NRGW summer school, 2024.07.29~08.02

Data Quality (DQ) impact on GW Search

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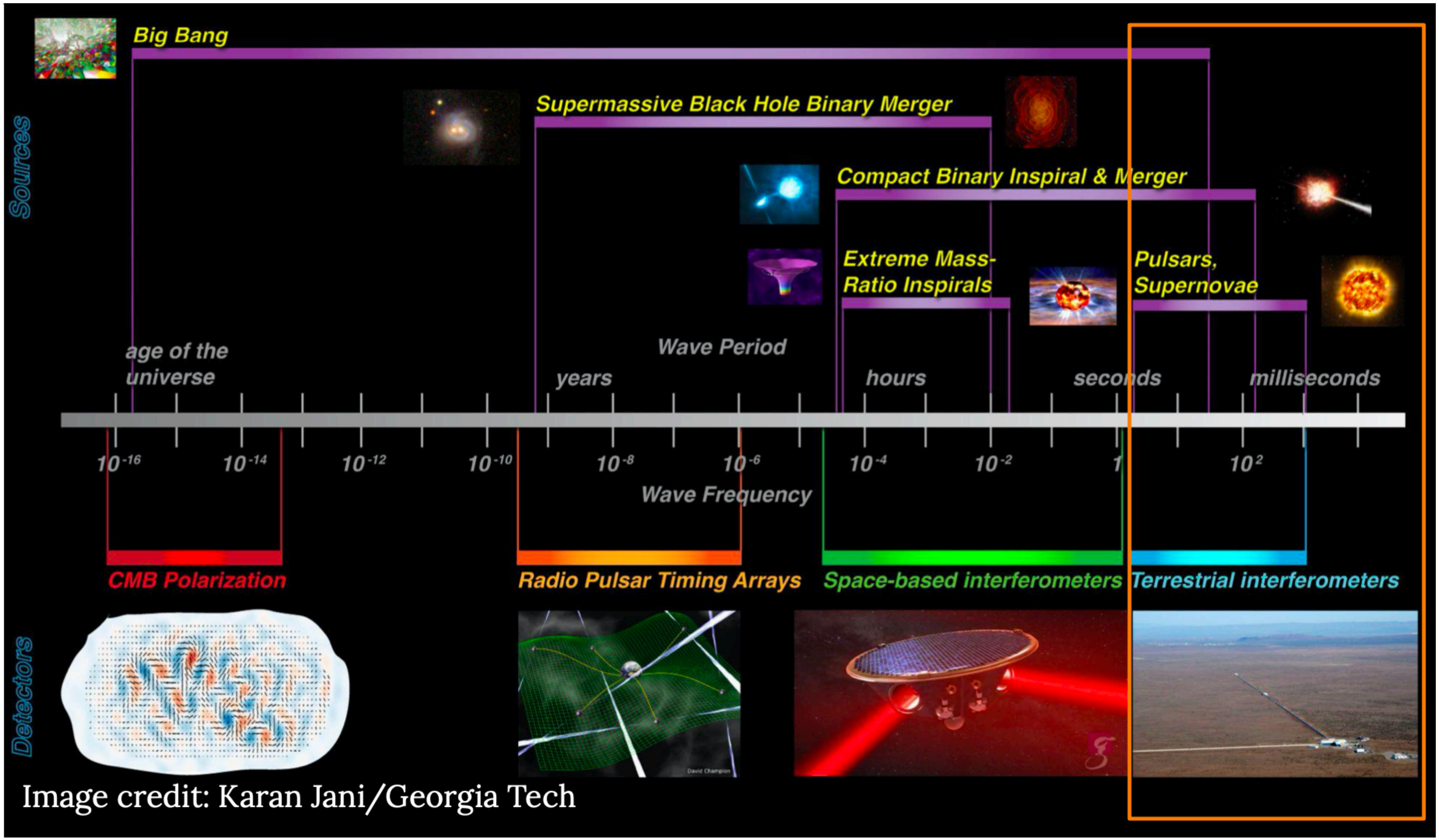
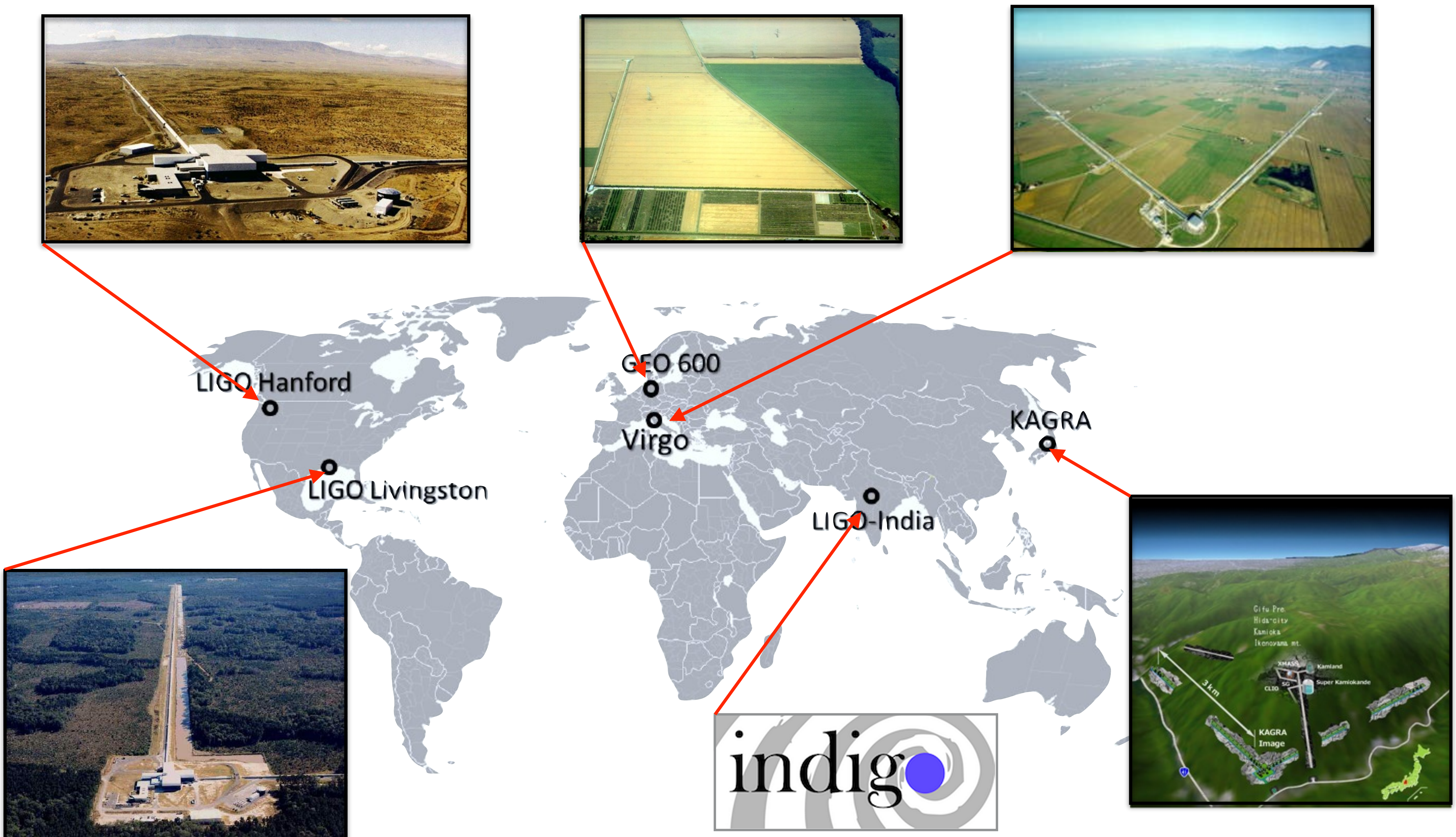
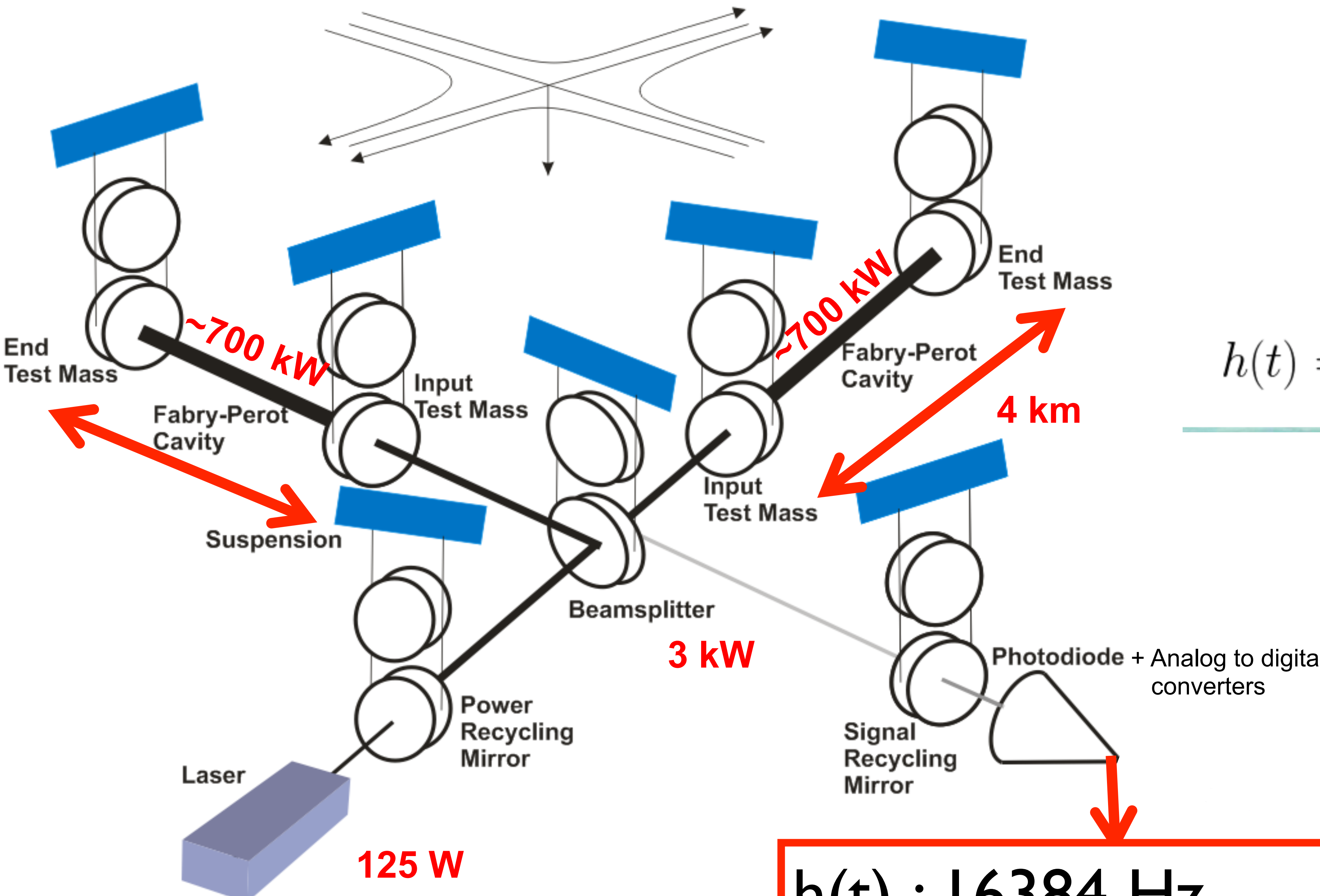
Astrophysical GW Sources



