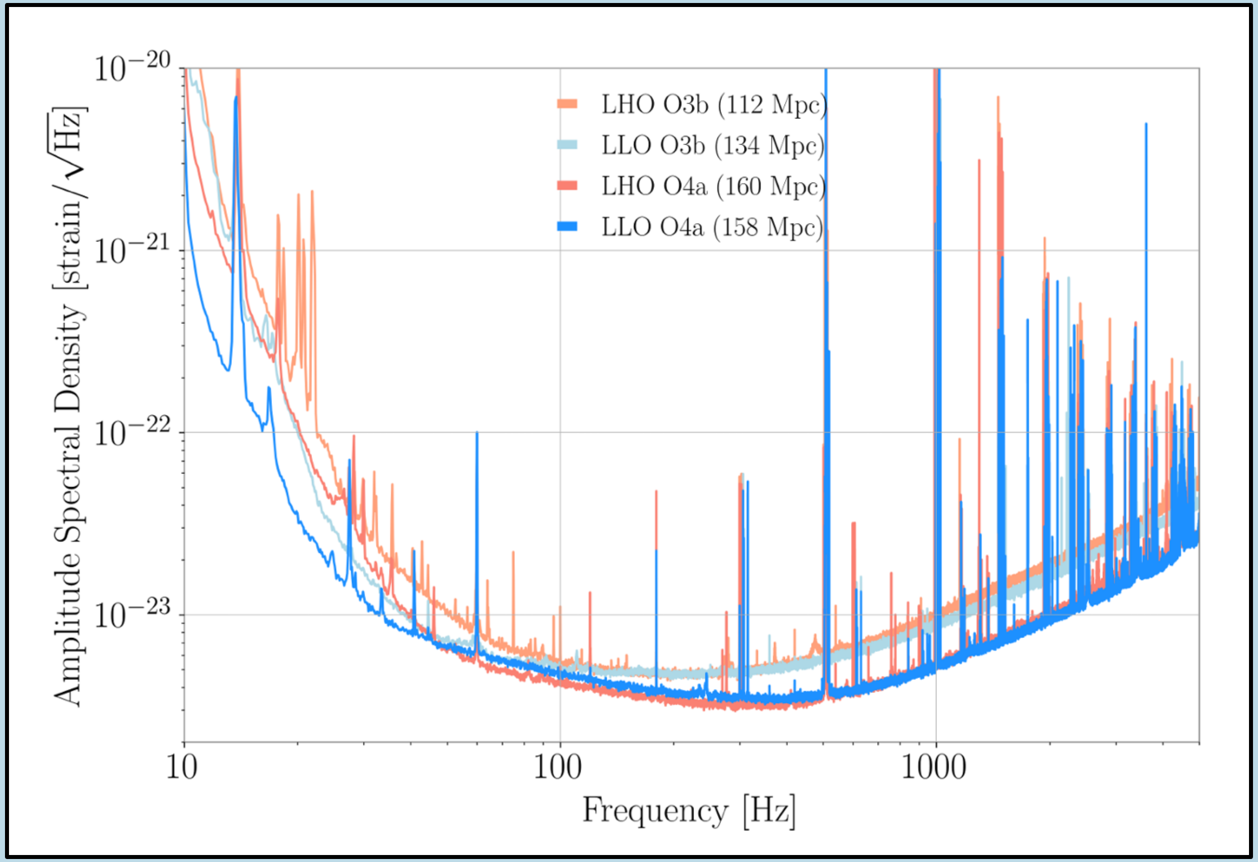
$$s(t) \xrightarrow{FFT} \tilde{S}(f) \rightarrow \frac{|\tilde{S}(f)|^2}{T}$$

The Power Spectral Density (PSD) of the data - and its square root, the Amplitude Spectral Density (ASD), evaluated over long time periods - characterizes the noise spectrum of a gravitational-wave detector, which is limited by various noise sources.

Gravitational-Wave Detector Data: Strain (Frequency Domain)

Comparison of the noise ASDs of the LIGO detectors during O3b and O4a

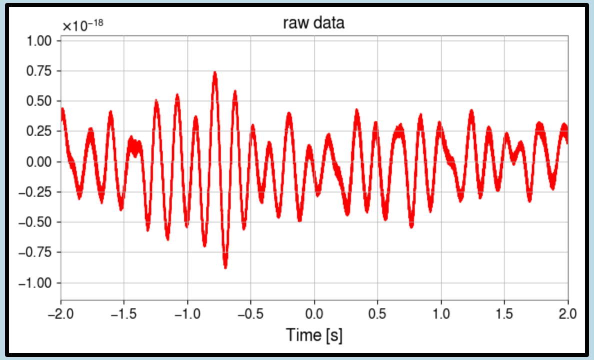
[1]

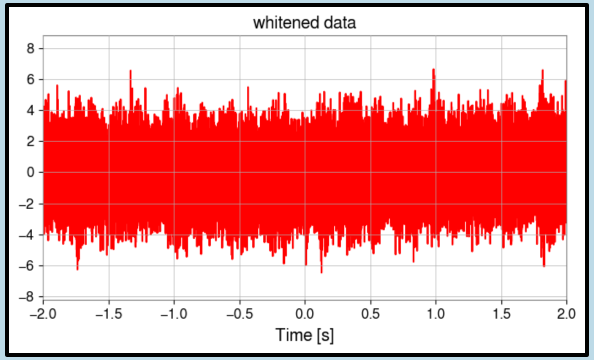


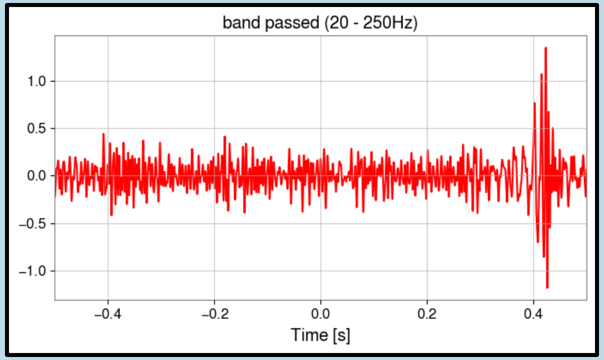
[1]: Soni et al. (2025)

