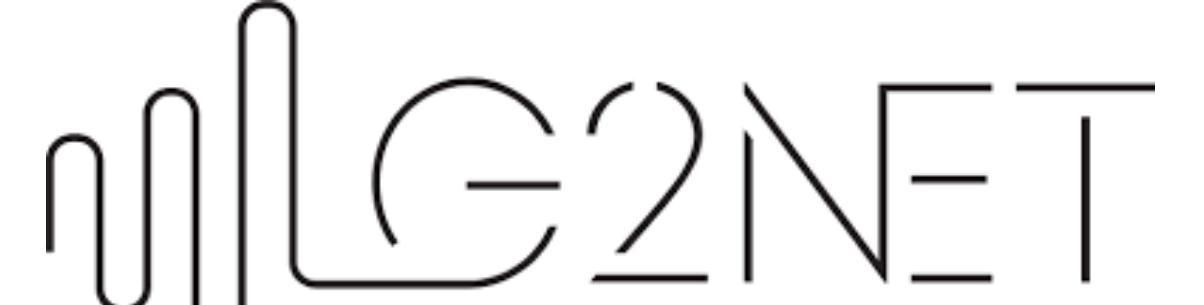




UNIVERSITÀ
DEGLI STUDI
DI TRIESTE



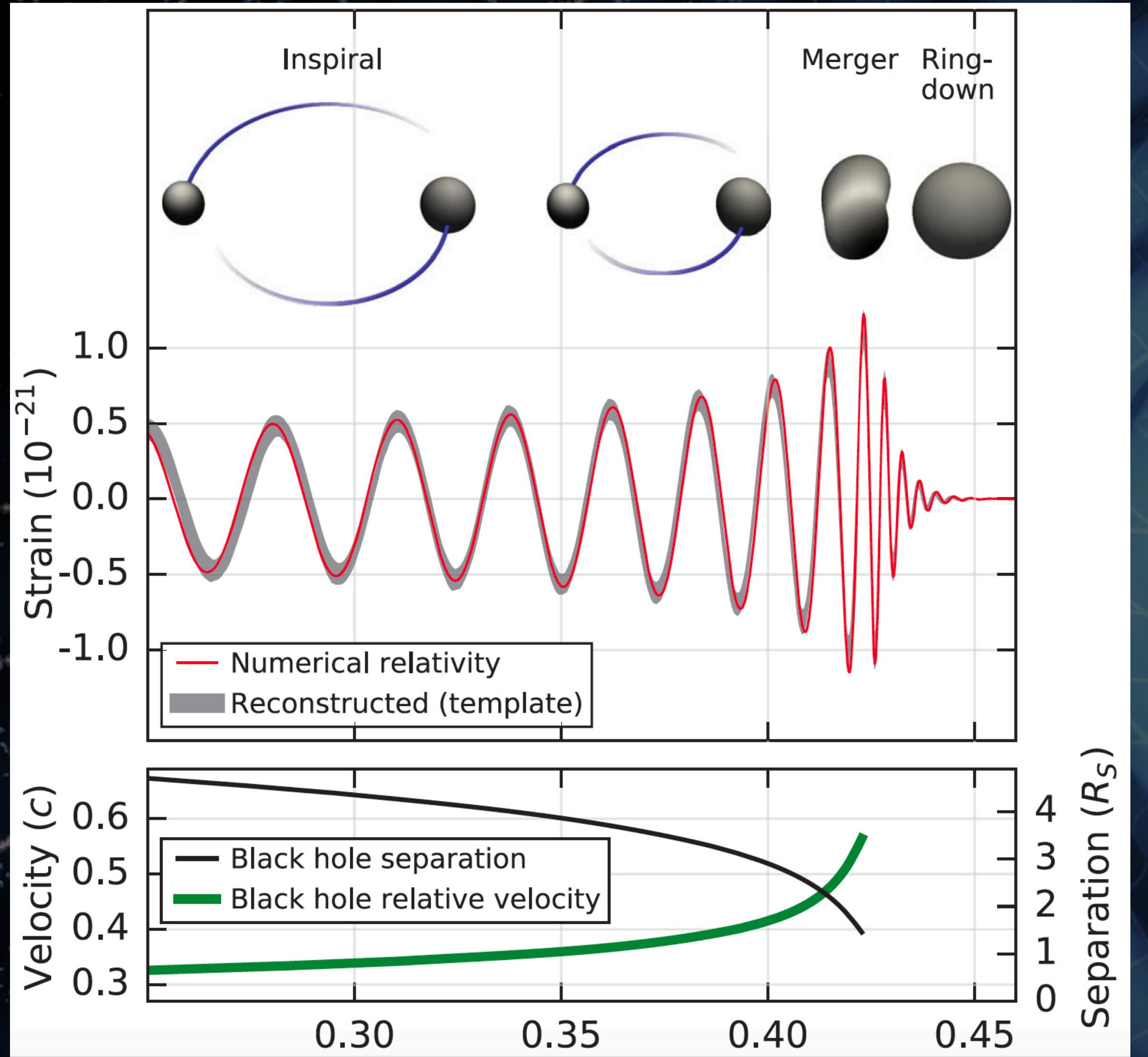
Gravitational-Wave (Open) Data

A. Trovato on behalf of the LVK Collaboration
Università di Trieste, INFN-Sezione Trieste

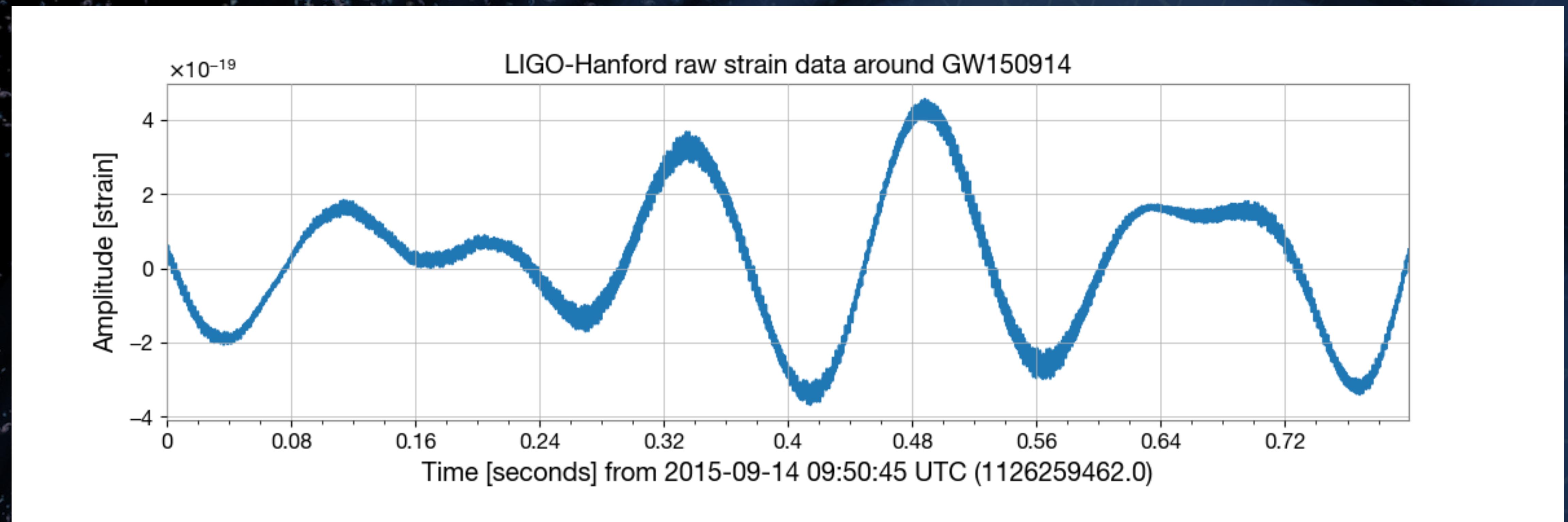
References:

- Gravitational Wave Open Science Center: www.gwosc.org
- Open data from the first and second observing runs of Advanced LIGO and Advanced Virgo: [SoftwareX 13 \(2021\) 100658](https://doi.org/10.1016/j.softx.2021.100658)
- Open data from the third observing run of LIGO, Virgo, KAGRA and GEO: [arXiv:2302.03676](https://arxiv.org/abs/2302.03676)

Gravitational waves (GW)

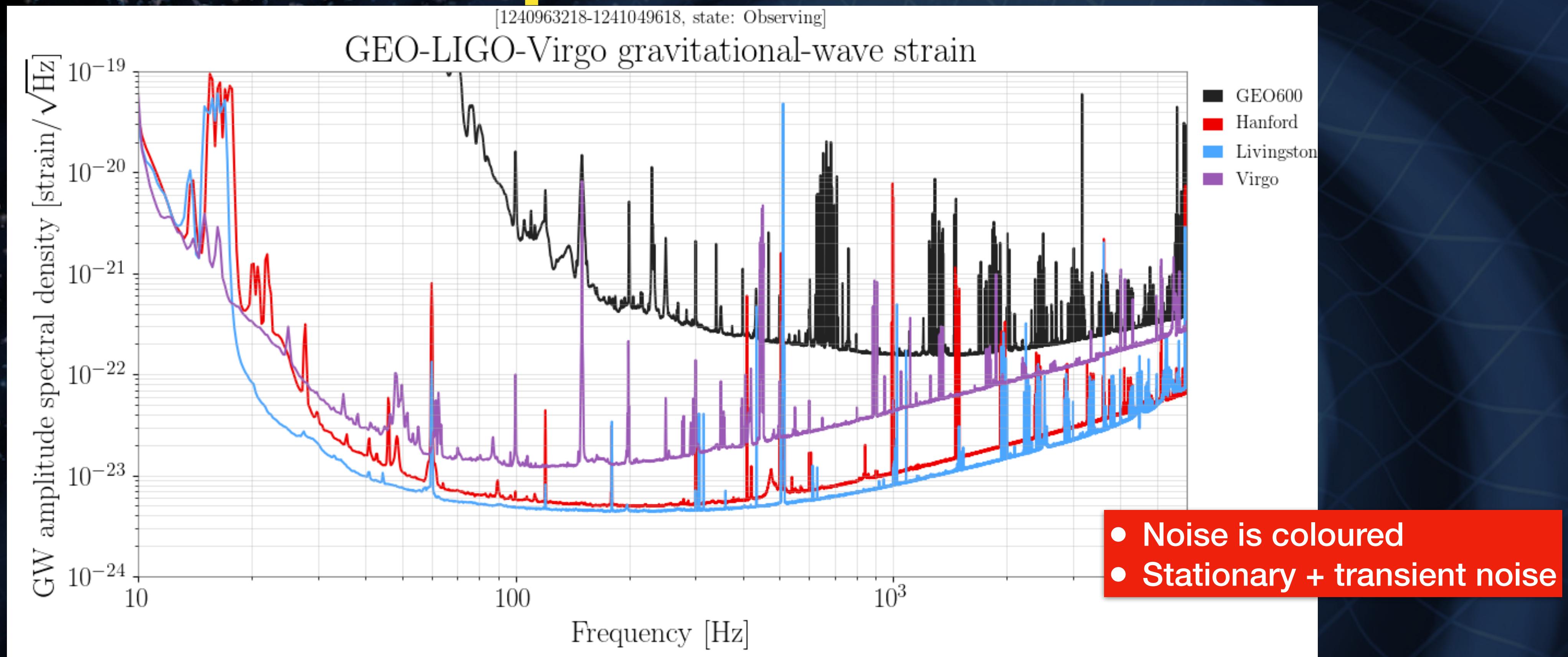


Recorded data



- Data are time series: strain data $h(t)$ are sampled at 16 kHz (16000 values for each second!) → main data but not the only type of data recorded
- Great part of data consist just of noise with eventually a very faint GW signal hidden in it
- GW signals are in an audible frequency (see e.g. Black Hole Hunter)

Complex noise



- **GW amplitude spectral density:** which is the amount of noise for each frequency?
- Data needs to be whitened (divided by the ASD) to normalise each frequency contribution

$$d(t) \xrightarrow{\text{FFT}} \tilde{d}(f) \xrightarrow{\text{Whiten}} \tilde{d}_w(f) = \frac{\tilde{d}(f)}{S_n^{1/2}(f)} \xrightarrow{\text{iFFT}} d_w(t)$$

Keep this in mind for the tutorials ;-)

Observing runs

The detectors alternate periods of data taking and periods of upgrades to the machines



2015 2016 2017 2018 2019 2020 2021



LIGO



O1

4 months
~50 days
coincident

1.5 TB (16 kHz)



O2

6 months
~ 100 days
coincident

Virgo

3.3 TB (16 kHz)

LIGO & Virgo



O3

1 yr
275 days
coincident

Kagra & GEO

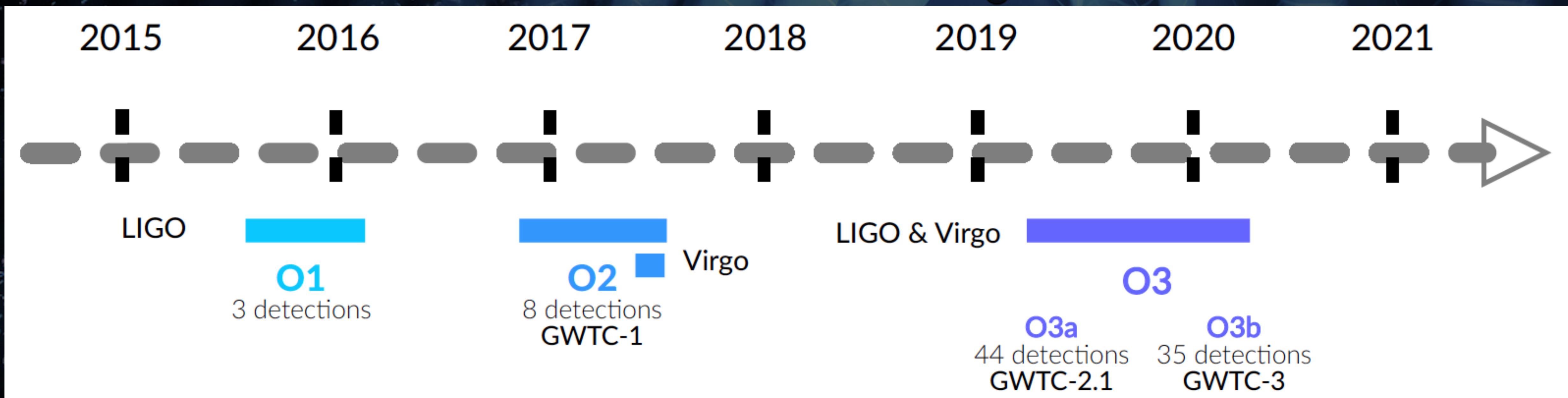
6.6 TB (16 kHz)

O4 will start the
24th May 2023

(Courtesy of E. Chassande-Mottin)