Gravitational-Wave Detection Network



Laser Interferometer

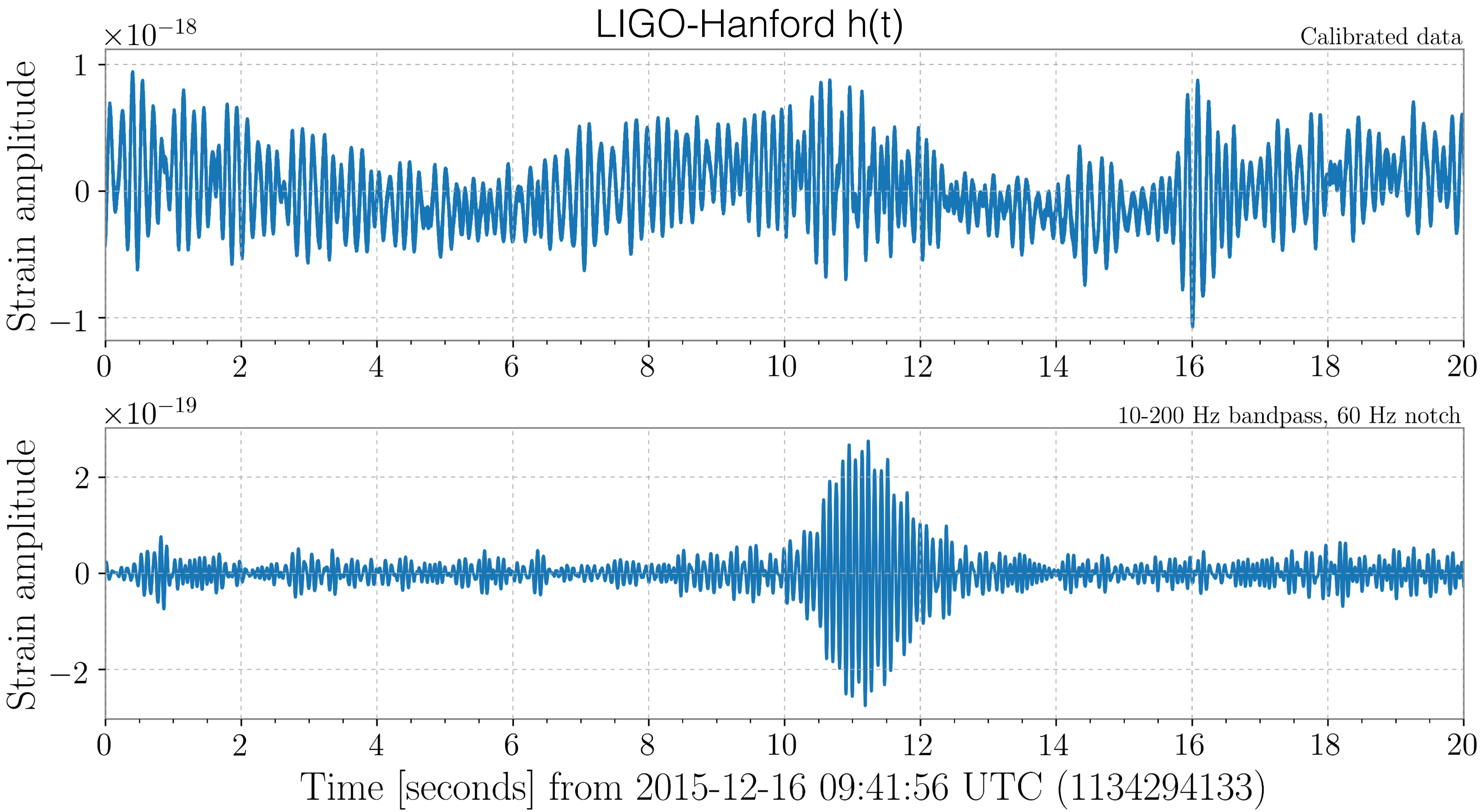


$$h(t) = \frac{\delta L_x(t) - \delta L_y(t)}{L}$$

"GW"