Gravitational-Wave Detector Data: Time-Domain (Post-Processing)

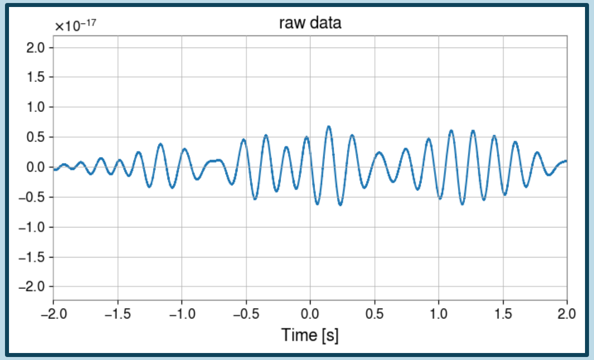
H1: GW150914

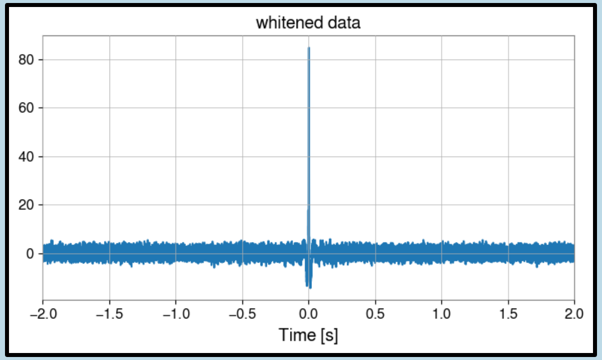


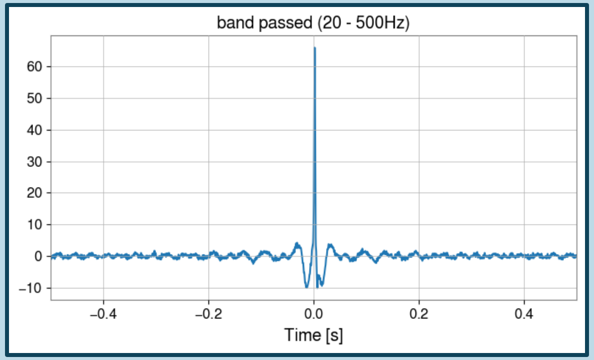




L1: Loud Glitch (transient noise)







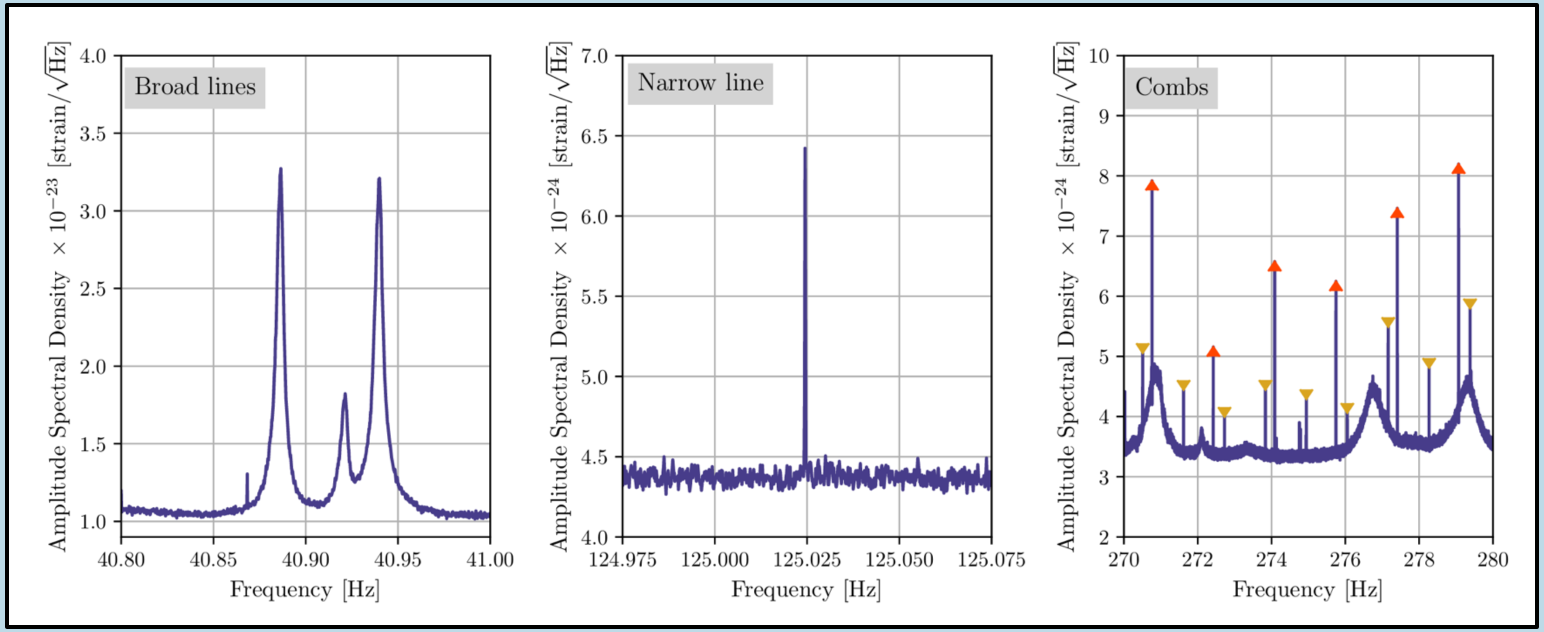
Categories of Gravitational-Wave Detector Noise

Gravitational-Wave Detector Noise Sources: Lines

Persistent (or slowly time-varying) artifacts are usually referred to as *lines*.
These features increase the noise amplitude at certain frequencies and can impact continuous-wave searches.