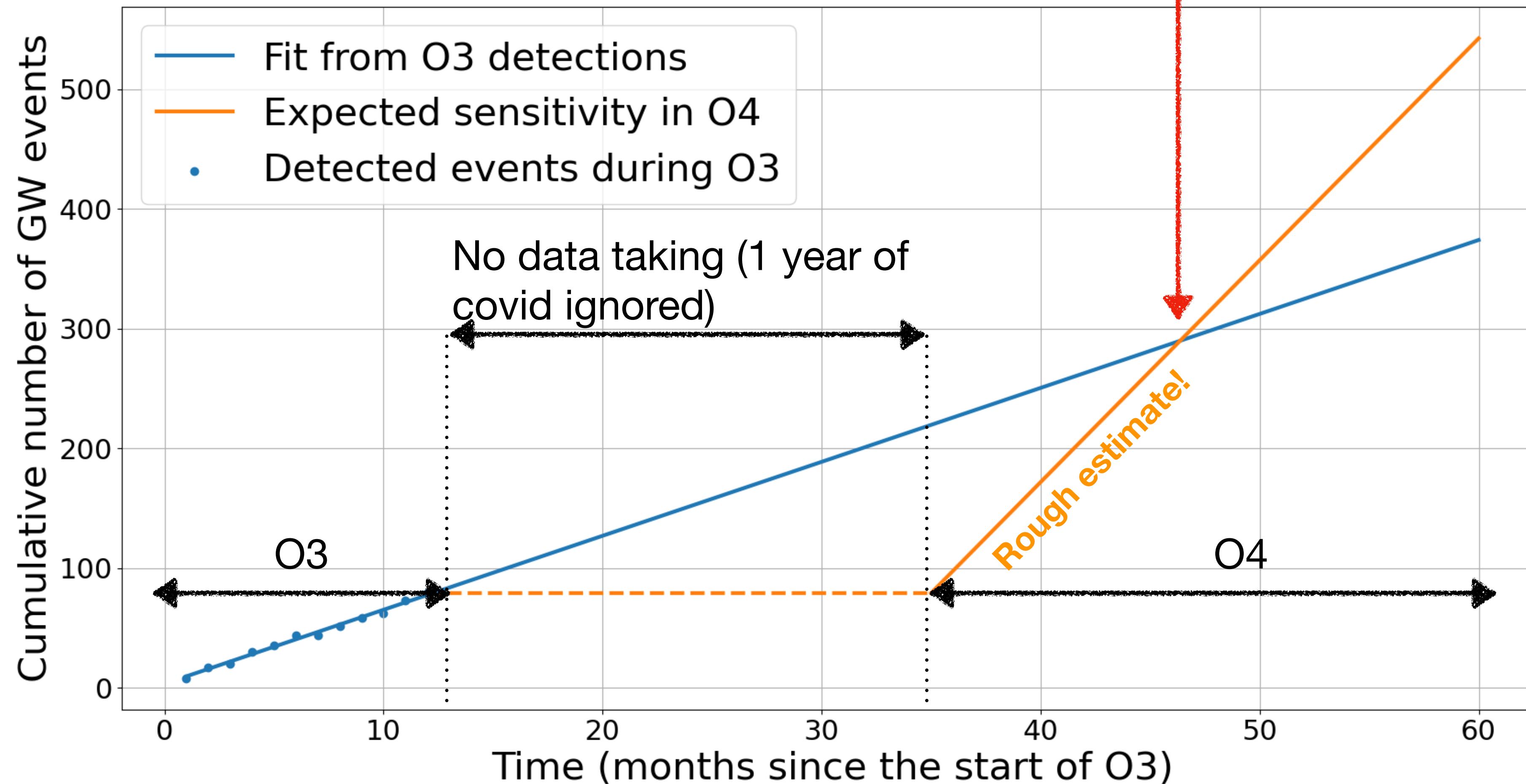
GW detections and catalogs

- A total of **90** GW events have been collected until now
- Events are named after the date of their discovery
- Events are grouped in catalogs named “Gravitational Wave Transient Catalog” (GWTC)



Why on/off data taking?

The number of events we expect to detect becomes higher than if we had continued O3





<https://www.gwosc.org/>

Get Data

Tutorials

Software

About

Gravitational Wave Open Science Center

Discover Gravitational-Wave Observatory Data,
Tutorials, and Software Tools.

Explore Data

Learn



Event
Catalog



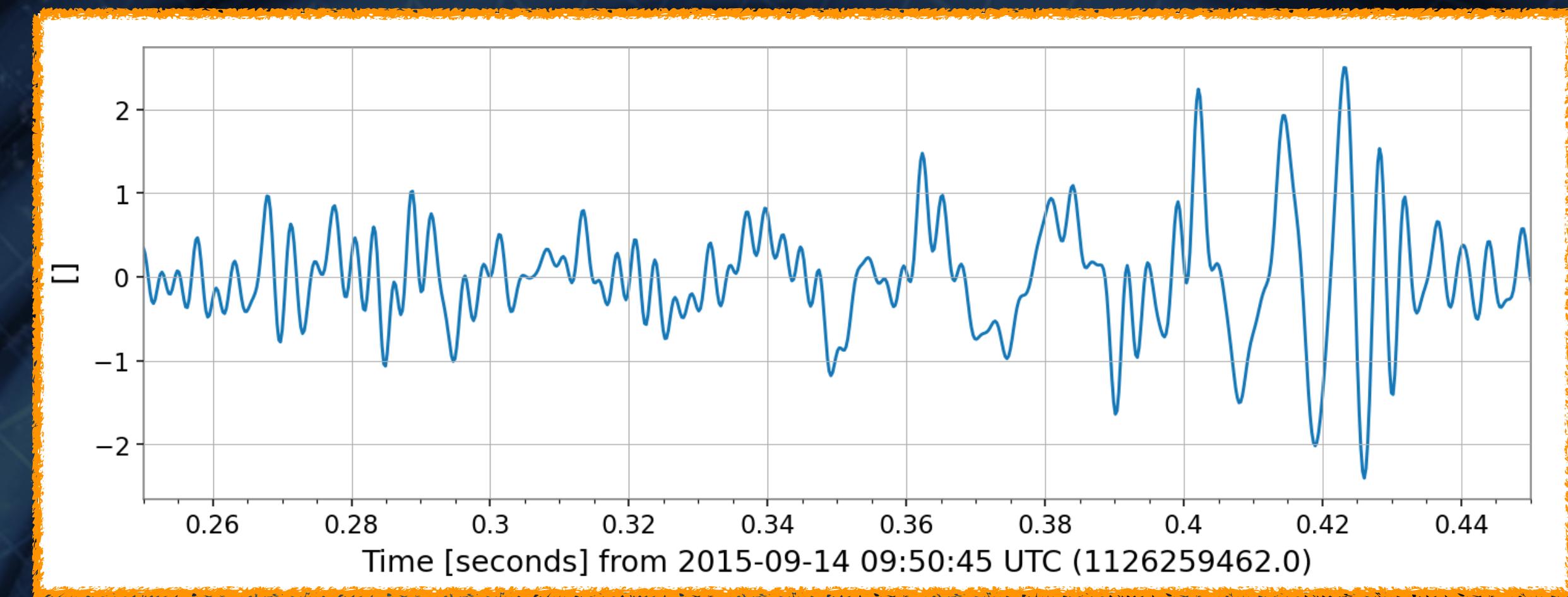
Open Data
Workshop



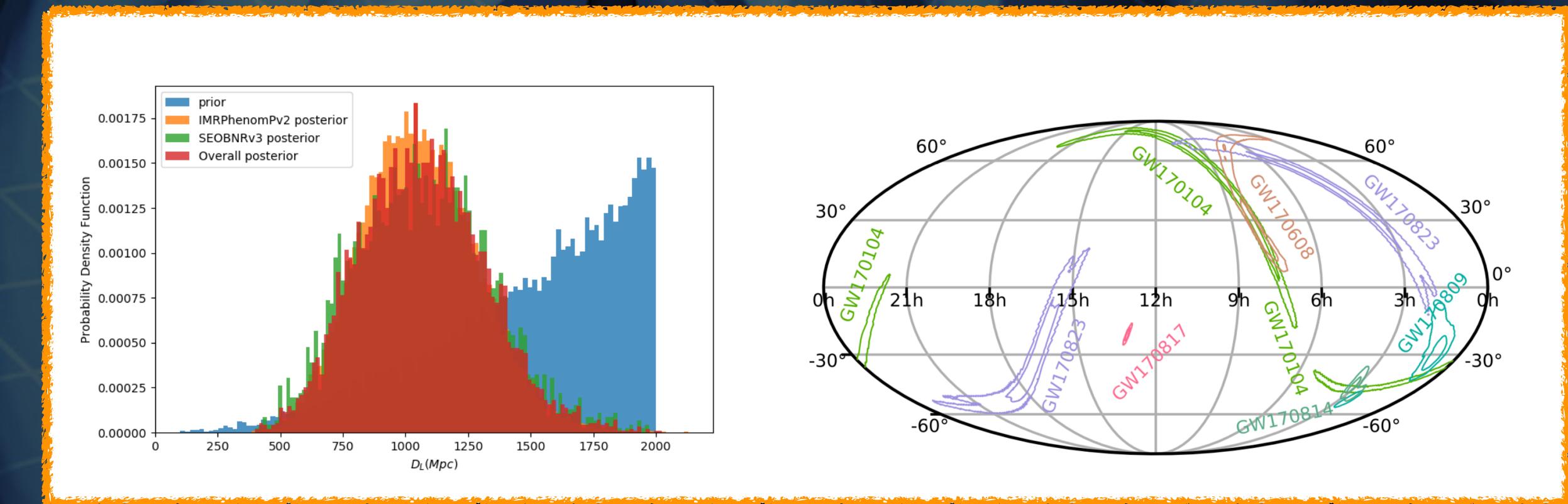
Tutorials

Available data products

Strain Data



Analysis Results (mainly related to events or event catalogs)



Segments (Timelines)

	Start	Stop	Duration
	1164559440	1164559654	214
	1164560599	1164561392	793
	1164562093	1164569775	7682

GWOSC releases

Two different types of strain data releases ([data page](#))

Data taken during a whole observation run

Gravitational wave data surrounding discoveries

O3b Data Release

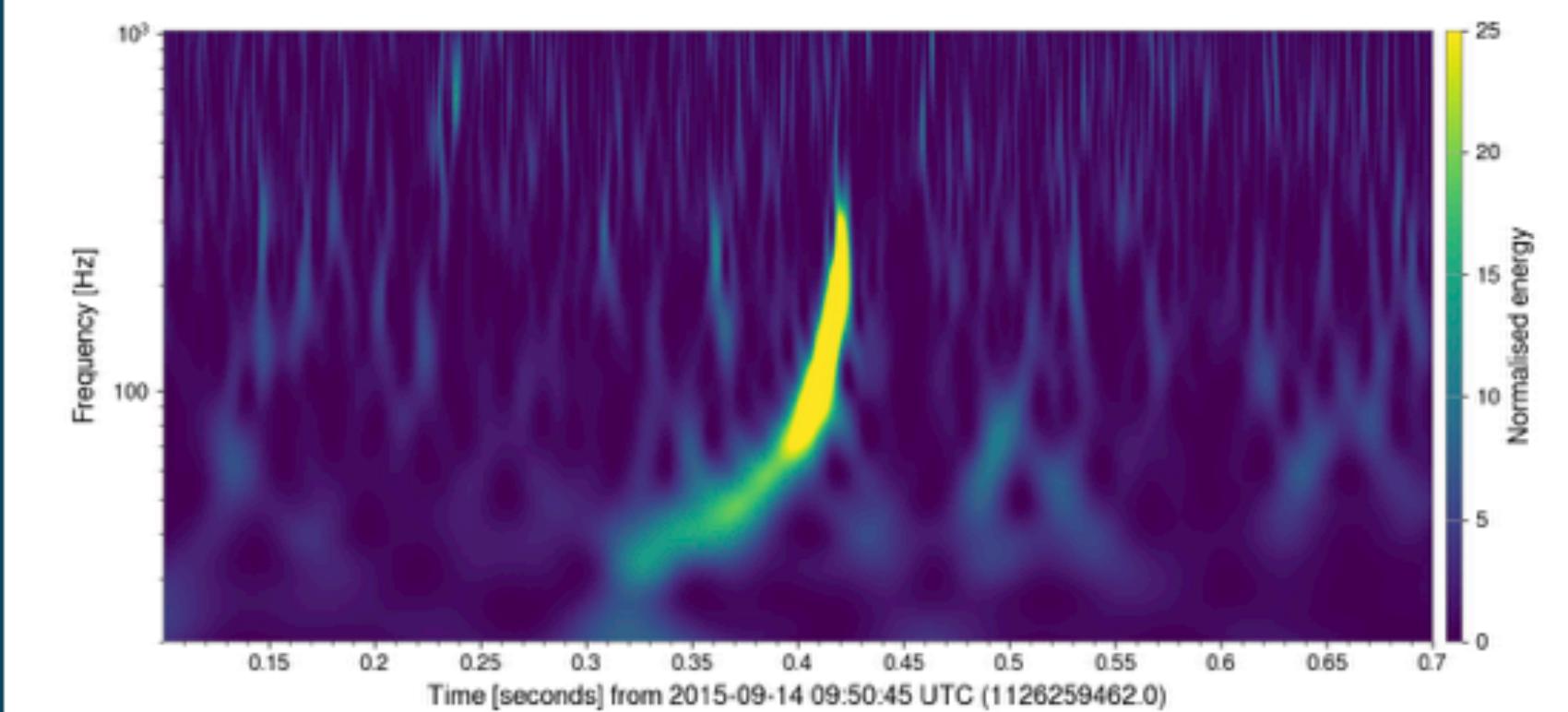
O3b Time Range: November 1, 2019 through March 27, 2020

Detectors: H1, L1 and V1

4 kHz Data 16 kHz Data Documents
Timeline

For details on LVK open data see:

- O1+O2: [SoftwareX 13 \(2021\) 100658](#)
- O3: [arXiv:2302.03676](#)



32sec · 16KHz:	GWF	HDF	TXT
32sec · 4KHz:	GWF	HDF	TXT
4096sec · 16KHz:	GWF	HDF	TXT
4096sec · 4KHz:	GWF	HDF	TXT

Example of a run page

This page lists:

[Link to this page](#)

- Files that are available from the **O3b_4KHZ_R1** dataset
- Times from 1256655618 to 1269363618
- L1 detector.
- Each file covers a 4096-second period, with strain data at either 16kHz or downsampled to 4 kHz.
- File sizes are shown in megabytes.
- The time of the beginning of the file is shown as 'GPS start time', and is linked to a timeline showing which parts of the tile have science-mode data.
- The last column of the table shows the percentage of each file that has data.
- For instructions on downloading many files, see the [Automatic Download Tutorial](#).