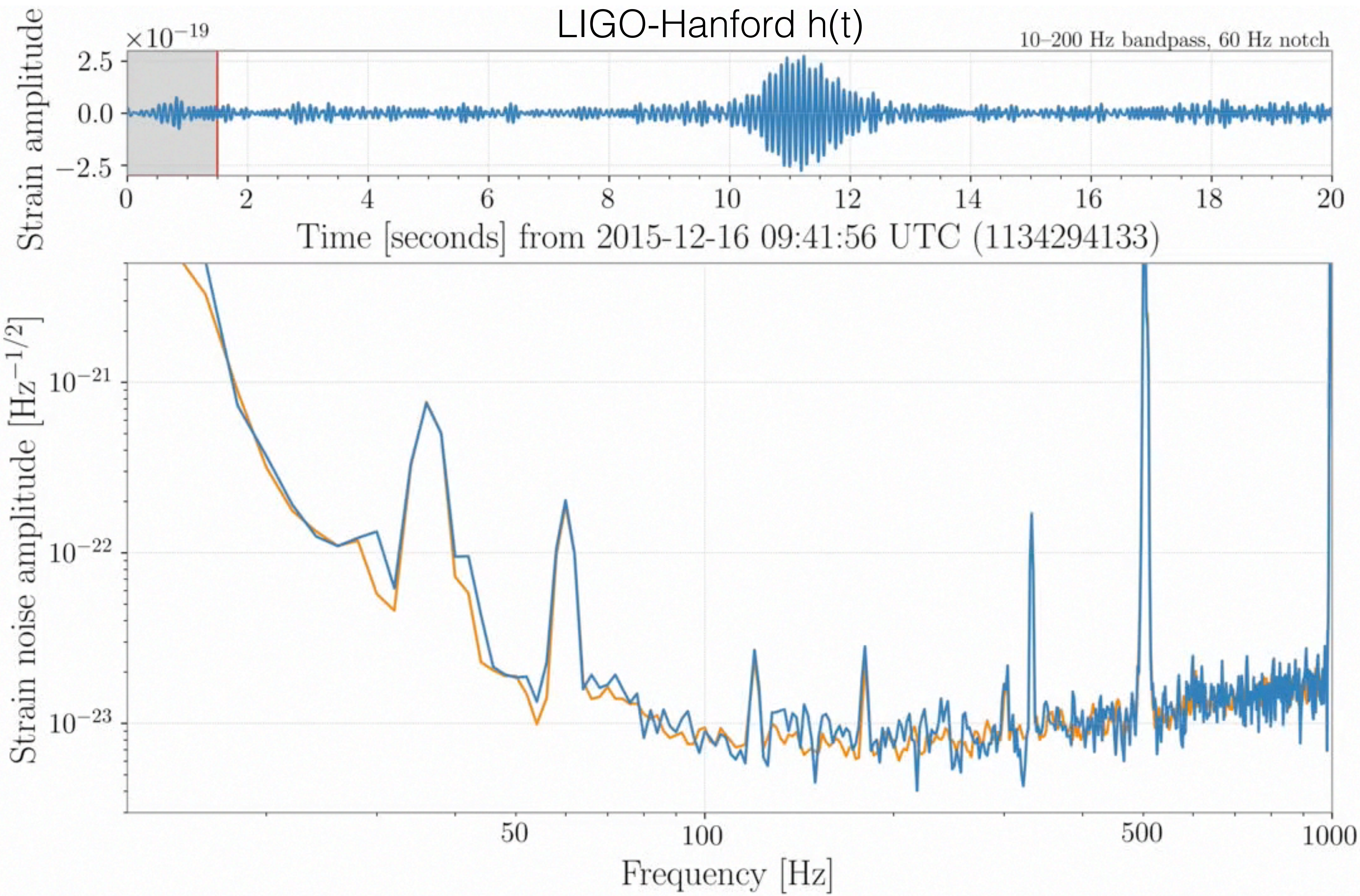
h(t) : 16384 Hz
GWOSC h(t) : 4096 Hz

What does LIGO data look like?



Made with GWpy by Duncan Macleod

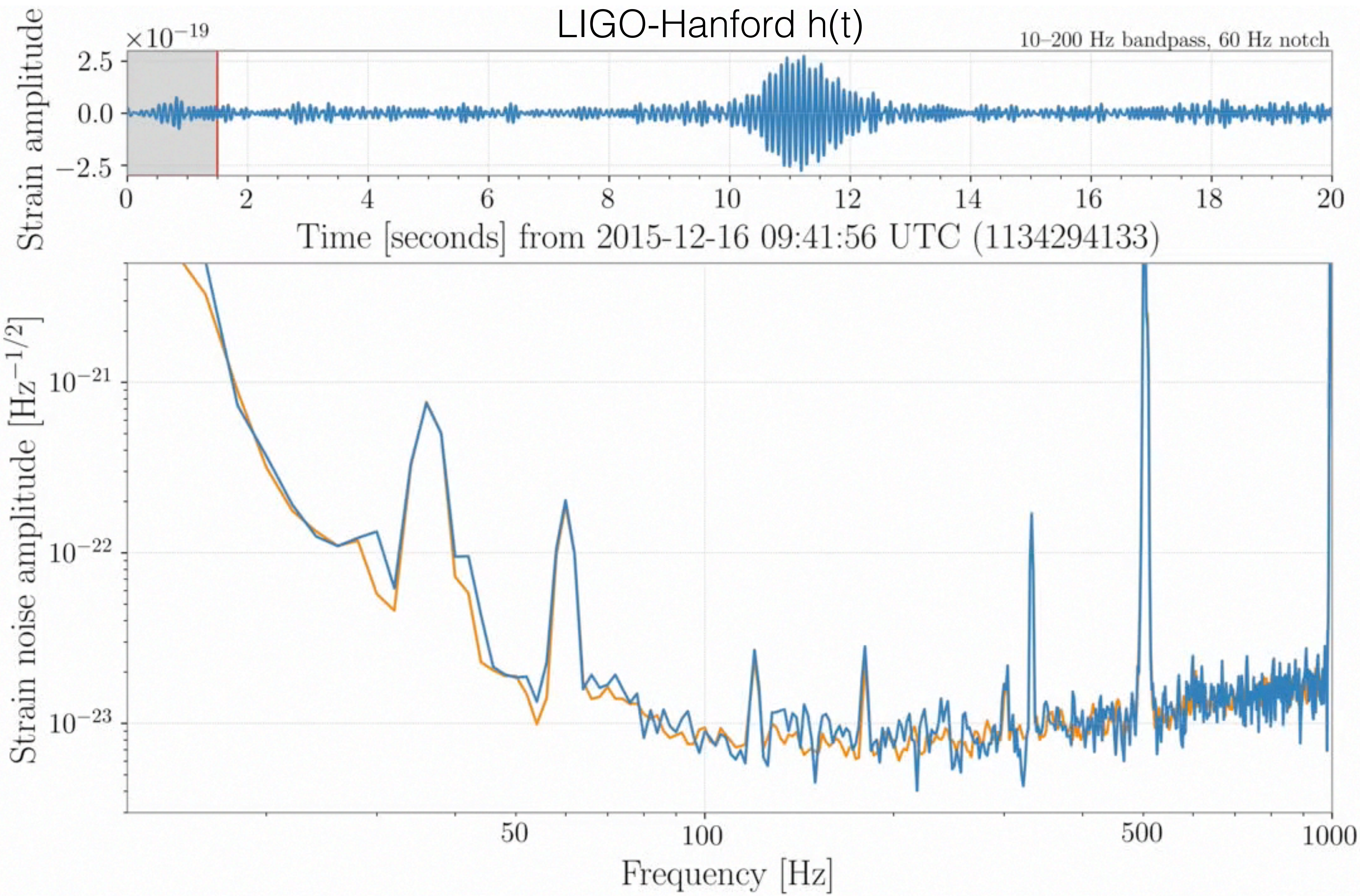
LIGO data in the frequency domain



Made with GWpy by Duncan Macleod. Code: https://git.io/gwpy-ligo-scattering-animation