[1]

Complementary information about spectral lines comes from tools such as *Fscan* and *StochMon*.

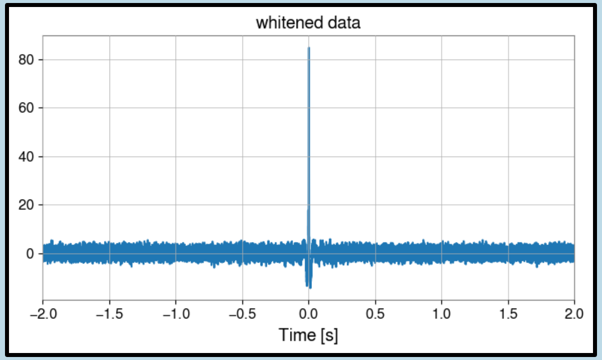


[1]: Soni et al. (2025)

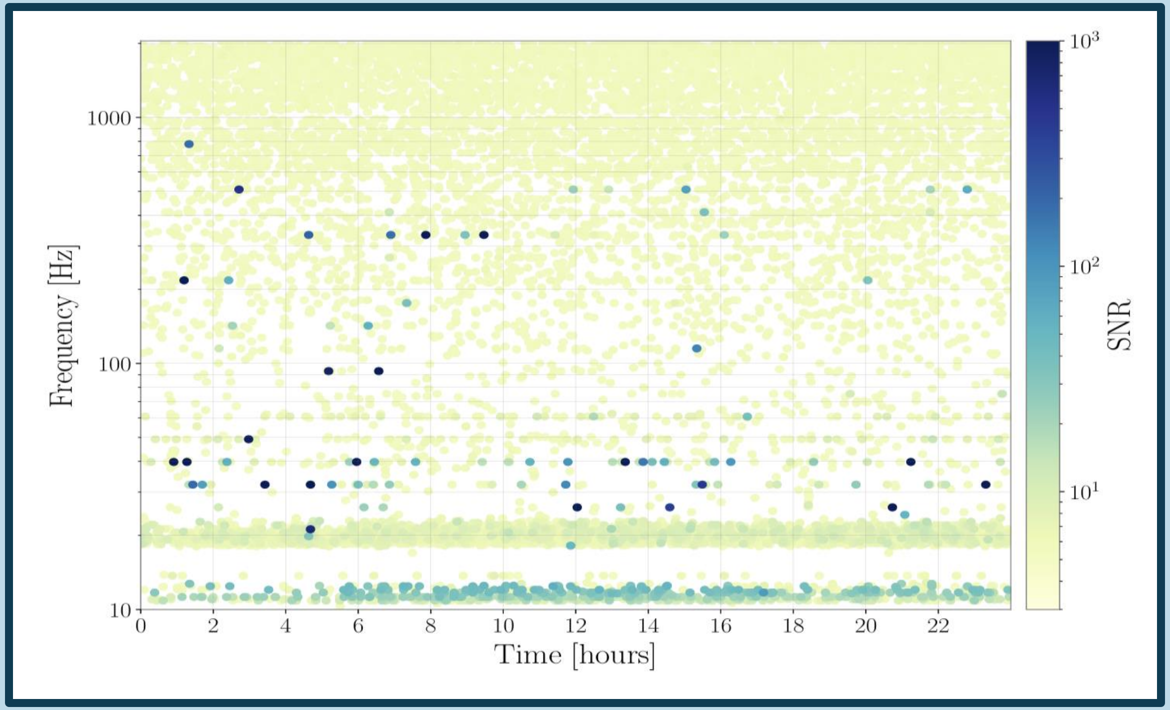
Gravitational-Wave Detector Noise Sources: Glitches

Short-duration artifacts are usually referred to as glitches.
They increase the background noise, impacting transient gravitational-wave searches. Glitches may also affect parameter estimation, overlap with, or even mimic real gravitational-wave signals.

Omicron is the main tool used to search for excess power in the data, characterizing it by assigning information such as time, frequency, and signal-to-noise ratio (SNR).



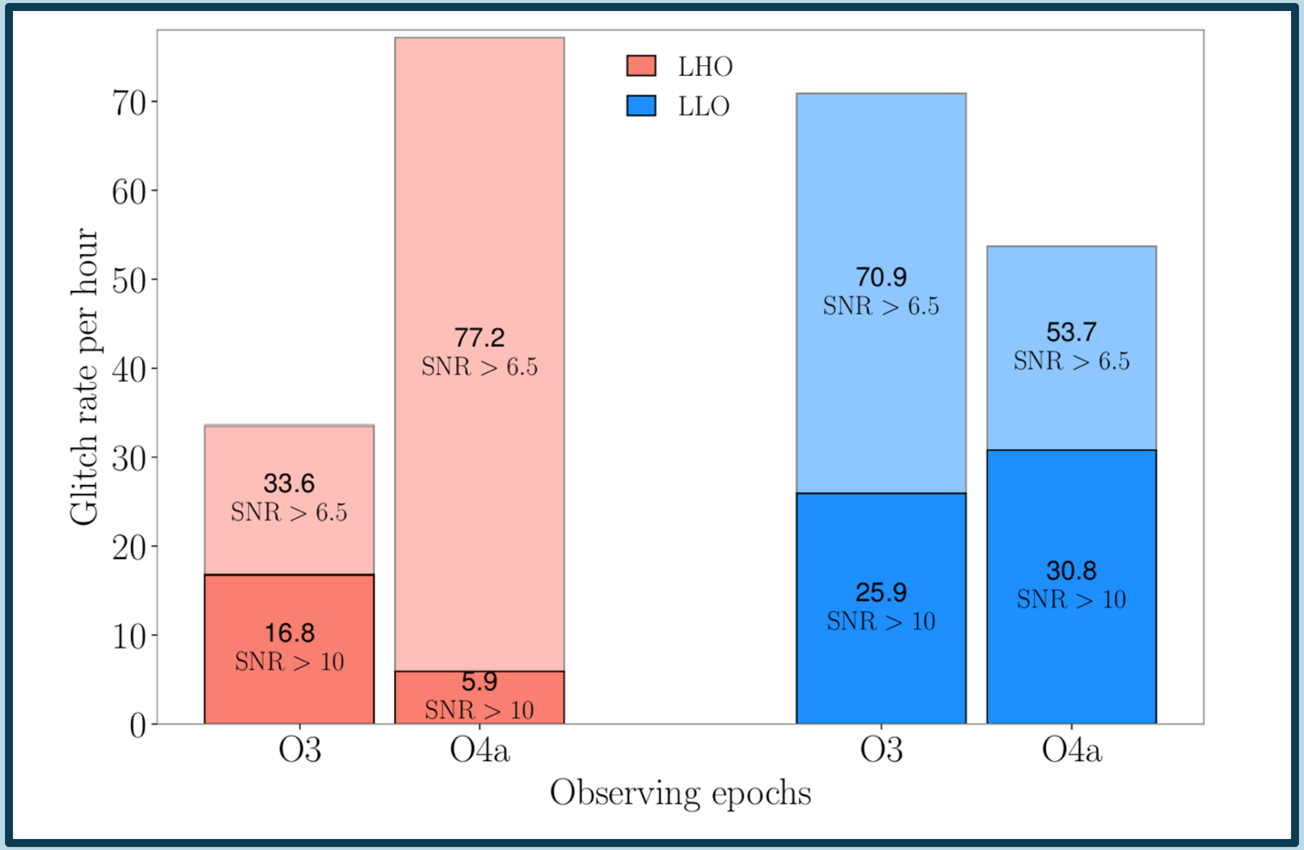
[1]