Timeline	UTC	Mbytes	HDF5	Frame	Percent
1256652800	2019-11-01T14:13:02	40 MB	HDF5	Frame	30
1256656896	2019-11-01T15:21:18	27 MB	HDF5	Frame	20
1256660992	2019-11-01T16:29:34	36 MB	HDF5	Frame	27

Content of a strain data file

5 L-L1_GWOSC_O3b_4KHZ_R1-1256652800-4096.hdf5

- meta
 - Description
 - DescriptionURL
 - Detector
 - Duration
 - FrameType
 - GPSstart
 - Observatory
 - StrainChannel
 - Type
 - UTCstart
- quality
 - detail
 - injections
 - GWOSCmeta
 - InjDescriptions
 - InjShortnames
 - Injmask
 - simple
 - DQDescriptions
 - DQShortnames
 - DQmask
 - GWOSCmeta
 - strain
 - GWOSCmeta
 - Strain

- Metadata of the file
- Informations about the data quality and injections (sampled at 1 Hz)
- Strain data (sampled at 16 kHz or 4 kHz)

Bit	Short Name	Description
Data Quality Bits		
0	DATA	data present
1	CBC_CAT1	passes the cbc CAT1 test
2	CBC_CAT2	passes cbc CAT2 test
3	CBC_CAT3	passes cbc CAT3 test
4	BURST_CAT1	passes burst CAT1 test
5	BURST_CAT2	passes burst CAT2 test
6	BURST_CAT3	passes burst CAT3 test
Injection Bits		
0	NO_CBC_HW_INJ	no cbc injection
1	NO_BURST_HW_INJ	no burst injections
2	NO_DETCHAR_HW_INJ	no detchar injections
3	NO_CW_HW_INJ	no continuous wave injections
4	NO_STOCH_HW_INJ	no stoch injections

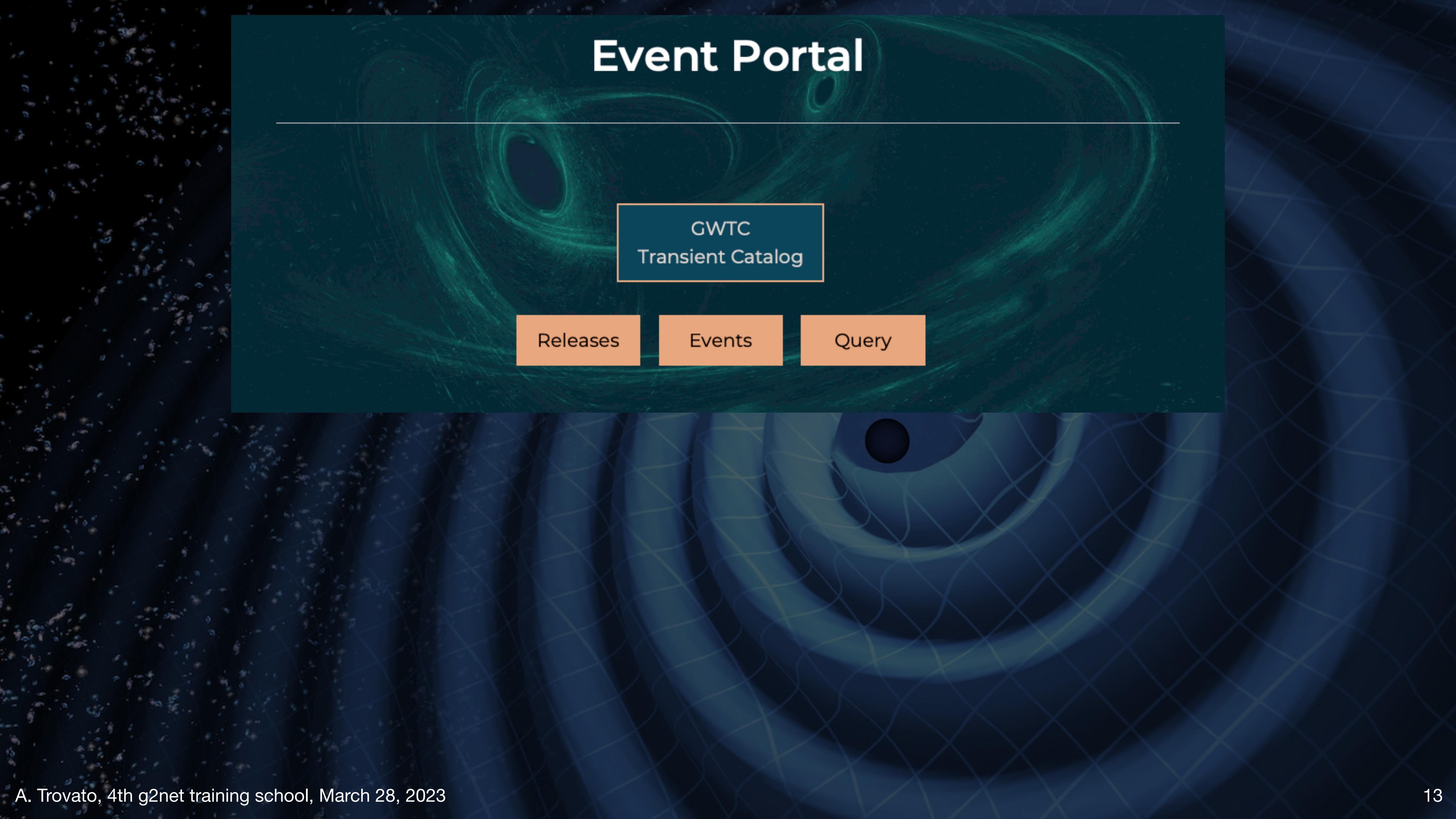
Event Portal

GWTC
Transient Catalog

Releases

Events

Query



Event Portal

GWTC
Transient Catalog

Releases

Events

Query

Release List

Release Name	Description
--------------	-------------

GWTC

The Gravitational-wave Transient Catalog (GWTC) is a cumulative set of gravitational wave transients maintained by the LIGO/Virgo/KAGRA collaboration. The online GWTC contains confidently-detected events from multiple data releases.

GWTC-1-confident

Confident detections from "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs." Additional data products, including PE samples and skymaps, are linked from the documentation at <https://doi.org/10.7935/82H3-HH23>

GWTC-1-marginal

Marginal candidates from "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs." Additional data products are linked from the documentation at <https://doi.org/10.7935/82H3-HH23>

GWTC-2

Events from the O3A observation run of LIGO and Virgo, as described in the GWTC-2 catalog paper. These events are also included in a cumulative list of [all GWTC events](#) published to date. Details and additional data products are linked from the [documentation page](#).

Event Portal

GWTC Transient Catalog

Releases

Events

Query

Name	Version	Release	GPS	Mass 1 (M_{\odot})	Mass 2 (M_{\odot})	Network SNR	Distance (Mpc)	X_{eff}	Total Mass (M_{\odot})
GW200322_091133	v1	GWTC-3-confident	1268903511.3	⁺⁴⁸ _{34 -18}	^{+16.8} _{14.0 -8.7}	^{+1.7} _{6.0 -1.2}	⁺⁷⁰⁰⁰ _{3600 -2000}	^{+0.45} _{0.24 -0.51}	⁺³⁷ _{55 -27}
GW200316_215756	v1	GWTC-3-confident	1268431094.1	^{+10.2} _{13.1 -2.9}	^{+1.9} _{7.8 -2.9}	^{+0.4} _{10.3 -0.7}	⁺⁴⁷⁰ _{1120 -440}	^{+0.27} _{0.13 -0.10}	^{+7.2} _{21.2 -2.0}
GW200311_115853	v1	GWTC-3-confident	1267963151.3	^{+6.4} _{34.2 -3.8}	^{+4.1} _{27.7 -5.9}	^{+0.2} _{17.8 -0.2}	⁺²⁸⁰ _{1170 -400}	^{+0.16} _{-0.02 -0.20}	^{+5.3} _{61.9 -4.2}
GW200311_103121	v1	GWTC-3-marginal	1267957899.7	--	--	9.2	--	--	--
GW200308_173609	v1	GWTC-3-confident	1267724187.7	^{+11.2} _{36.4 -9.6}	^{+7.2} _{13.8 -3.3}	^{+0.5} _{7.1 -0.5}	⁺²⁷⁰⁰ _{5400 -2600}	^{+0.17} _{0.65 -0.21}	^{+10.9} _{50.6 -8.5}
GW200306_093714	v1	GWTC-3-confident	1267522652.1	^{+17.1} _{28.3 -7.7}	^{+6.5} _{14.8 -6.4}	^{+0.4} _{7.8 -0.6}	⁺¹⁷⁰⁰ _{2100 -1100}	^{+0.28} _{0.32 -0.46}	^{+11.8} _{43.9 -7.5}
GW200302_015811	v1	GWTC-3-confident	1267149509.5	^{+8.7} _{37.8 -8.5}	^{+8.1} _{20.0 -5.7}	^{+0.3} _{10.8 -0.4}	⁺¹⁰²⁰ _{1480 -700}	^{+0.25} _{0.01 -0.26}	^{+9.6} _{57.8 -6.9}
GW200225_060421	v1	GWTC-3-confident	1266645879.3	^{+5.0} _{19.3 -3.0}	^{+2.8} _{14.0 -3.5}	^{+0.3} _{12.5 -0.4}	⁺⁵¹⁰ _{1150 -530}	^{+0.17} _{-0.12 -0.28}	^{+3.6} _{33.5 -3.0}
GW200224_222234	v1	GWTC-3-confident	1266618172.4	^{+6.9} _{40.0 -4.5}	^{+5.0} _{32.5 -7.2}	^{+0.2} _{20.0 -0.2}	⁺⁴⁹⁰ _{1710 -640}	^{+0.15} _{0.10 -0.15}	^{+7.2} _{72.2 -5.1}
GW200220_124850	v1	GWTC-3-confident	1266238148.1	^{+14.1} _{38.9 -8.6}	^{+9.2} _{27.9 -9.0}	^{+0.3} _{8.5 -0.5}	⁺²⁸⁰⁰ _{4000 -2200}	^{+0.27} _{-0.07 -0.33}	⁺¹⁷ _{67 -12}
GW200220_061928	v1	GWTC-3-confident	1266214786.7	⁺⁴⁰ _{87 -23}	⁺²⁶ _{61 -25}	^{+0.4} _{7.2 -0.7}	⁺⁴⁸⁰⁰ _{6000 -3100}	^{+0.40} _{0.06 -0.38}	⁺⁵⁵ _{148 -33}

Event Portal

GWTC Transient Catalog

Releases

Events

Query

Query Events

Event Name:

Release:

GWTC-1-marginal
GWTC-1-confident
O1_O2-Preliminary
O3_Discovery_Papers

Mass 1 Range:

0

∞

Mass 2 Range:

0

∞

Total Mass Range:

0

∞

Final Mass Range:

0

∞

Chirp Mass Range:

0

∞

Detector Frame Chirp
Mass Range:

0

∞

Distance (Mpc) Range:

0

∞

Redshift Range:

0

∞

Network SNR Range:

0

∞

Xeff Range:

-1

1

False Alarm Rate Range:

0

∞

Pastro Range:

0

1

UTC Time Range:



Example of an event page

GWTC-2.1 PE for GW190412 (update)

Waveform Family: C01:Mixed

Date added: May 13, 2022

[show / hide parameters](#)

chi_eff	$0.21^{+0.12}_{-0.13}$
chirp_mass_source (M_sun)	$13.3^{+0.5}_{-0.5}$
final_mass_source (M_sun)	$35.6^{+4.8}_{-4.5}$
final_spin	$0.66^{+0.05}_{-0.04}$
luminosity_distance (Mpc)	720^{+240}_{-220}
mass_1_source (M_sun)	$27.7^{+6.0}_{-6.0}$
mass_2_source (M_sun)	$9.0^{+2.0}_{-1.4}$
network_matched_filter_snr	$19.8^{+0.2}_{-0.3}$
redshift	$0.15^{+0.04}_{-0.04}$
sky_area (deg^2)	240
total_mass_source (M_sun)	$36.8^{+4.7}_{-4.4}$

[Source File](#)

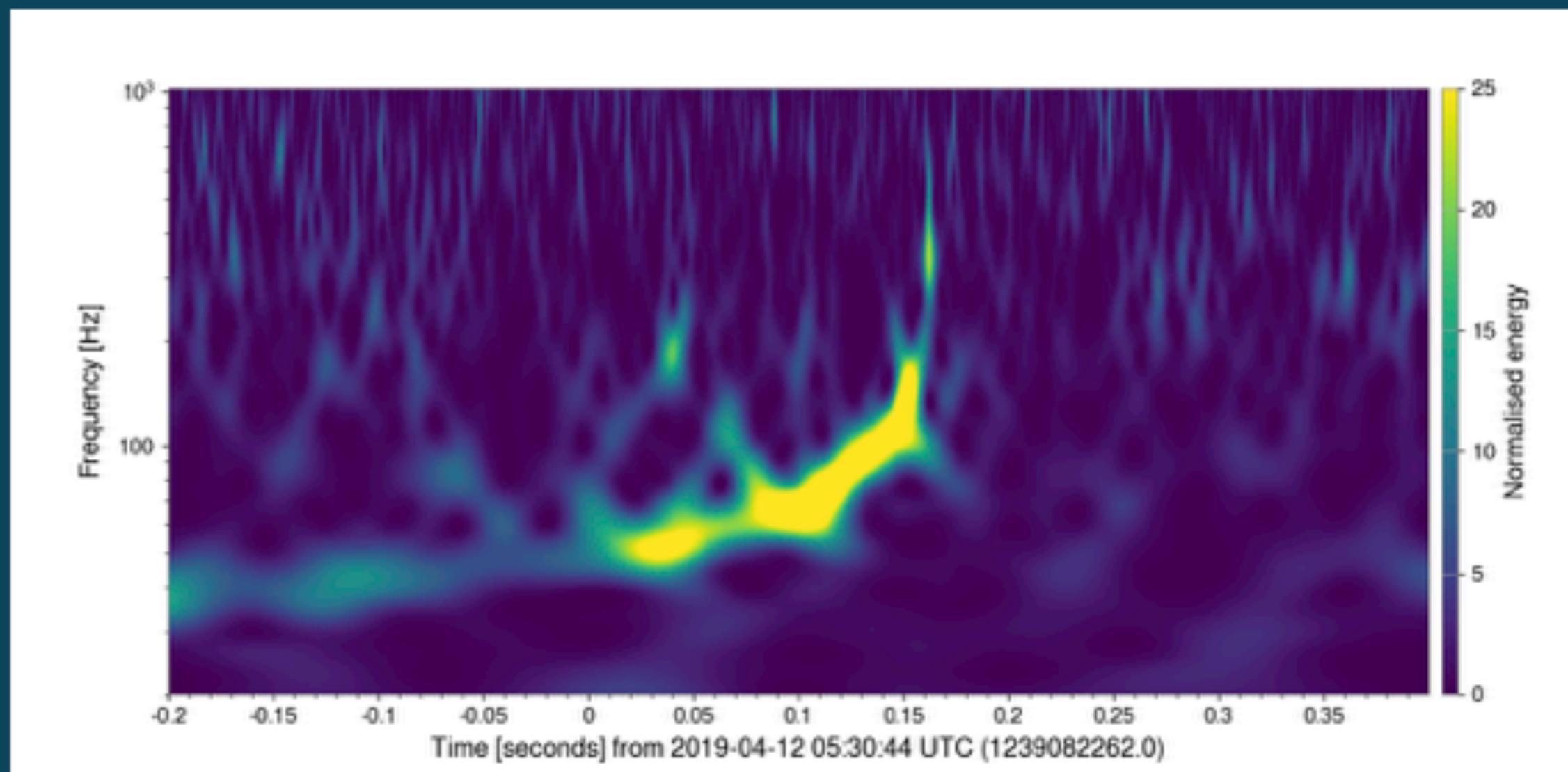
[Posterior Samples Zenodo Entry](#)