0.5 second FFT; 5 averages covering 1.5 seconds; 50% overlap

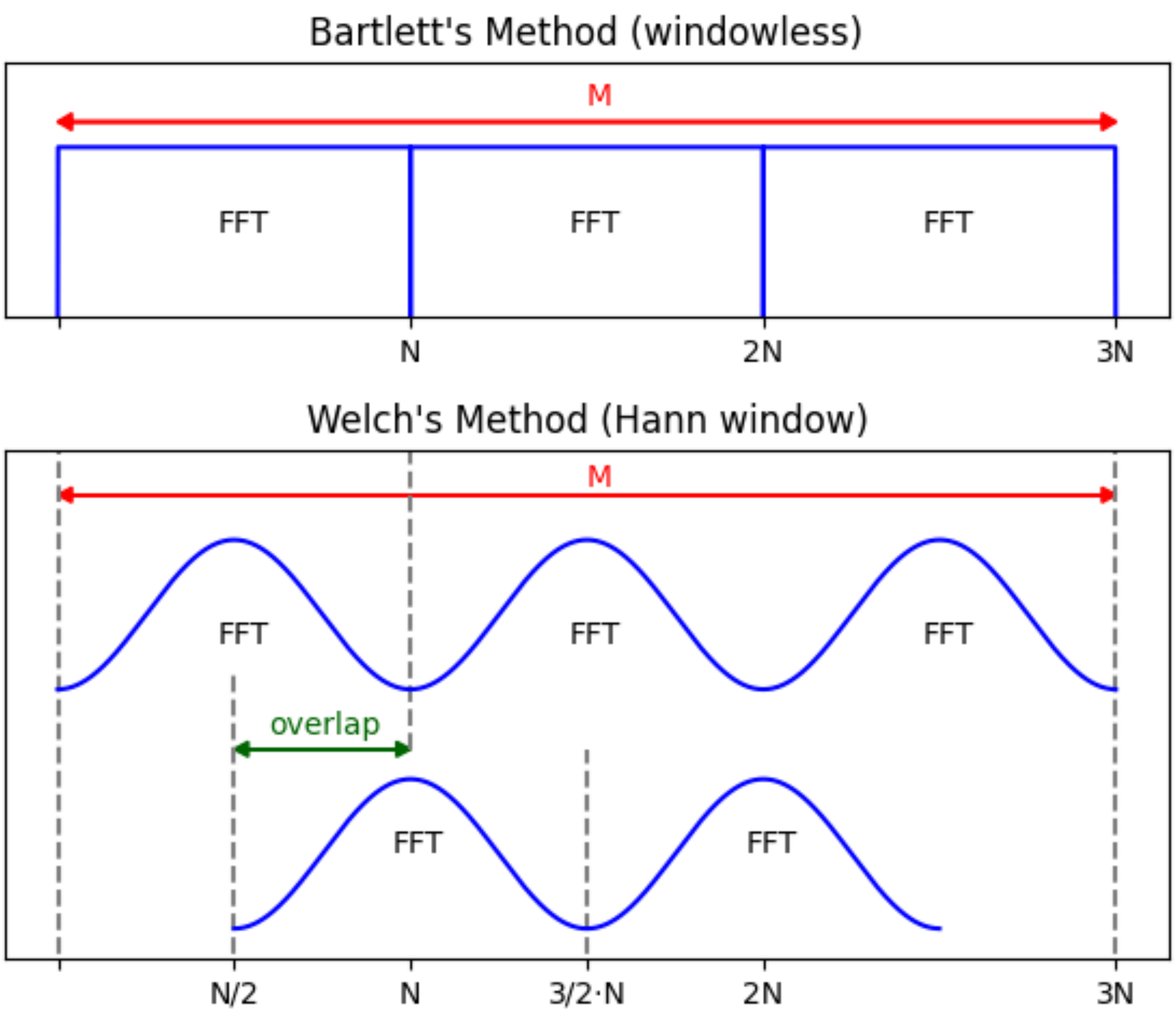
LIGO data in the frequency domain



Made with GWpy by Duncan Macleod. Code: https://git.io/gwpy-ligo-scattering-animation

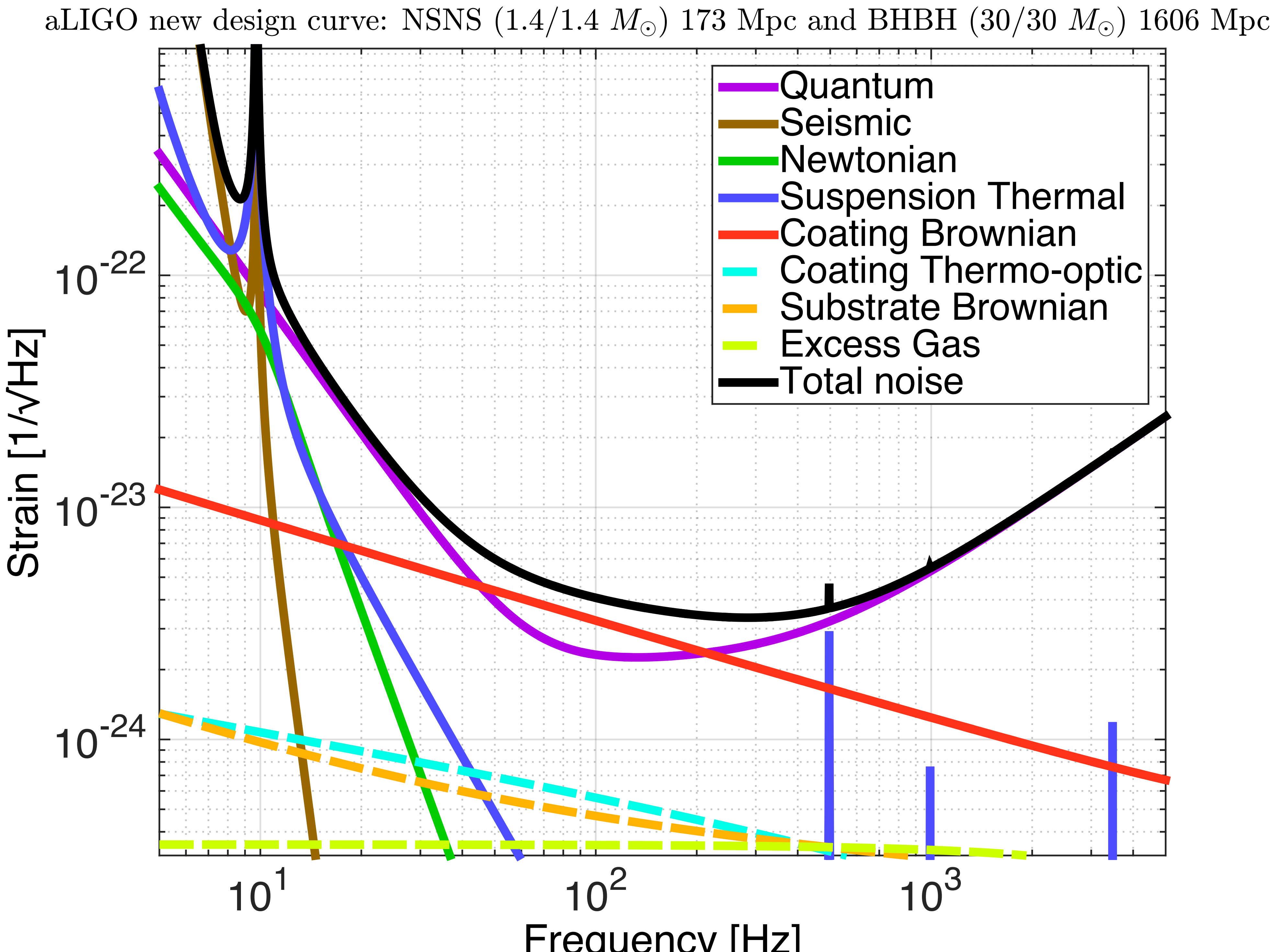
0.5 second FFT; 5 averages covering 1.5 seconds; 50% overlap