[1]: Soni et al. (2025)

Gravitational-Wave Detector Noise Sources: Glitches

[1]



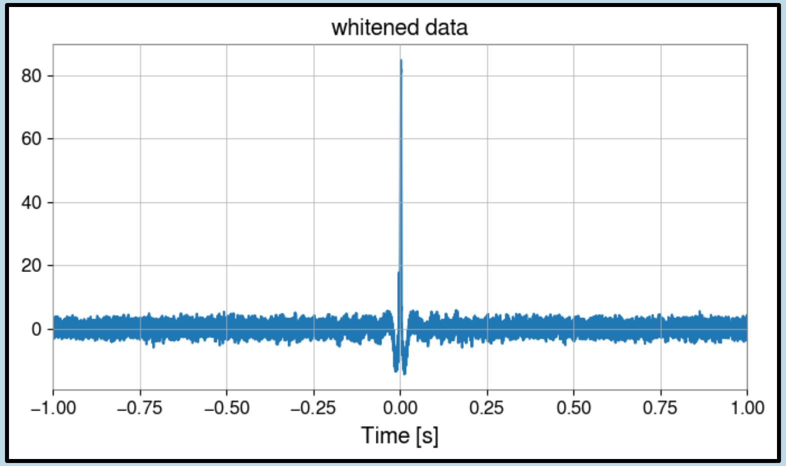
Comparison of the noise transient (glitch) rates of the LIGO detectors during O3b and O4a for different SNR thresholds.

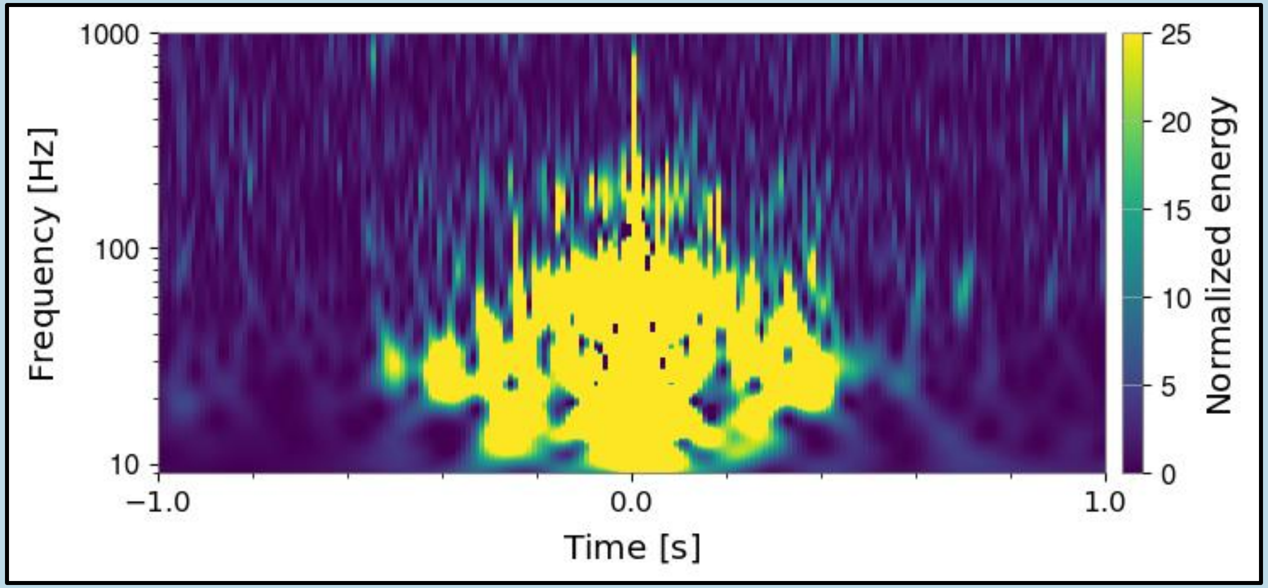
How are glitches usually studied?

[1]: Soni et al. (2025)

Spectrograms

- We’ve seen the data in the time and frequency domains - now, let’s put them together in the form of spectrograms.