[Skymap for GW190412](#)

[Default PE](#)

[Link to this page](#)

L1 strain



32sec · 16KHz: [GWF](#) [HDF](#) [TXT](#)

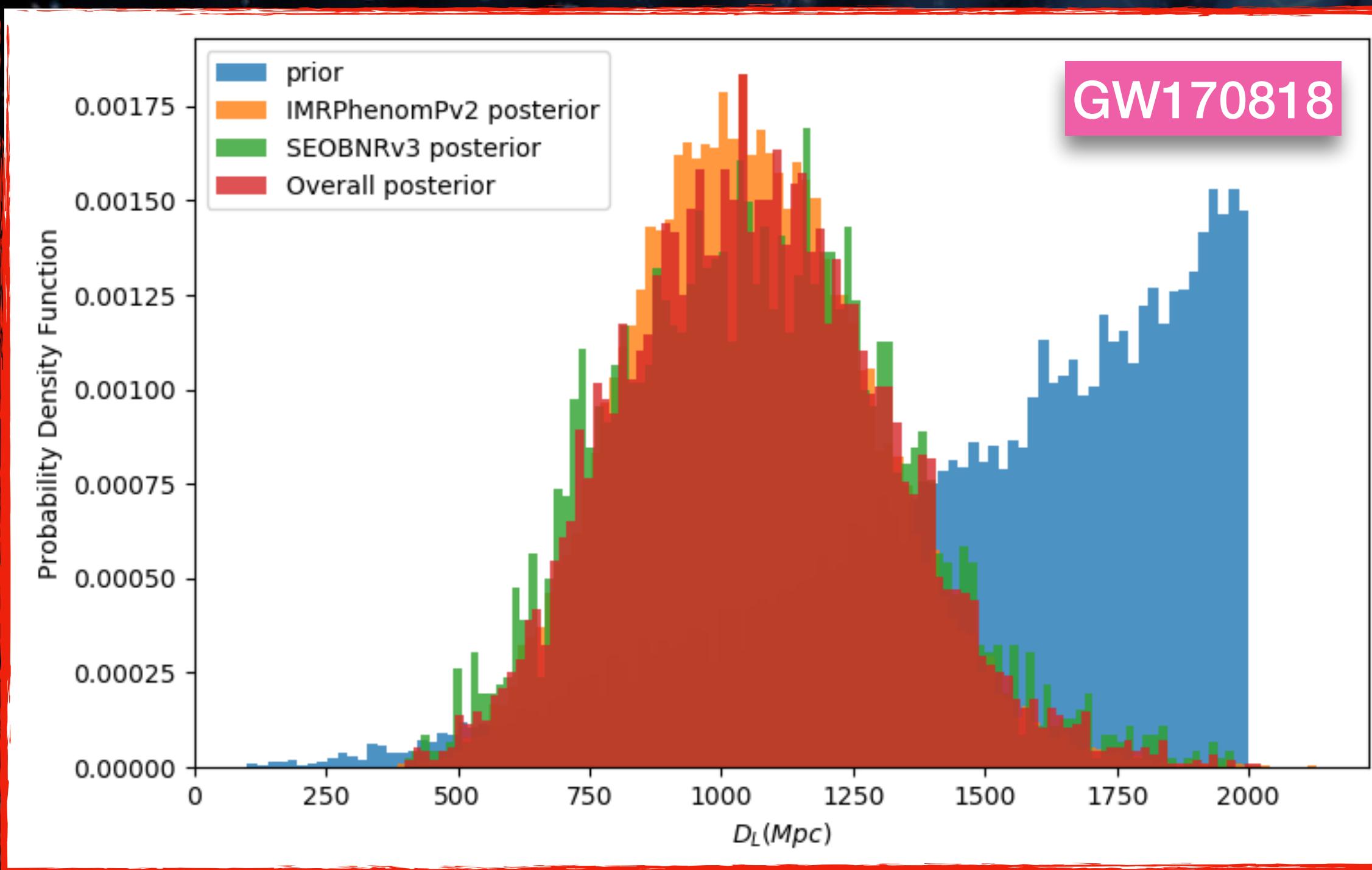
32sec · 4KHz: [GWF](#) [HDF](#) [TXT](#)

4096sec · 16KHz: [GWF](#) [HDF](#) [TXT](#)

4096sec · 4KHz: [GWF](#) [HDF](#) [TXT](#)

Other analysis products

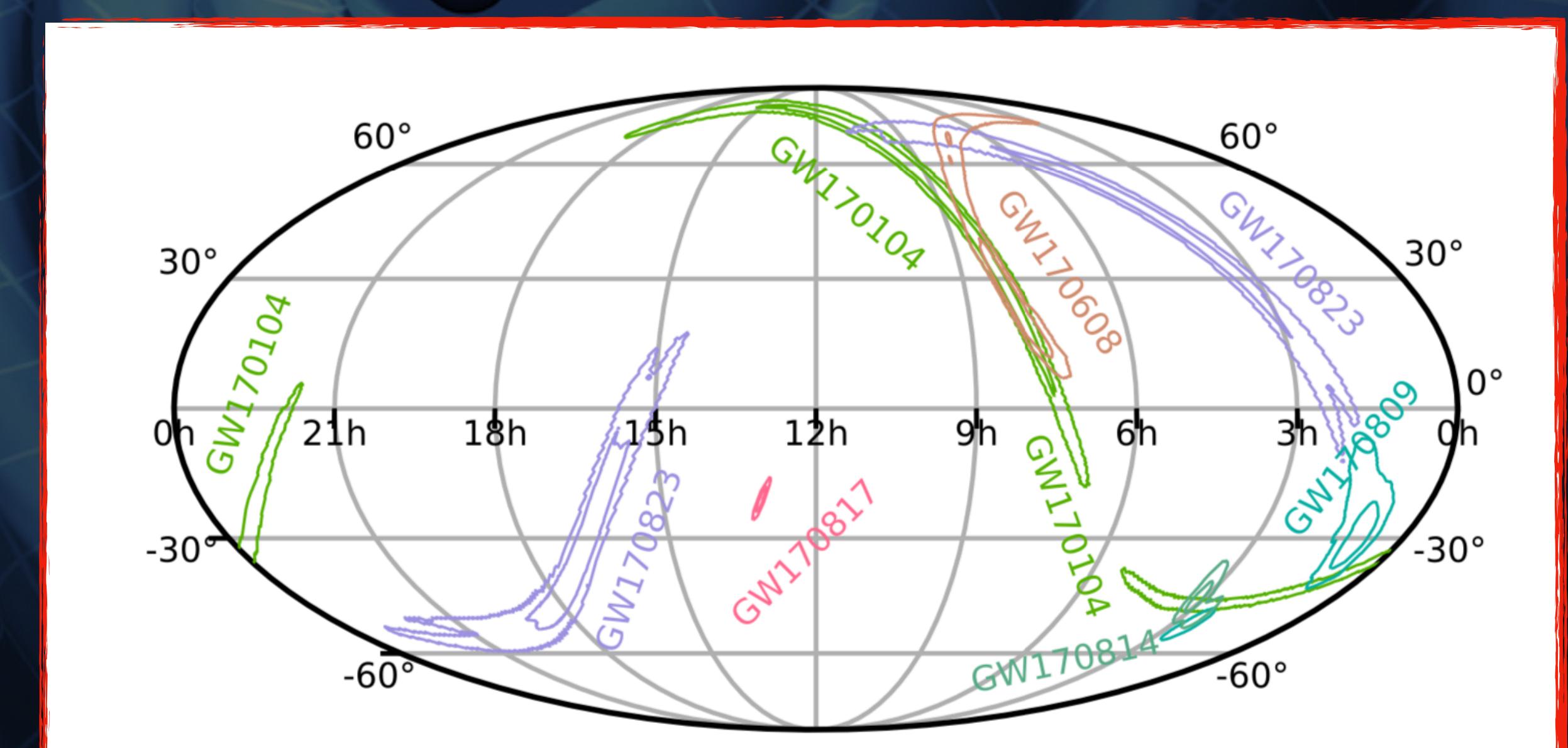
- The event portal contains links to:
 - ✓ Posterior samples
 - ✓ Confidence intervals
 - ✓ Skymaps



Data Products and Publications

- Catalog Paper and Figures: [P2000061](#)
- Strain Data: [Event Portal](#)
- Parameter Estimation Samples & Skymaps: [P2000223](#)
- Tests of General Relativity: [P2000091](#)
- Population Properties: [P2000077](#)
- Search Sensitivity: [P2000217](#)
- Glitch Models: [P2000289](#)
- Low-Latency Alerts: [GraceDB](#)

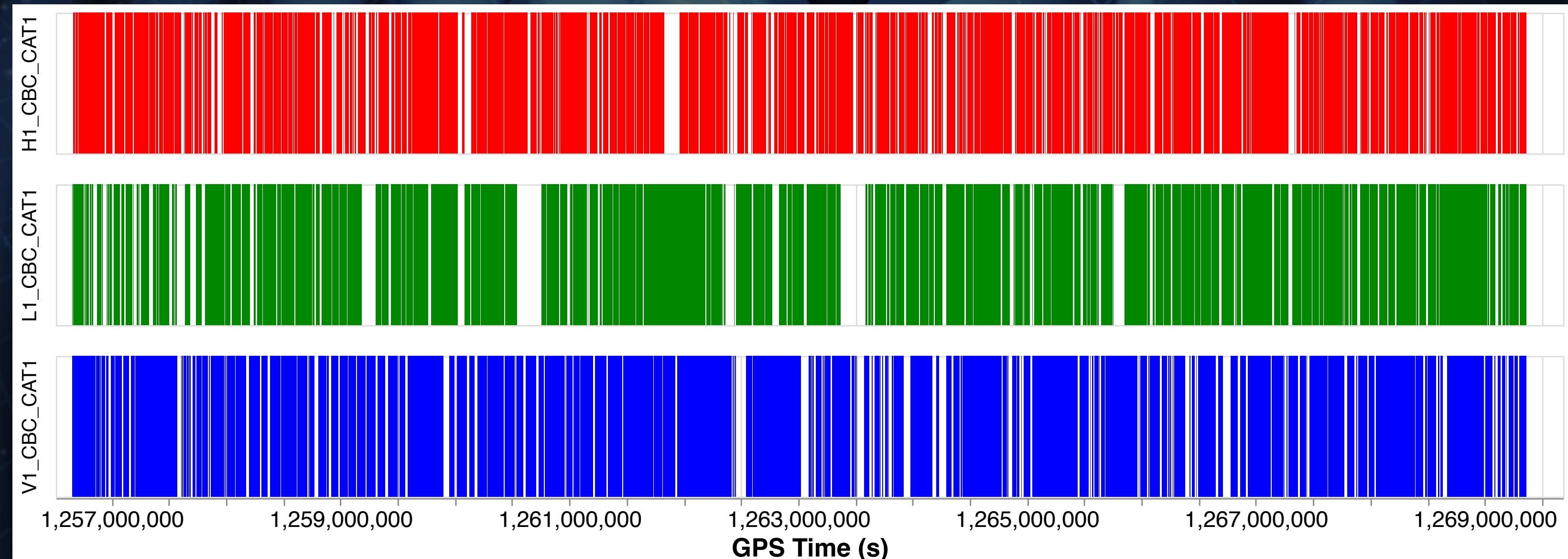
GWTC-2 documentation page



Segment Lists

- LIGO/Virgo detectors are not always 'on' (in science mode)
- Data quality may not meet basic requirements
- Consequence : GW data analysis is applied to data segments (different in each detector)
- The “Timeline” tool of the GWOSC website allows you to select segments that fulfill specific data quality checks in a time period that can be selected specifying GPS time and duration

Timelines for O3b



Software for GW data

- Software for working with Gravitational Wave Data available to the public:
<https://www.gwosc.org/software/>
- API on the GWOSC web site + python client (called “gwosc”)
- Part of the software developed by LIGO/Virgo and open-source

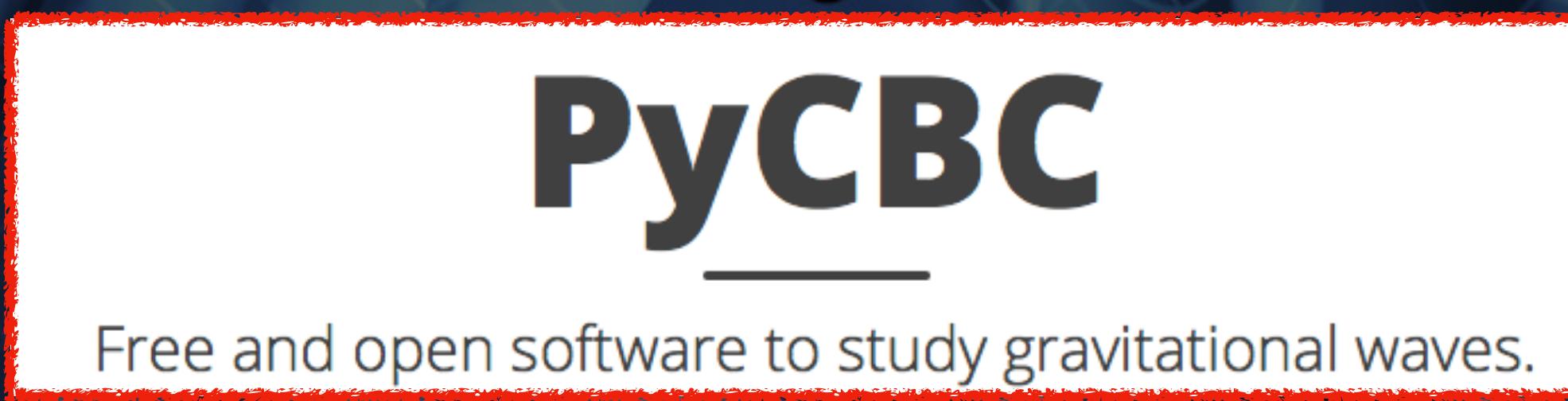


ligo.skymap

The ligo.skymap package provides tools for reading, writing, generating, and visualizing gravitational-wave probability maps from LIGO and Virgo. It includes the rapid sky localization code BAYESTAR, tools for making sky maps from MCMC samples, observation planning utilities, and tools for making beautiful astronomical maps.

GstLAL

gstlal provides a suite of GStreamer elements that expose gravitational-wave data analysis tools from the LALSuite library for use in GStreamer signal-processing pipelines.



Used in the tutorials
just after this lecture

Bilby

Bilby: a user-friendly Bayesian inference library.

LALSuite

The LSC Algorithm Library Suite (LALSuite) is a collection of component packages, each of which is tagged, packaged, and released separately.