PSD - averaging



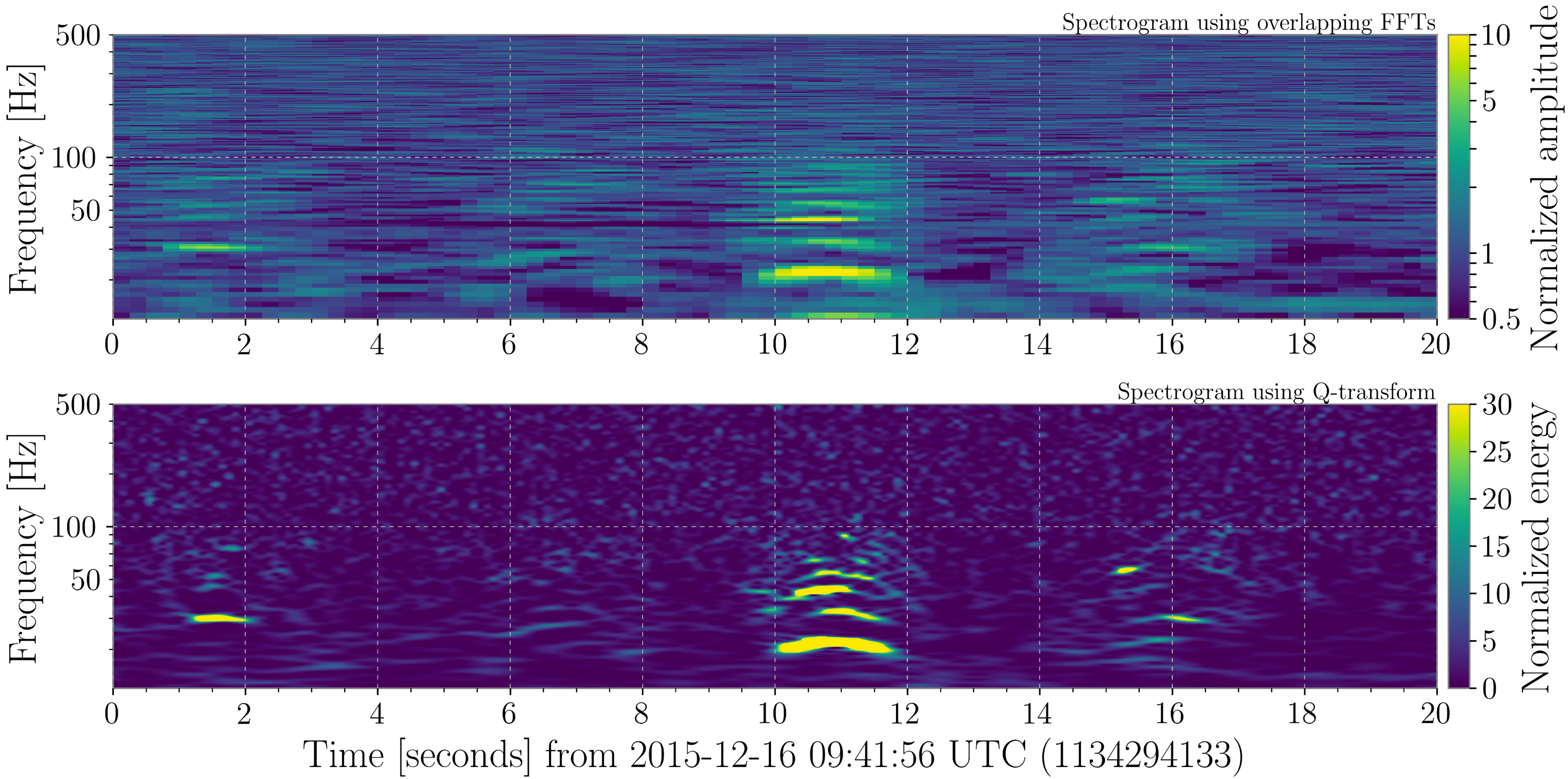
https://www.researchgate.net/figure/Welchs-and-Bartletts-methods-for-power-spectral-density-estimation-The-Bartletts_fig1_349283231

Detector Sensitivity



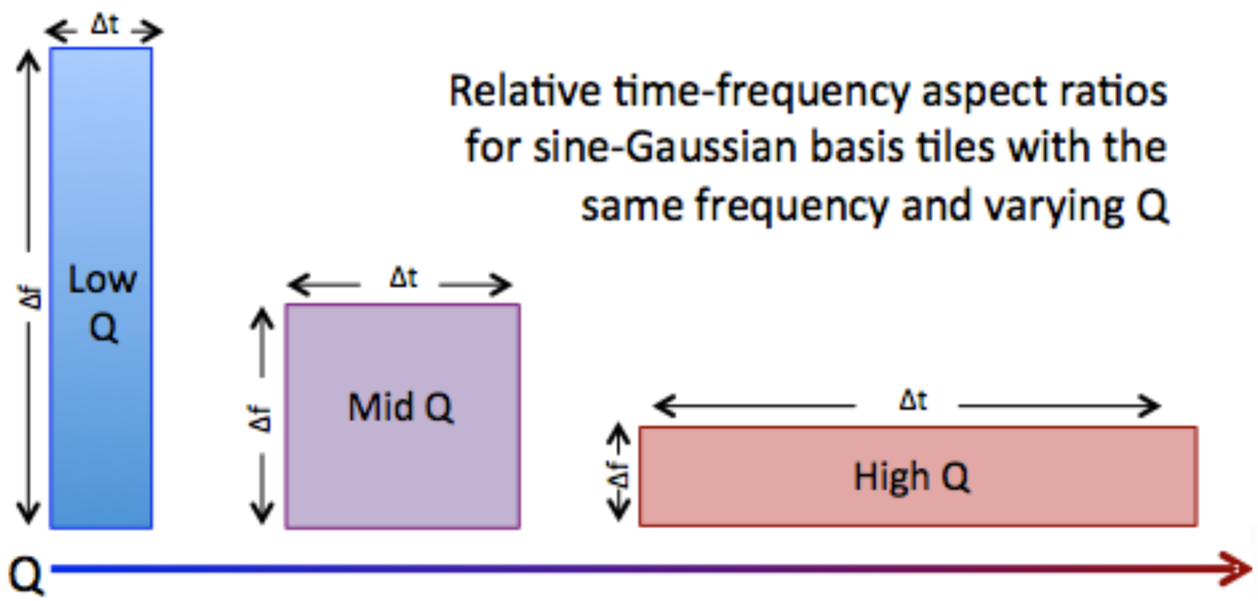
https://dcc.ligo.org/LIGO-T1800044/public