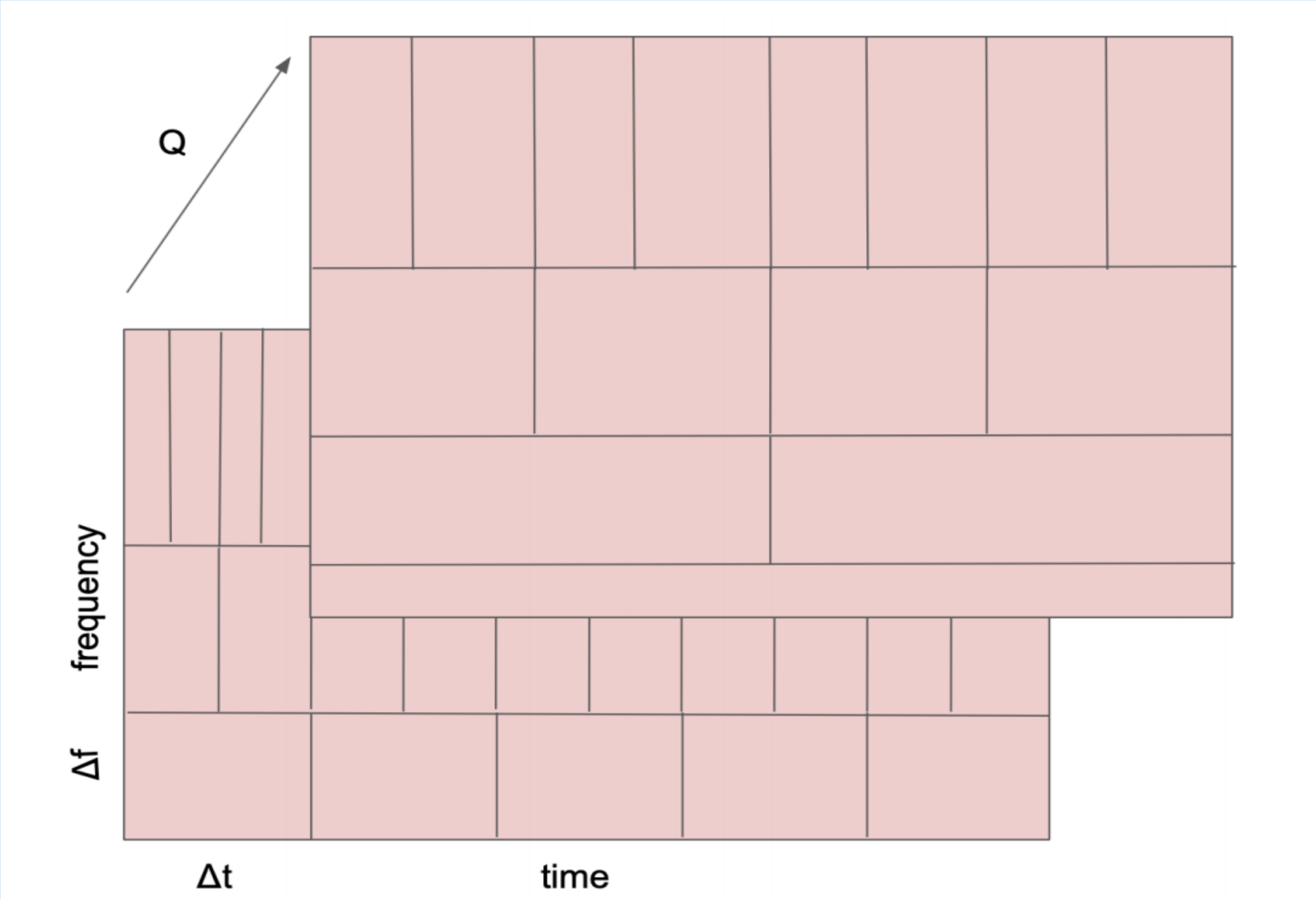


The Q-transform

$$Q \propto \frac{f_0}{\Delta f_0}$$

Time or frequency resolution can be optimized depending on the analysis objective.

[3]



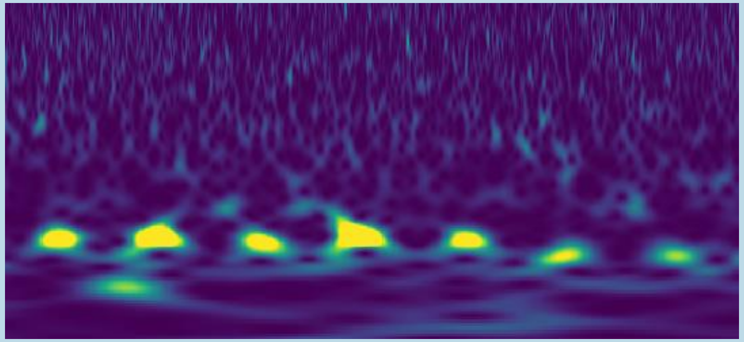
[3]: Soni, Siddharth (2021).

Q-values

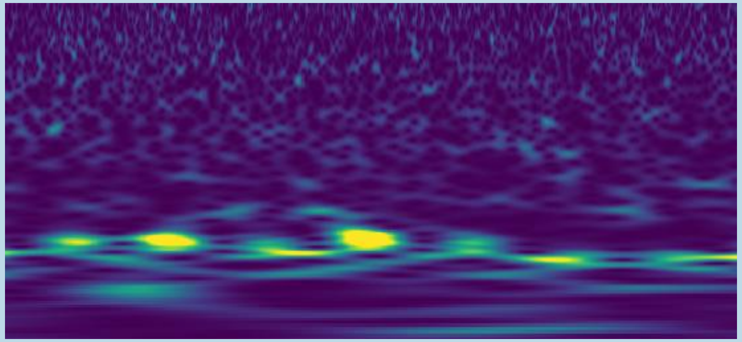
$$Q \propto \frac{f_0}{\Delta f_0}$$

- How do the Q-values affect the morphology of the signal?