GW Open Data Workshops

<https://www.gwosc.org/workshops>

GW Open Data Workshops

Gravitational Wave Open Data Workshop #6 (2023)



May 15-17, 2023

Workshop

Gravitational Wave Open Data Workshop #5 (2022)



May 23-25, 2022

Workshop

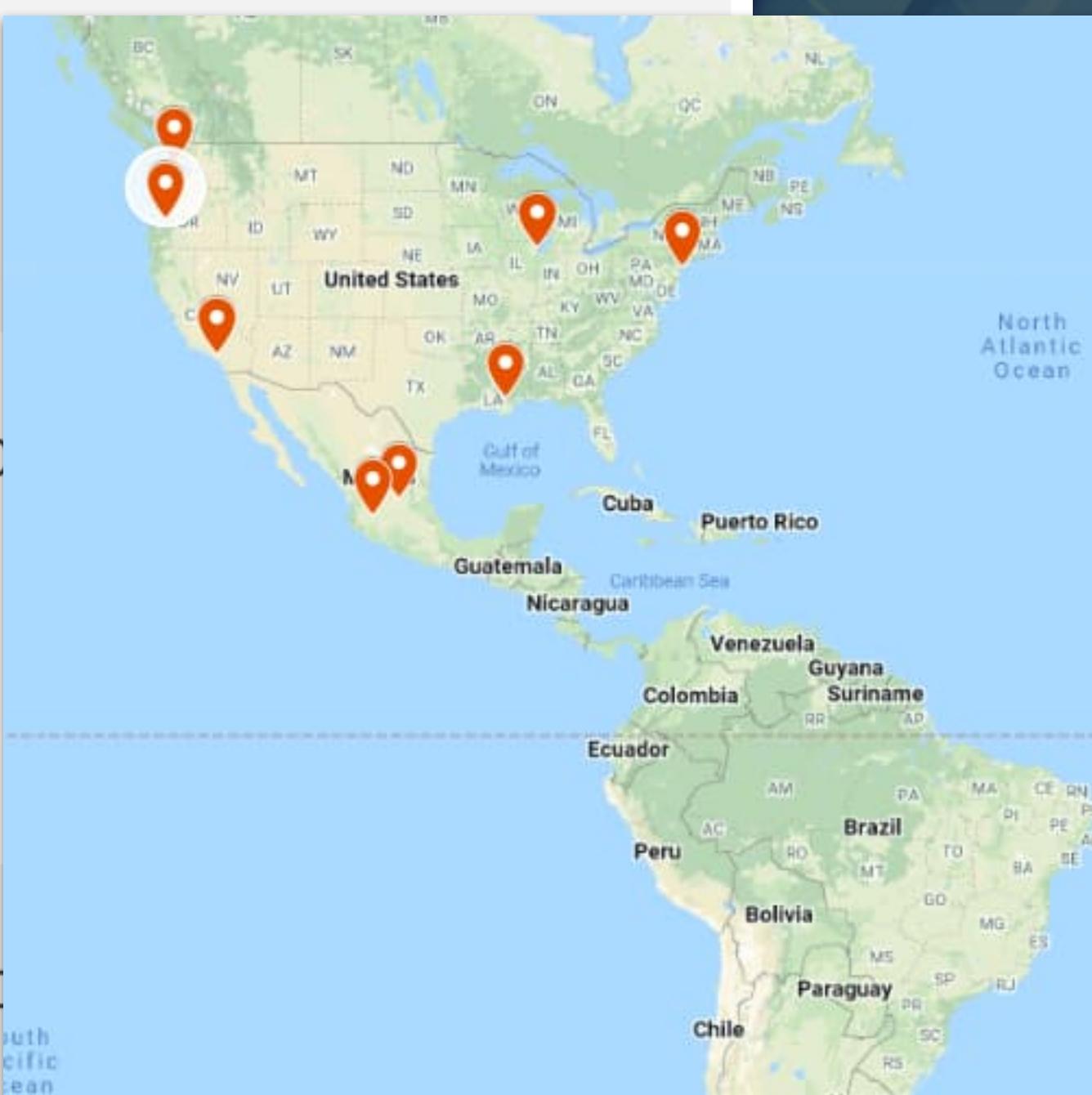
Gravitational Wave Open Data Workshop #4 (2021)



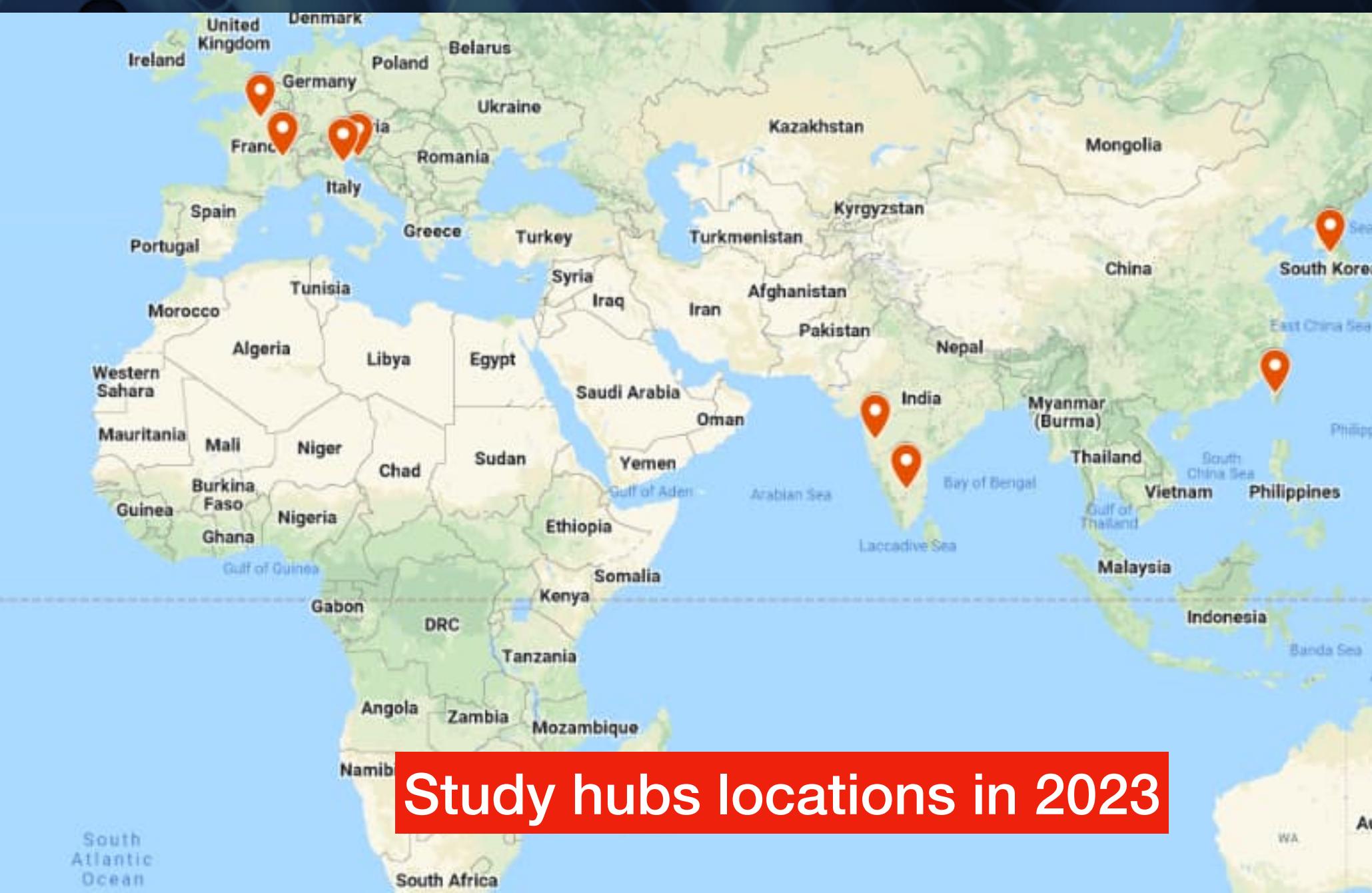
Remote workshop, May 10-14, 2021

Online Course

Workshop



- Organised every year since 2018
- Last year we had about 1000 registered
- Lectures + hands-on sessions
- Workshops become online courses
- Register to the next one if you are interested!
- Hybrid format (in person study hubs)



Study hubs locations in 2023

New program for students

<https://www.gwosc.org/path>

Web Apps with plotting tools without coding!

Learning Path
Teachers & Students
Objectives

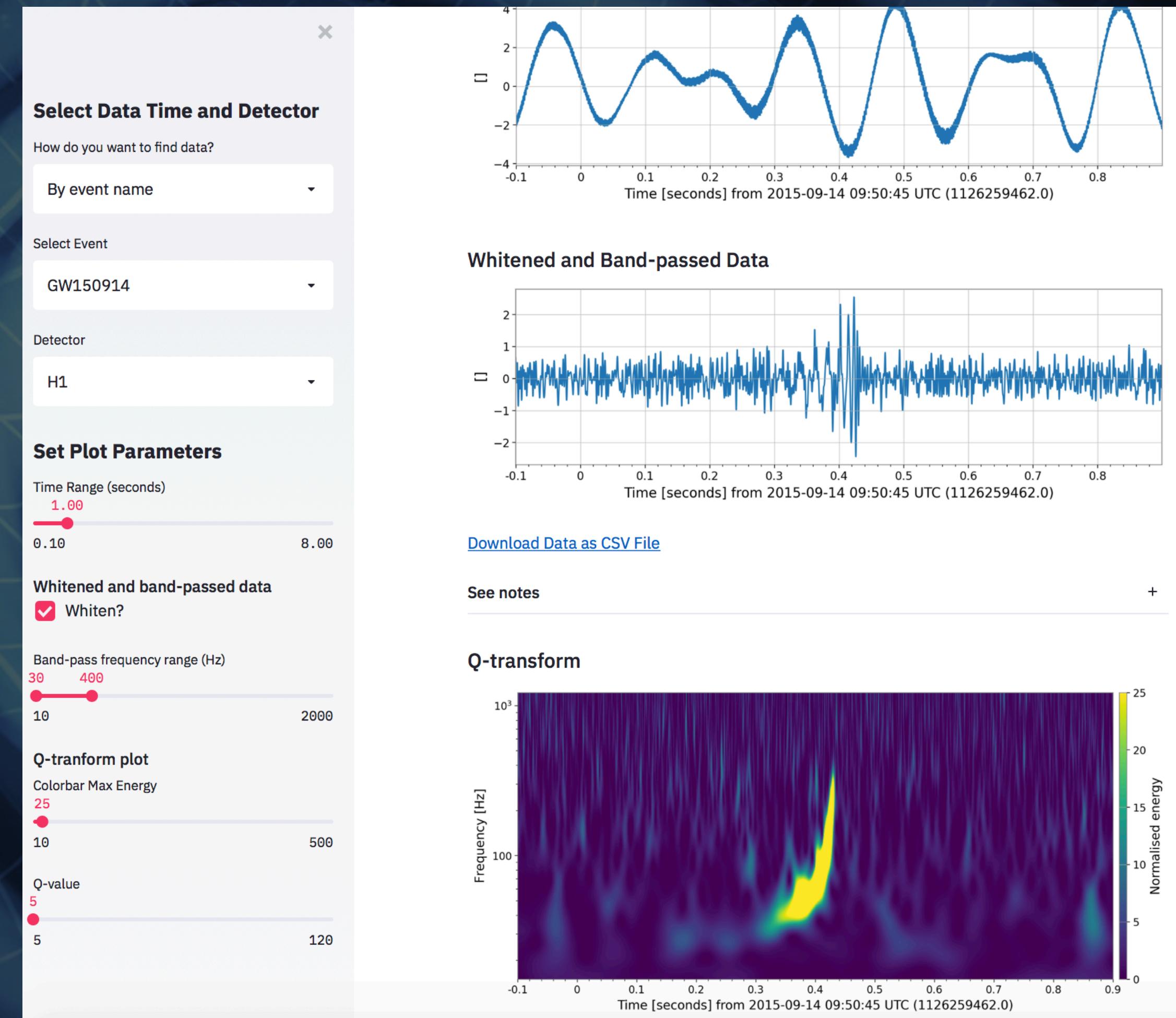
Step 1: Watch Introductory Video (1)
7 Minutes

- How are gravitational waves created?
- How are gravitational waves measured?

Educational resource - gravitational waves video (part 1)



Footnote: Construction of the KAGRA detector in Japan has been completed since the production of this video.

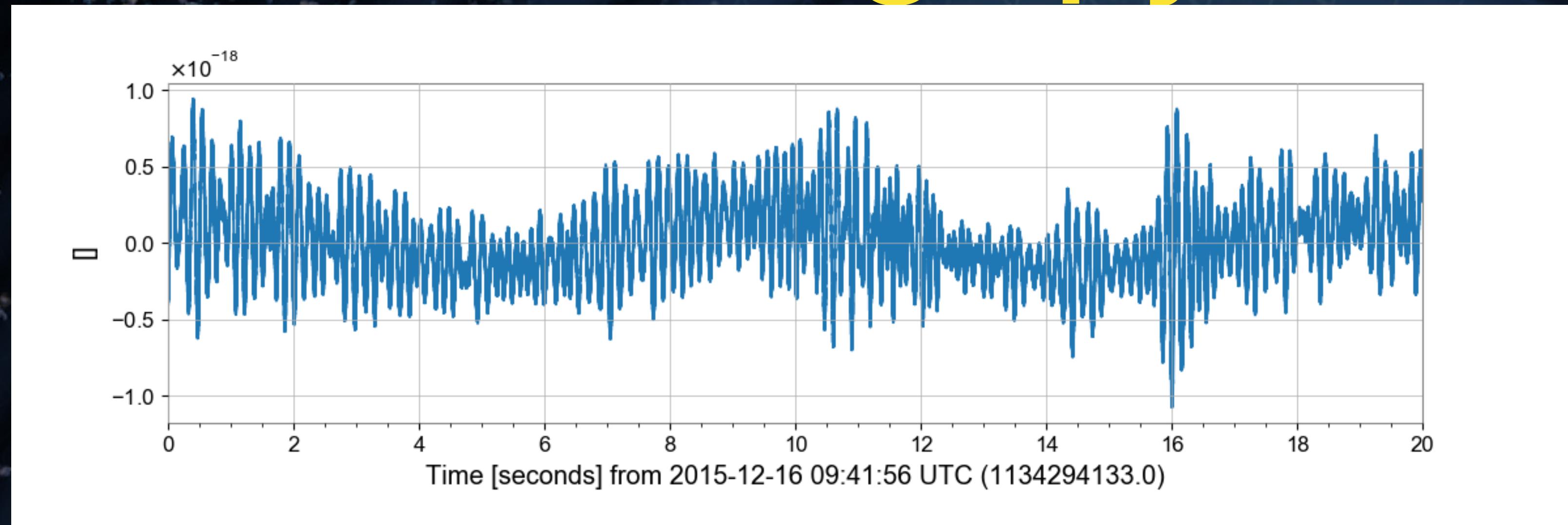


Conclusion

- ⦿ Gravitational-wave data are accessible through the GWOSC website!
- ⦿ GWOSC is a successful open science project
 - ✓ A large and growing community of users
 - ✓ Data used in a good fraction of the publications related to GW astronomy
- ⦿ Reproducibility of LVK results (see e. g. arXiv:2010.07244)
- ⦿ Next observing run will start in about 2 month!!!
- ⦿ A wealth of science to come and to share!
- ⦿ A post-doc position opening in Trieste at the end of this year (contact agata.trovato@units.it if you are interested)
- ⦿ For further questions write to gwosc@igwn.org or use ask.igwn.org