Features in GW data



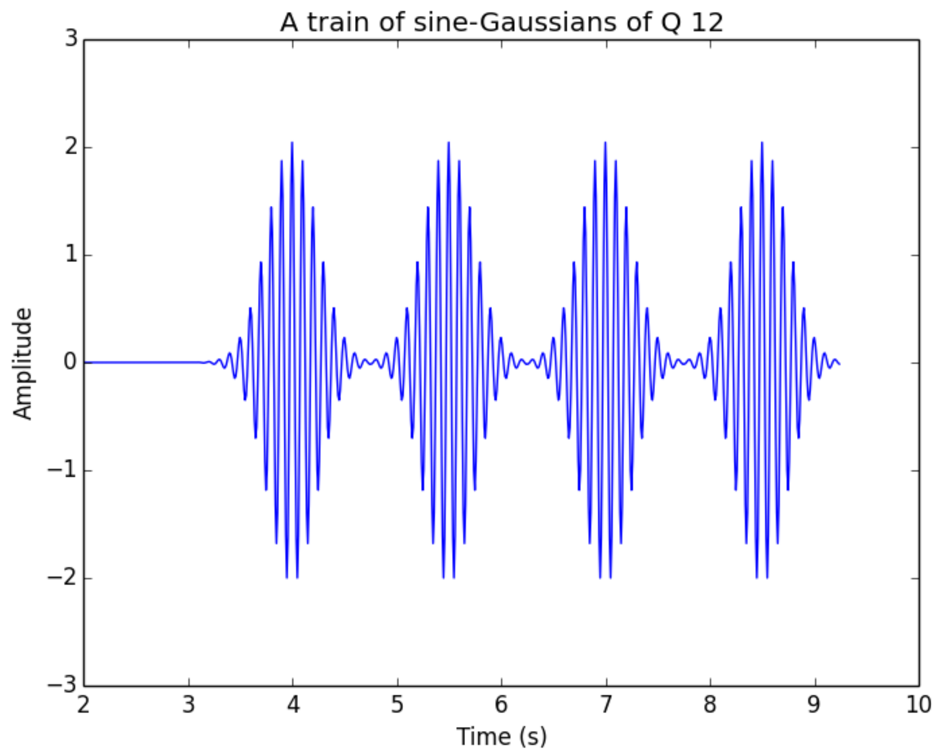
Laura Nuttall in GW ODW #4, 2021

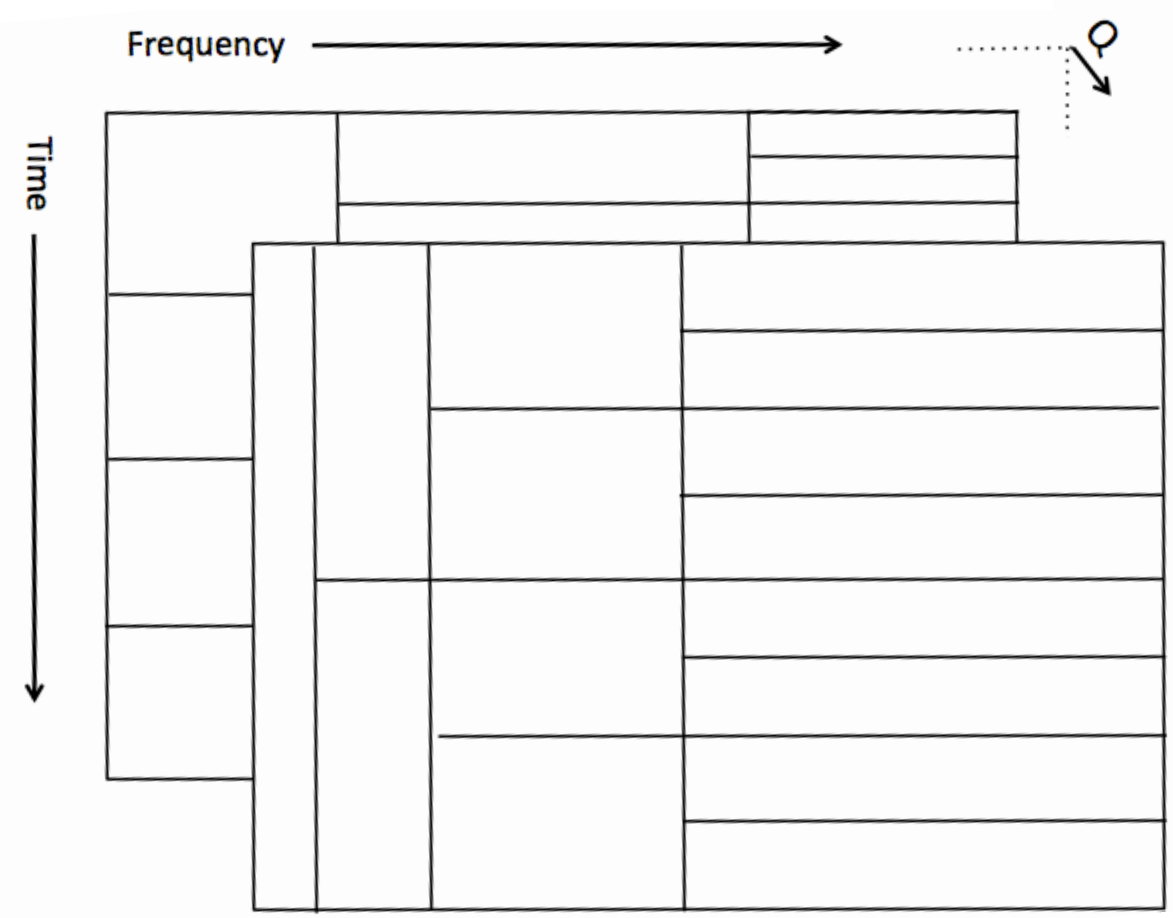
Q-transform



$$\Delta t \Delta f = 1/4\pi$$

$$Q = f_0/\Delta f \; = \; 4\pi f_0 \Delta t.$$



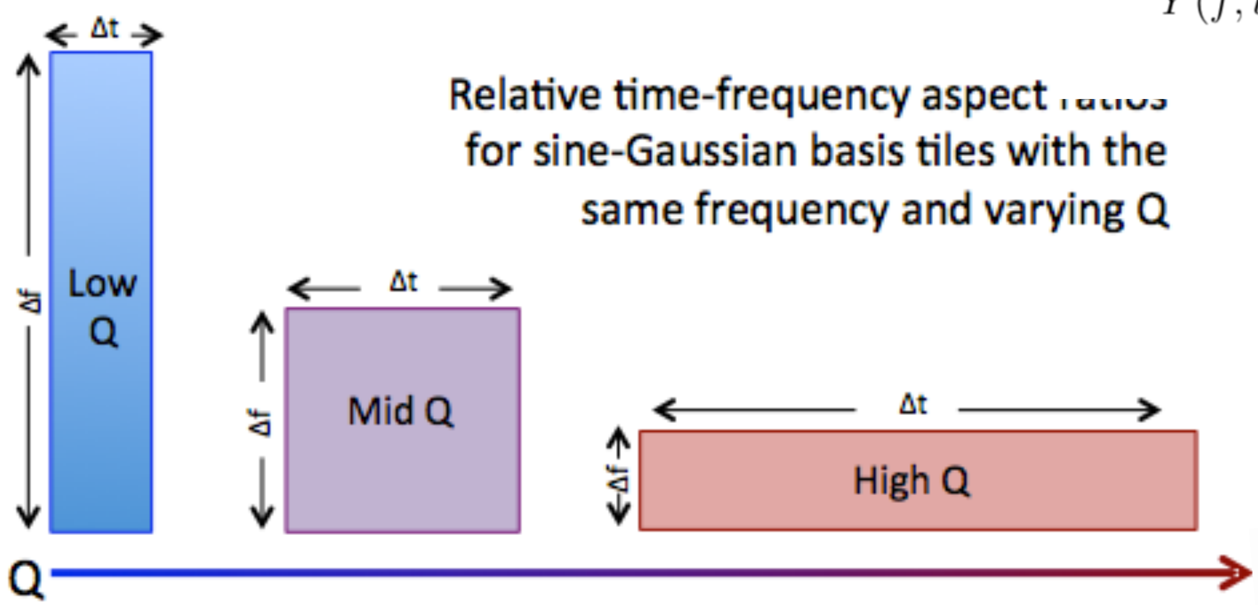