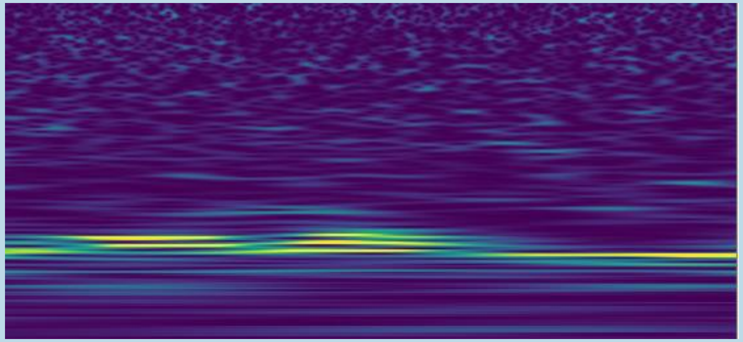
Q ~ 5



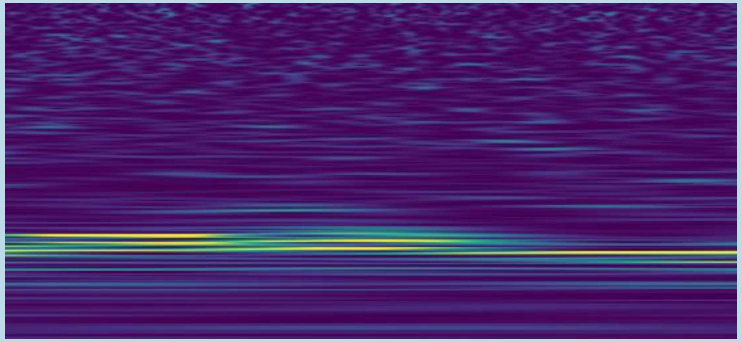
Q ~ 30



Q ~ 60



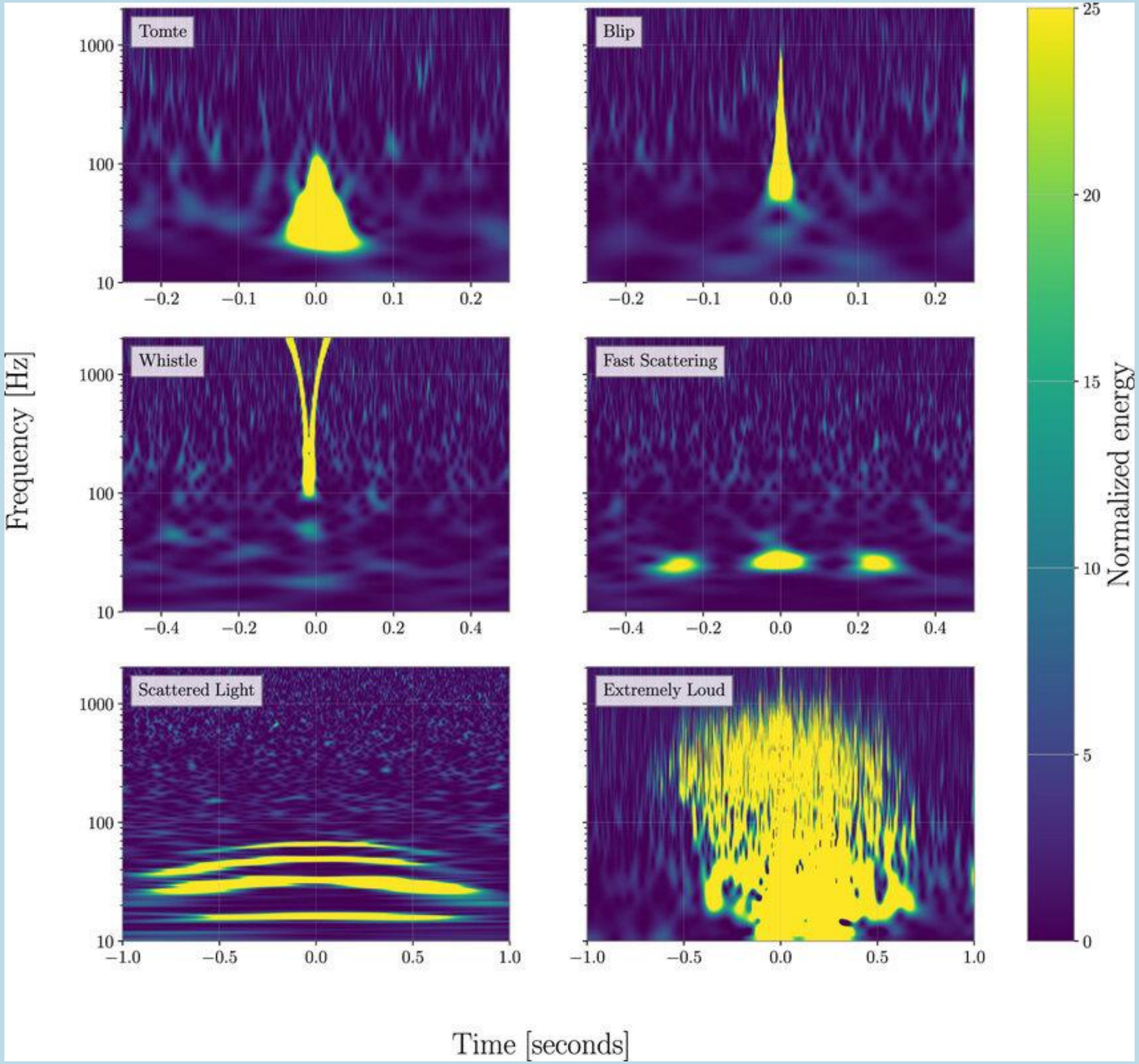
Q ~ 90



Glitch Classes

[4]

Glitches can be classified according to their morphology in spectrograms:



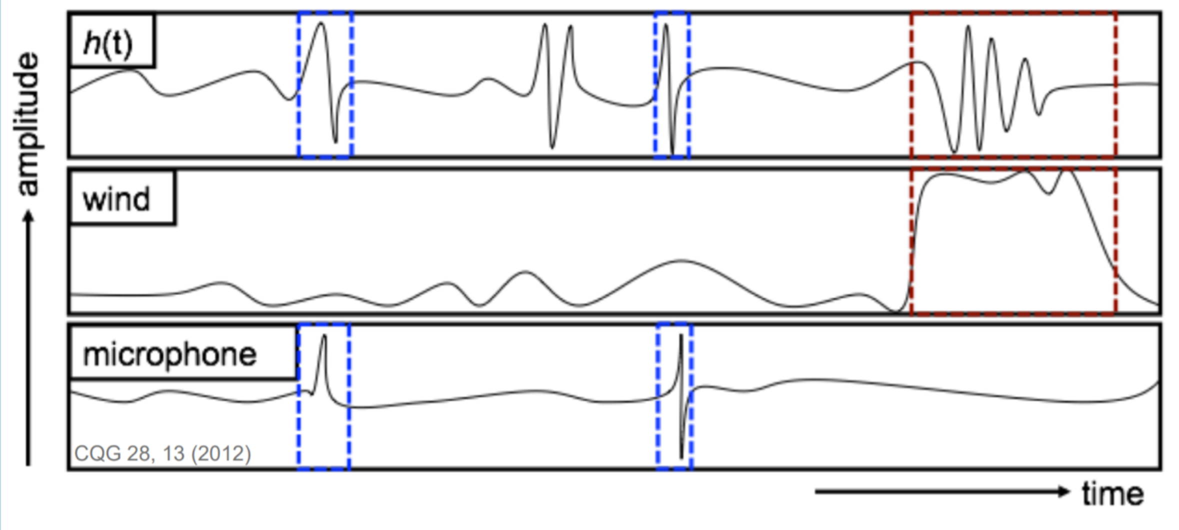
Example of tool to classify glitches:
Gravity Spy (Zooniverse platform)

[4]: Glanzer et al. (2023)

Auxiliary Channels (Information from Various Sensors)

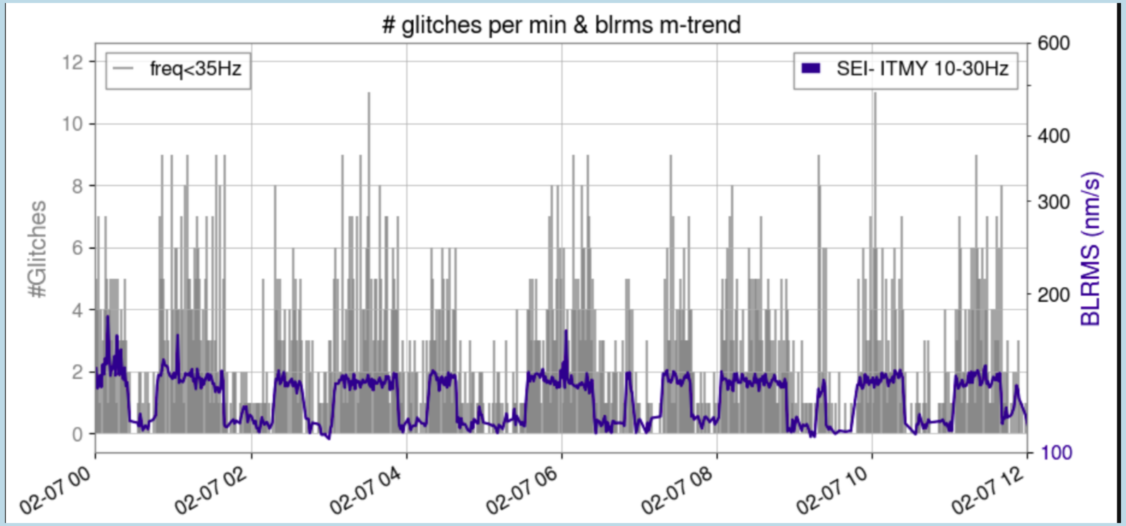
Why does DetChar perform all this analysis? To help investigate the sources of glitches and lines.

[5]



Examples of tools to analyze auxiliary channels: Hveto, iDQ

[6]



How to validate whether an auxiliary channel is safe: Hardware Injections

[5] and [6] are from Smith et al. (2011) and Debasmita et al. (2025), respectively.

Data Quality Products

The DetChar group analyzes potential issues in the data, defining segments to be vetoed. These vetoes are categorized according to the severity and understanding of the underlying problems:

- **CAT1:** Indicates periods with technical problems or critical issues involving key detector components not operating in their nominal configuration.

- **CAT2:** Marks times with *known noise couplings* to the strain channel — for example, due to high ground motion or environmental disturbances.

- **CAT3:** Flags times with *statistical correlations* between the strain and auxiliary channels, where the coupling is not fully understood.

REF: Abbott, R. *et al.* (2023). *Open data from the third observing run of LIGO, Virgo, KAGRA, and GEO.*

O4a Summary

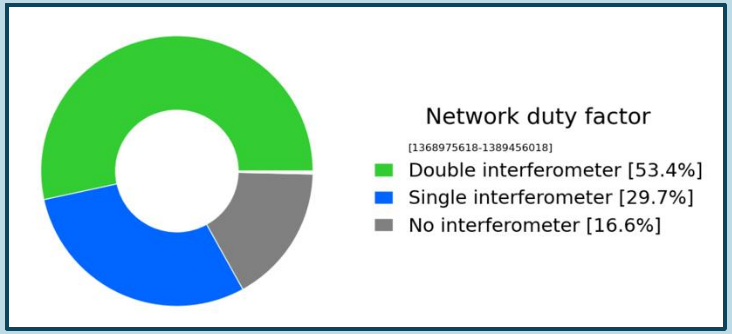
Gravitational-Wave Observatory Status

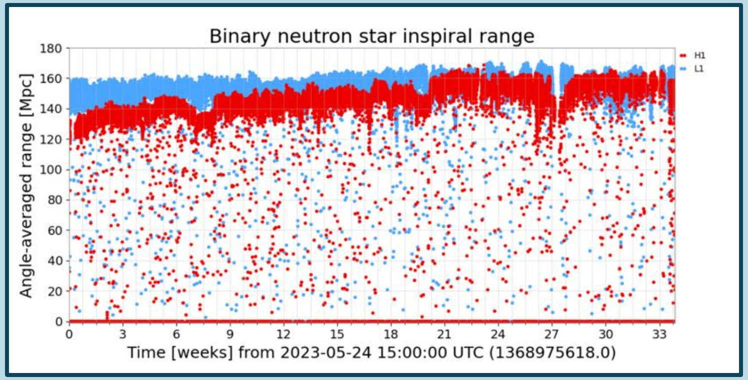
Please select a date from the calendar above to see archived or current status.