Part II: Hands-on session

Intro to gwpy



Install it:

```
pip install gwpy
```

Import the class you need:

```
from gwpy.timeseries import TimeSeries
```

Download the data:

```
data = TimeSeries.fetch_open_data('H1',  
1134294133,1134294153)
```

Plot the data:

```
plot = data.plot()
```

Show the plot:

```
plot.show()
```

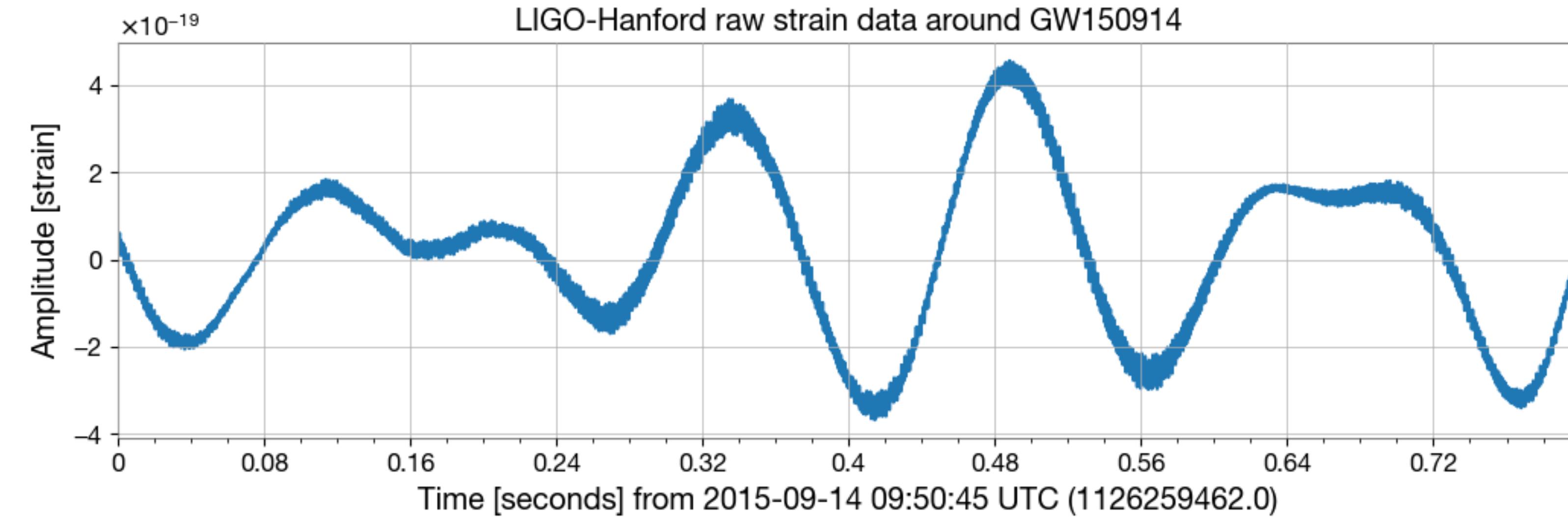
Example to plot GW150914 data

```
from gwpy.timeseries import TimeSeries
from gwpy.signal import filter_design

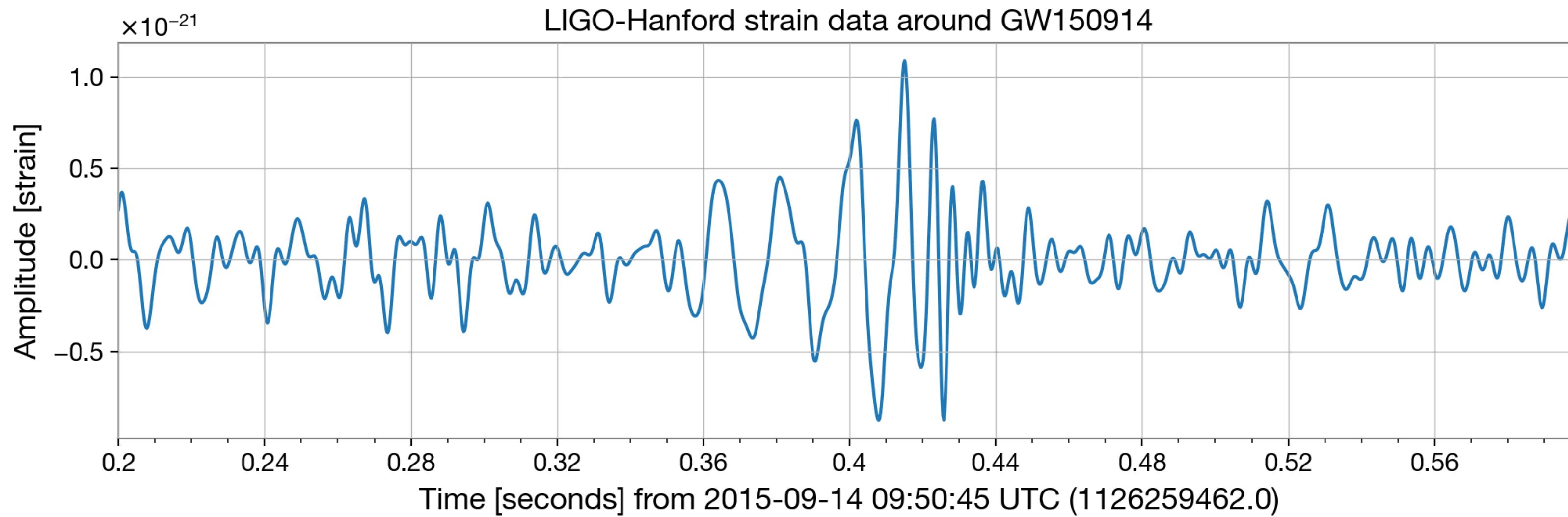
t0 = 1126259462.4
hdata = TimeSeries.fetch_open_data('H1', t0-0.4,t0+0.4)

bp = filter_design.bandpass(50, 250, hdata.sample_rate)
notches = [filter_design.notch(line, hdata.sample_rate) for line in (60, 120, 180)]
zpk = filter_design.concatenate_zpks(bp, *notches)
hfilt = hdata.filter(zpk, filtfilt=True)
hfilt = hfilt.crop(t0-0.2,t0+0.2)
plot = hfilt.plot()
ax = plot.gca()
ax.set_title('LIGO-Hanford strain data around GW150914')
ax.set_ylabel('Amplitude [strain]')
plot.show()
```

Example to plot GW150914 data



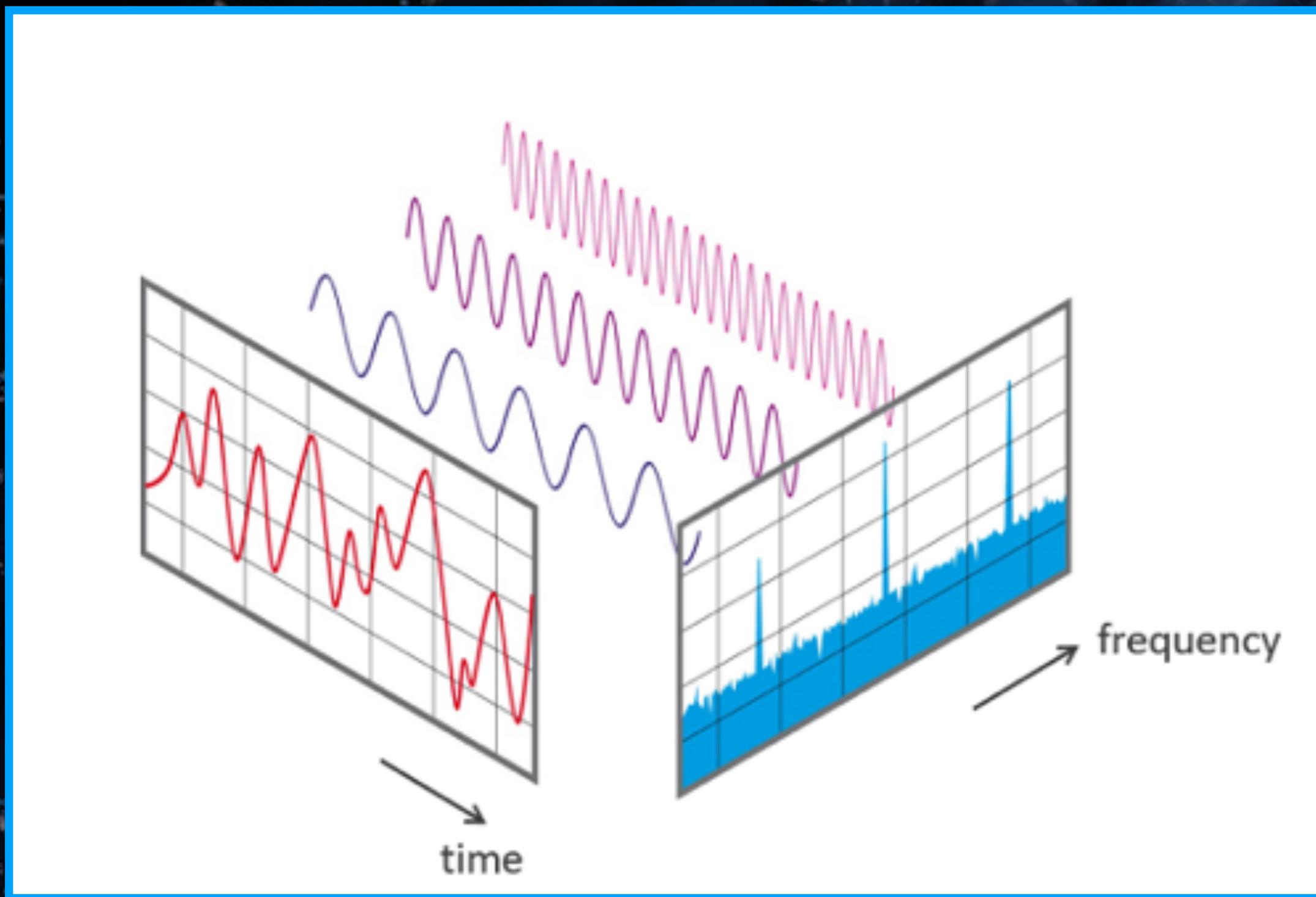
Raw data



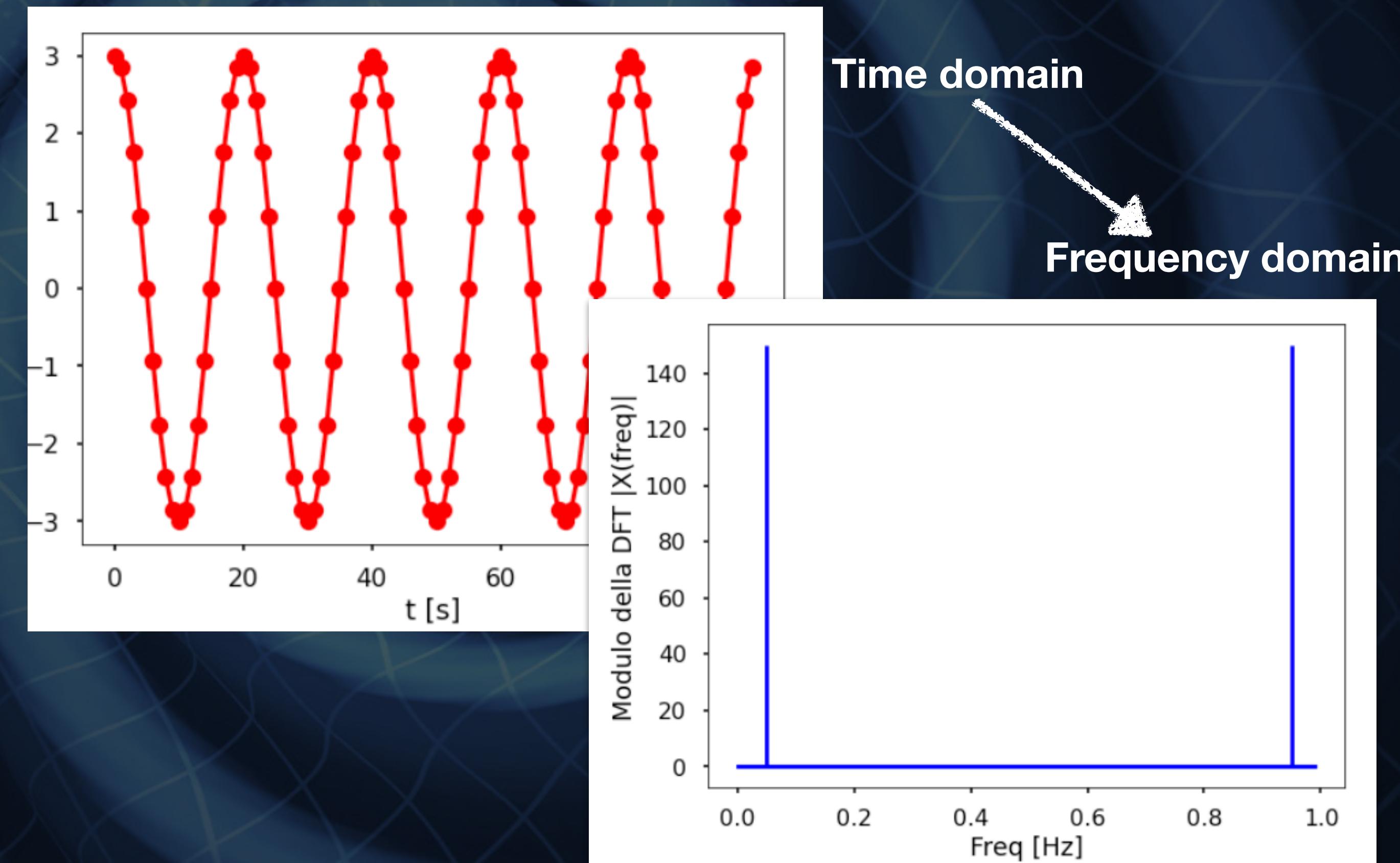
Data after
Band pass + notch

Fourier Transforms and FFT

Fourier transforms decompose a *continuous* signal into its constituent frequencies

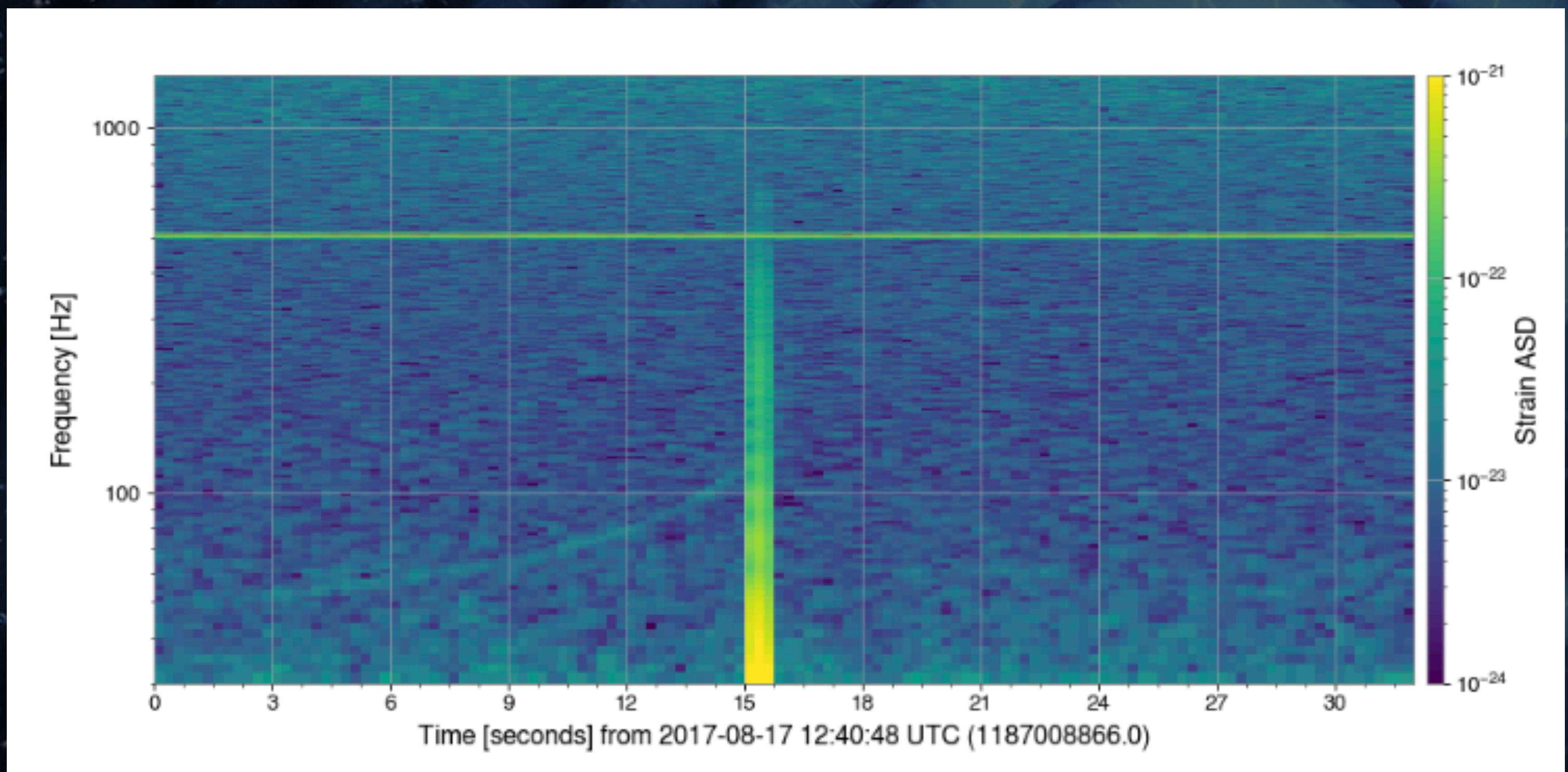


Fast Fourier Transformation (FFT) is an optimized mathematical algorithm to find the frequency components of a *discrete* signal



Spectrograms

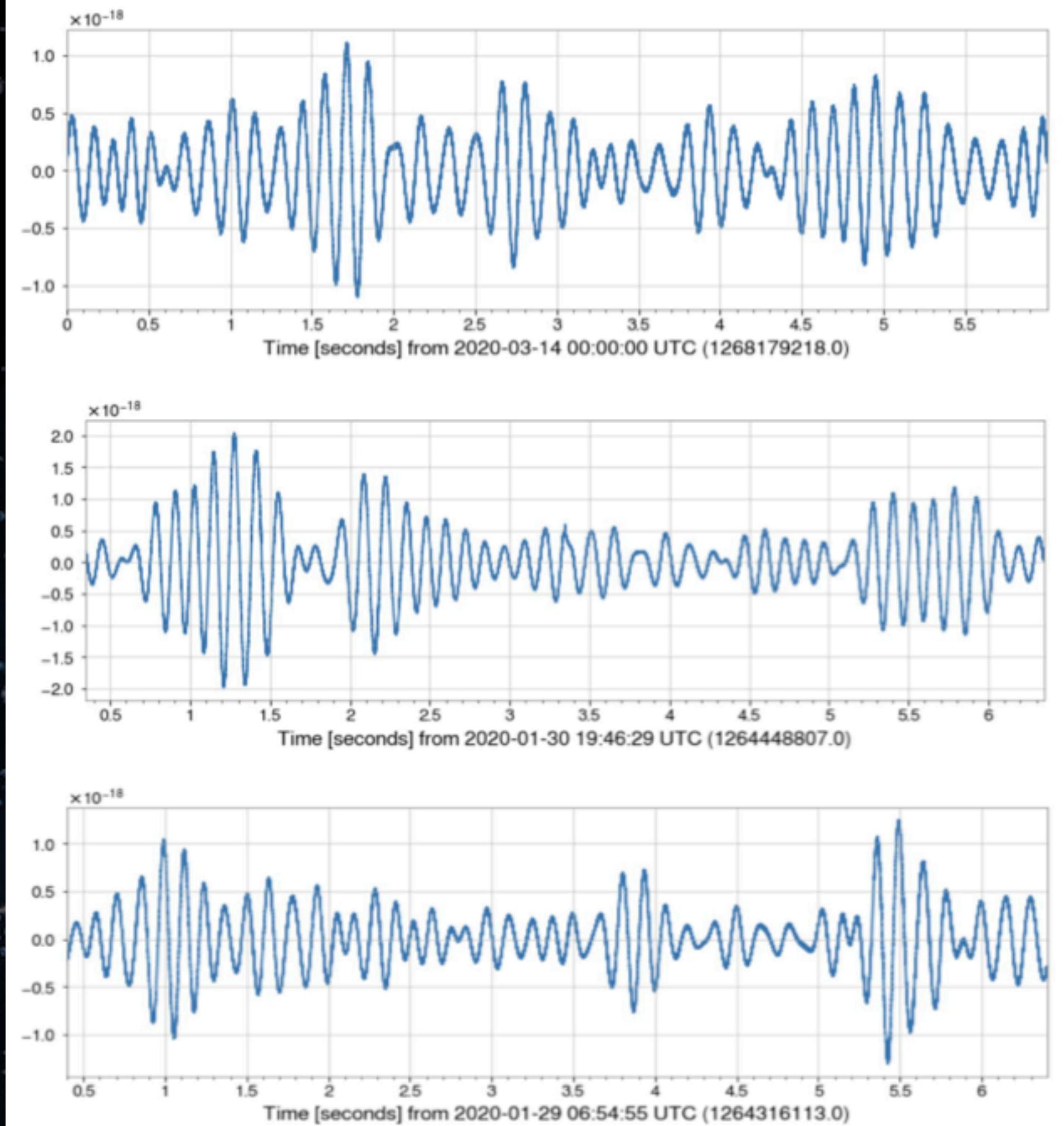
- Spectrograms: frequencies vs time
- The signal is broken into smaller time windows and the FFT is calculated for each window
- Time windows are usually partially overlapping



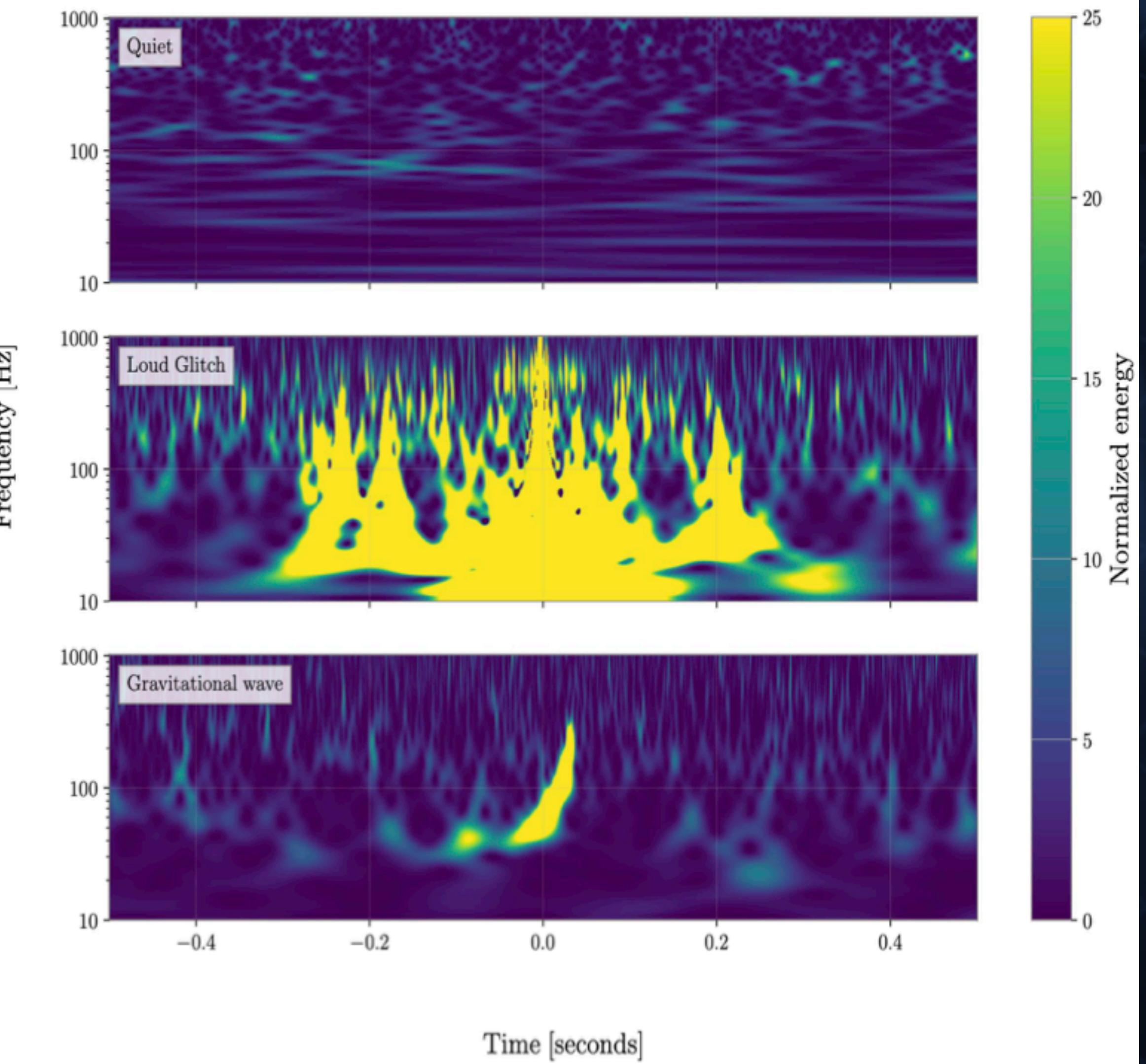
Plot taken from [gwpy documentation](#)

Intro to Q-transform - I

Strain time series plot



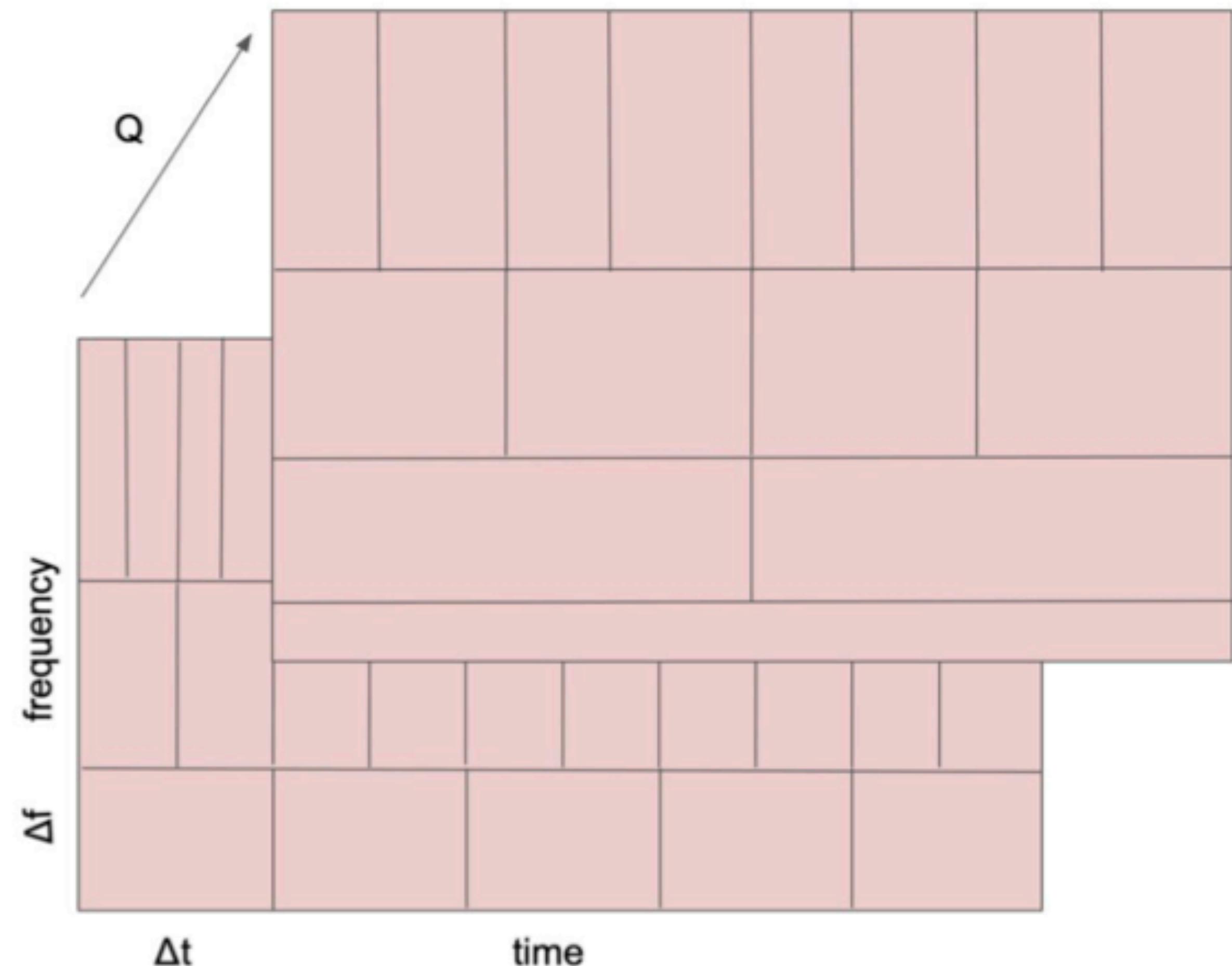
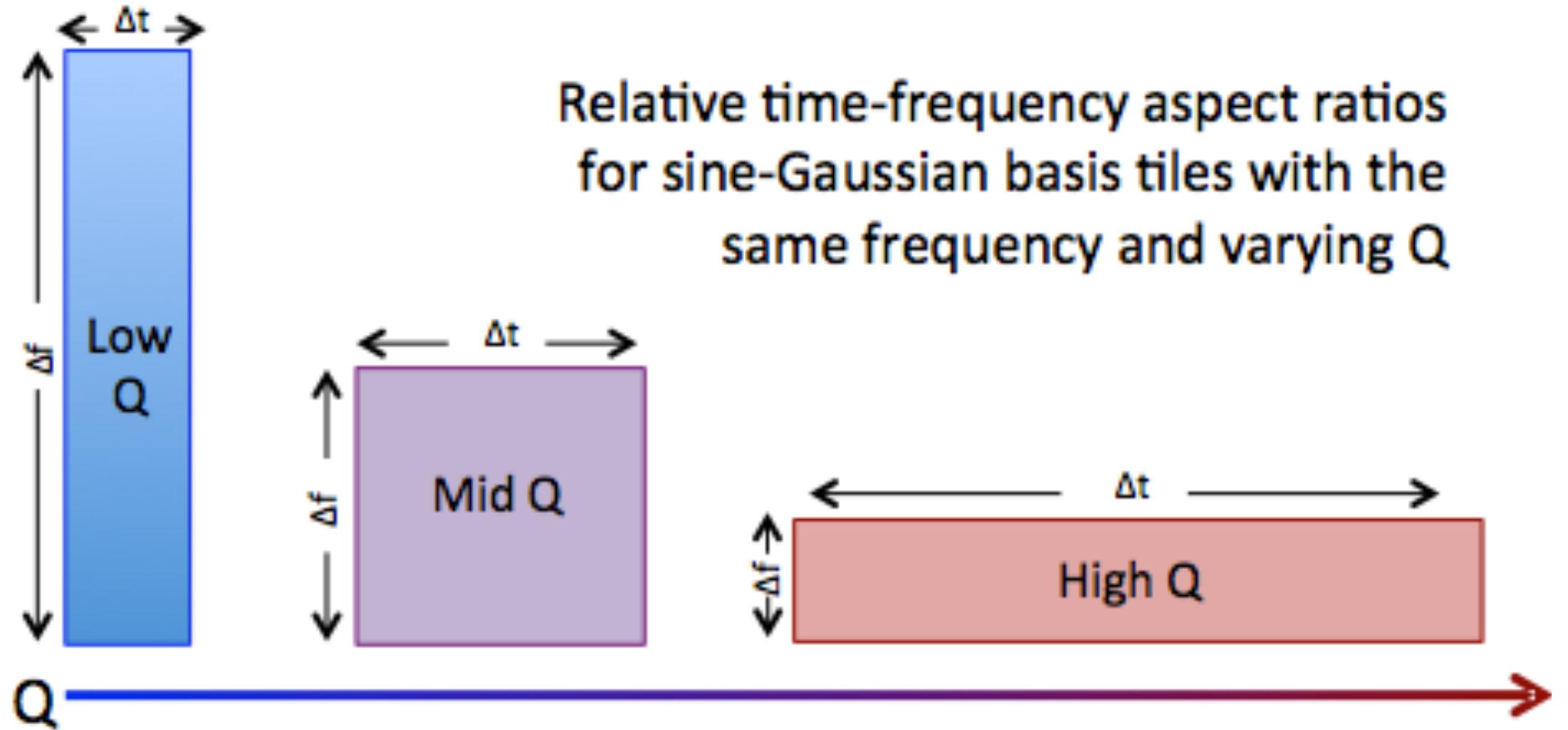
Q-transform