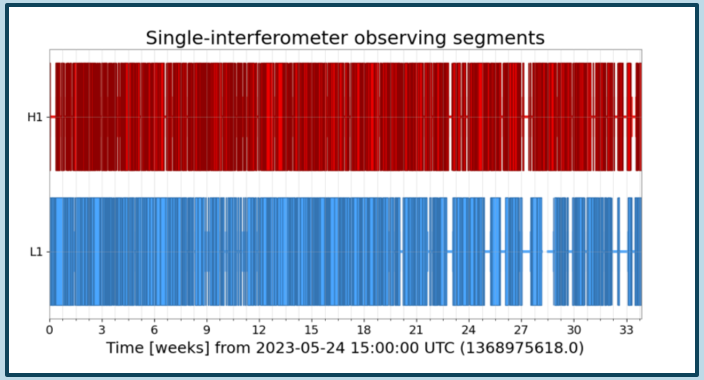
Information is available for dates after November 30, 2016. The Advanced LIGO and Virgo detectors have begun the third part of the fourth observing run, known as O4c, as of January 28, 2024. The entry of the KAGRA detector into O4c has been postponed in order to continue detector commissioning activities and further increase the sensitivity of the detector. All detectors are planned to rejoin O4 by the end of the run. Summaries of the current observing run and previous observing runs are available in the menu above. For overviews of LIGO, Virgo, and KAGRA observing runs, see the arXiv:1304.0670.

- **Today's Summary Page**
- Current Status (GWISTAT)
- LIGO/Virgo Alerts (GraceDB)
- Hanford alog – Livingston alog – Virgo logbook – KAGRA klog
- LIGO Laboratory – Virgo – KAGRA Observatory – GEO600

O4a Summary







O4a Significant Detection Candidates: **81** (92 Total - 11 Retracted)

O4b Significant Detection Candidates: **105** (114 Total - 9 Retracted)

Thank you!

References and suggestions

DetChar papers:

[1]: Soni, S., et al. "LIGO Detector Characterization in the first half of the fourth Observing run." Classical and Quantum Gravity 42.8 (2025): 085016.

Davis, Derek, et al. "LIGO detector characterization in the second and third observing runs." Classical and Quantum Gravity 38.13 (2021): 135014.

Acernese, F., et al. "Virgo detector characterization and data quality: tools." Classical and Quantum Gravity 40.18 (2023): 185005.

Other references:

[2]: Abbott, Benjamin P., et al. "GW170817: observation of gravitational waves from a binary neutron star inspiral." Physical review letters 119.16 (2017): 161101.

[3]: Soni, Siddharth. Identification and reduction of scattered light noise in LIGO. Louisiana State University and Agricultural & Mechanical College, 2021.

[6]: Debasmita et al. Correlation between LVEA floor noise and the 20 Hz glitches in DARM https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=75579

References and suggestions

Omicron: Robinet, Florent, et al. "Omicron: A tool to characterize transient noise in gravitational-wave detectors." *SoftwareX* 12 (2020): 100620.

Glitches:

Gravity Spy: Zevin, Michael, et al. "Gravity Spy: integrating advanced LIGO detector characterization, machine learning, and citizen science." *Classical and quantum gravity* 34.6 (2017): 064003.

[4]: Glanzer, Jane, et al. "Data quality up to the third observing run of advanced LIGO: Gravity Spy glitch classifications." *Classical and Quantum Gravity* 40.6 (2023): 065004.

Zooniverse: https://www.zooniverse.org/projects/zooniverse/gravity-spy

Alvarez-Lopez, Sofia, et al. "GSpyNetTree: a signal-vs-glitch classifier for gravitational-wave event candidates." *Classical and Quantum Gravity* 41.8 (2024): 085007.

Q-values: Ferreira, Tabata Aira, and Gabriela González. "Using t-SNE for characterizing glitches in LIGO detectors." *Classical and Quantum Gravity* (2024).

References and suggestions

Tools:
[5]: Hveto: Smith, Joshua R., et al. "A hierarchical method for vetoing noise transients in gravitational-wave detectors." *Classical and Quantum Gravity* 28.23 (2011): 235005.

iDQ: Essick, Reed, et al. "iDQ: Statistical inference of non-gaussian noise with auxiliary degrees of freedom in gravitational-wave detectors." *Machine Learning: Science and Technology* 2.1 (2020): 015004.

Summary pages: https://gwosc.org/detector_status/

FSCAN: Arceneaux, Cody. "Fscan Code Development For Advanced Ligo Detector Characterization." (2015).

BayesWave: Cornish, Neil J., and Tyson B. Littenberg. "Bayeswave: Bayesian inference for gravitational wave bursts and instrument glitches." *Classical and Quantum Gravity* 32.13 (2015): 135012.

Public alerts: https://gracedb.ligo.org/

Data: Abbott, Benjamin P., et al. "A guide to LIGO–Virgo detector noise and extraction of transient gravitational-wave signals." *Classical and Quantum Gravity* 37.5 (2020): 055002.

GWpy: Macleod, Duncan M., et al. "GWpy: A Python package for gravitational-wave astrophysics." *SoftwareX* 13 (2021): 100657.