Intro to Q-transform - II

- Q transform allows us to visualize the data in time-frequency space
- Multiple spectrograms with constant ratio of duration to bandwidth (Q factor)
- Optimize over time-freq tile energy to pick a plane

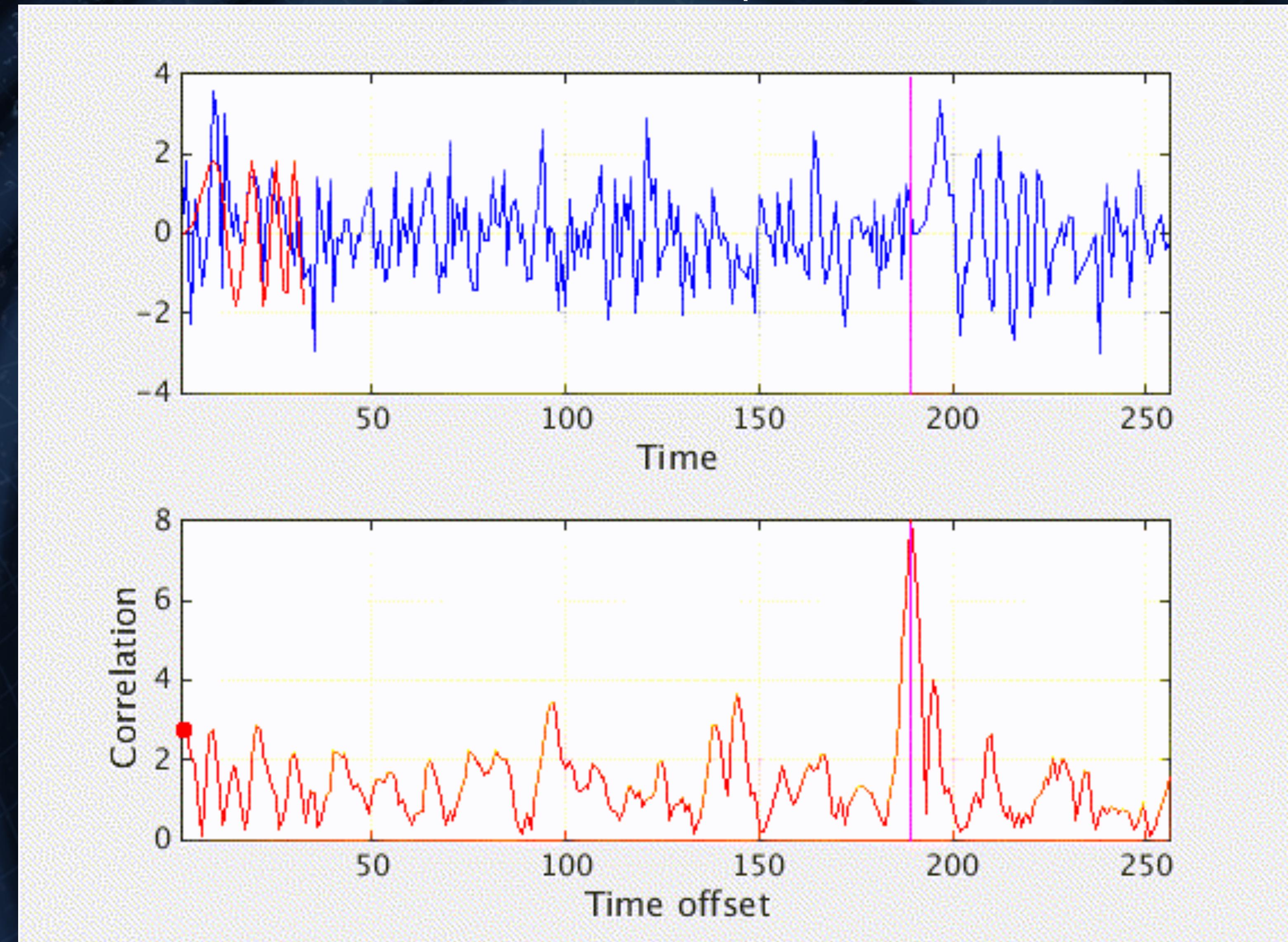
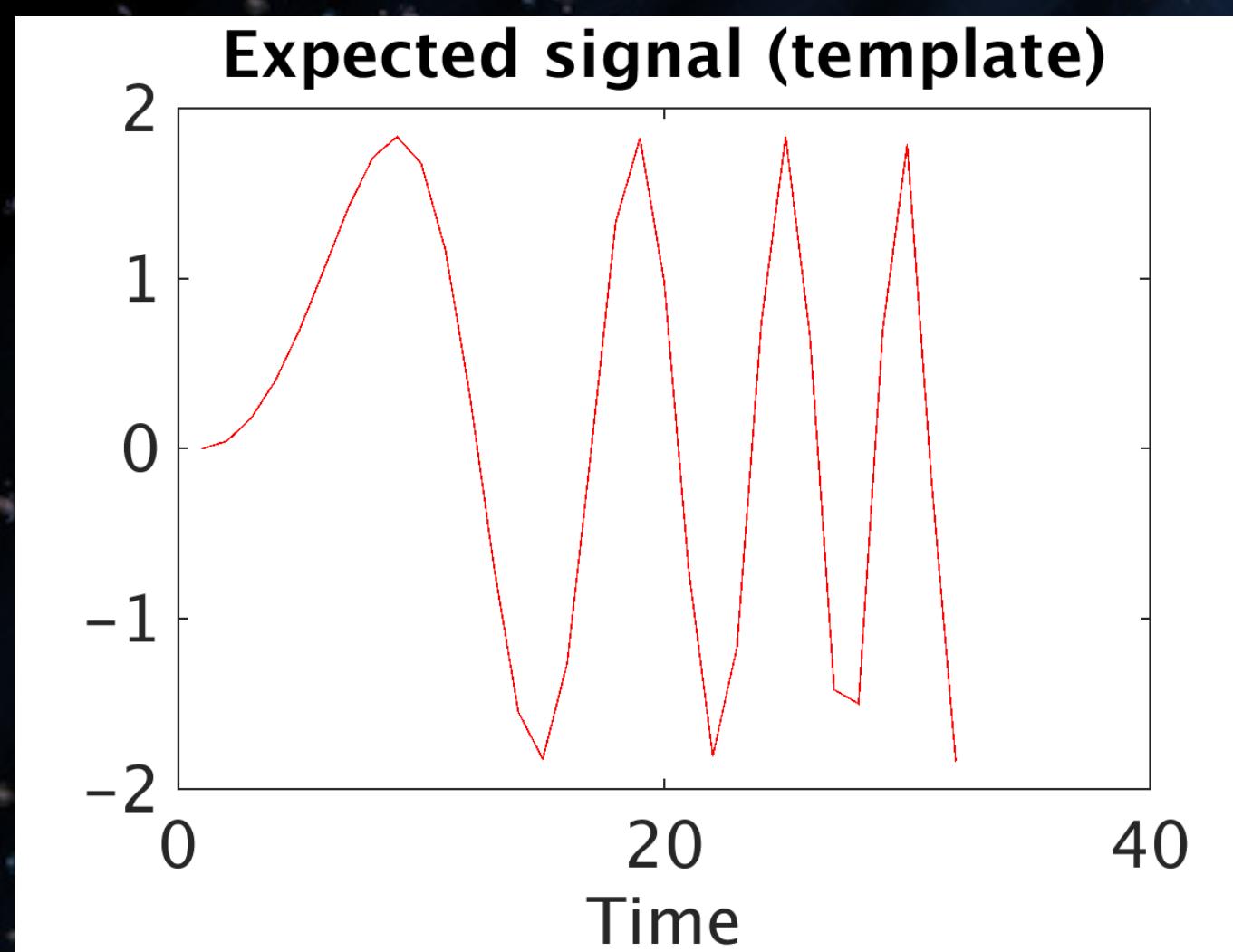
$$Q = \frac{f_0}{\Delta f}$$



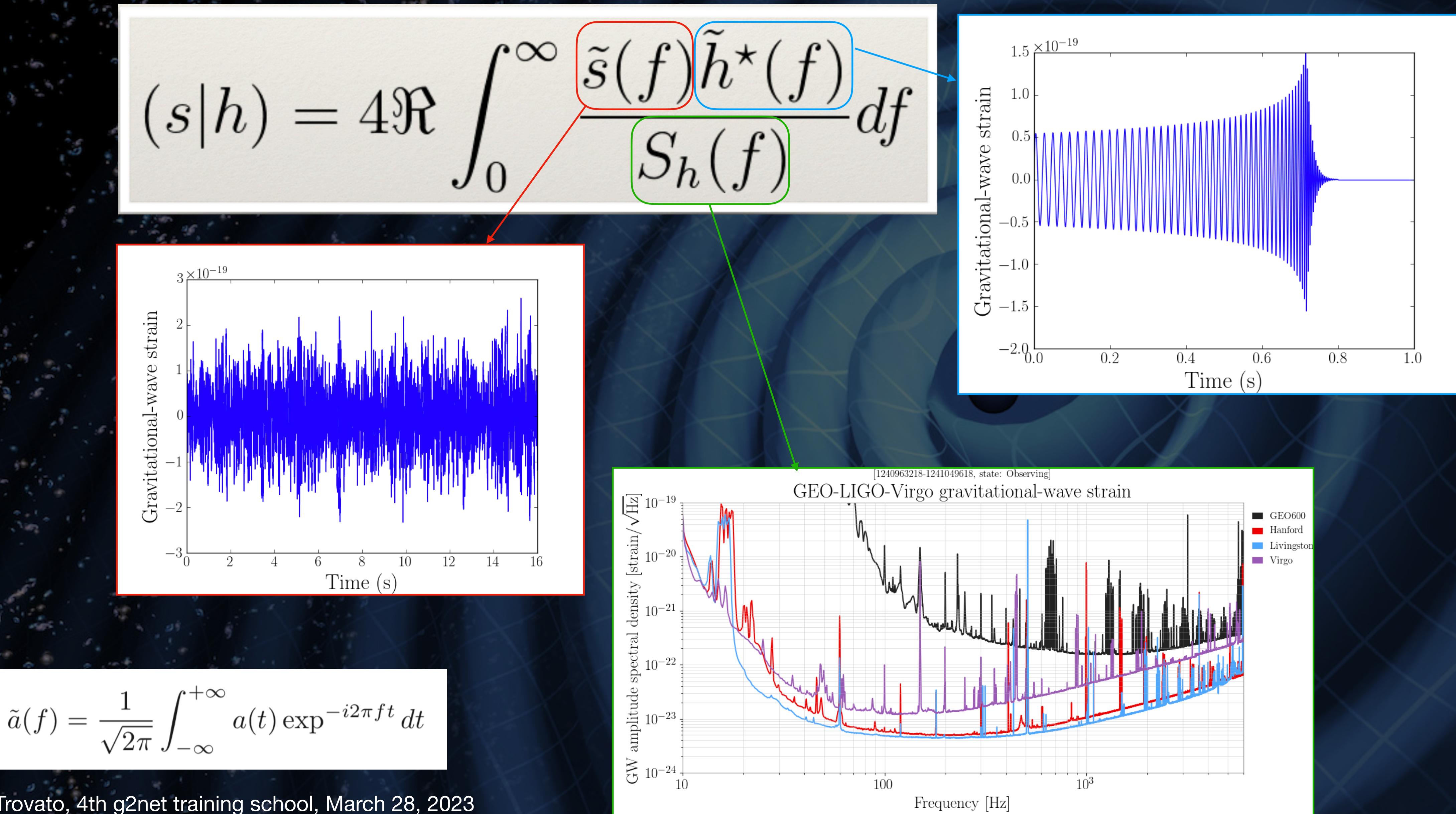
Matched filtering (I)

Filter: correlation between the template and the data

Simple example of a template



Matched filtering (II)



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