Q-transform

$$Y(t, t_0, f_0, Q) = \left(\frac{8\pi f_0^2}{Q^2}\right)^{\frac{1}{4}} \exp\left[\frac{-4\pi^2 f_0^2}{Q^2}(t - t_0)^2\right] \exp\left[-i2\pi f_0(t - t_0)\right] \quad (3.11)$$

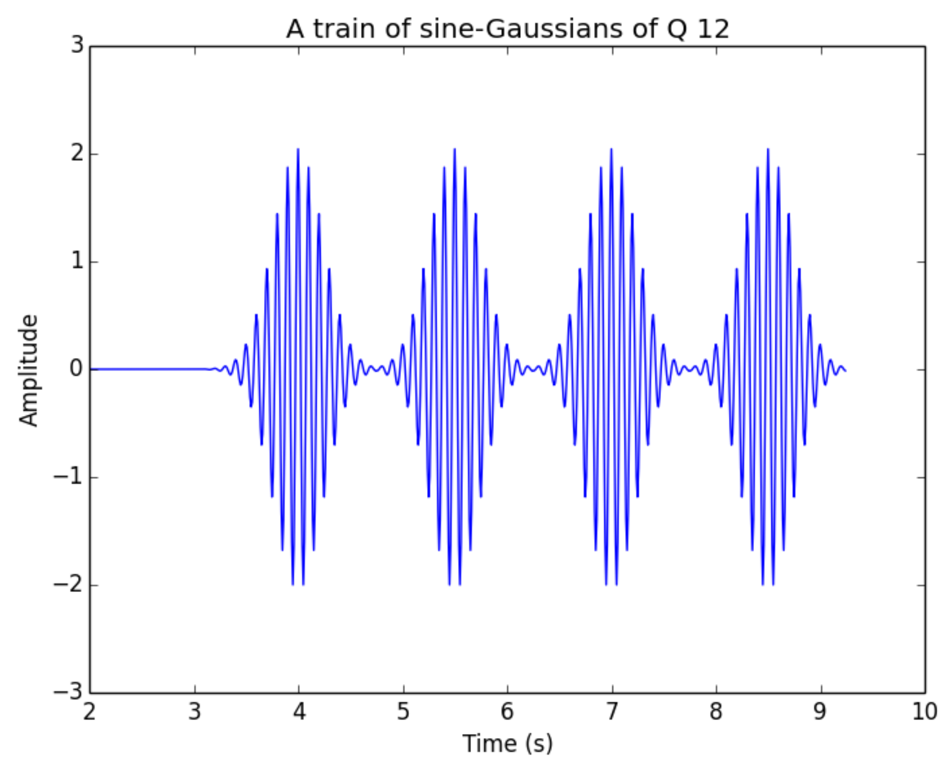
or equivalently in the frequency domain:

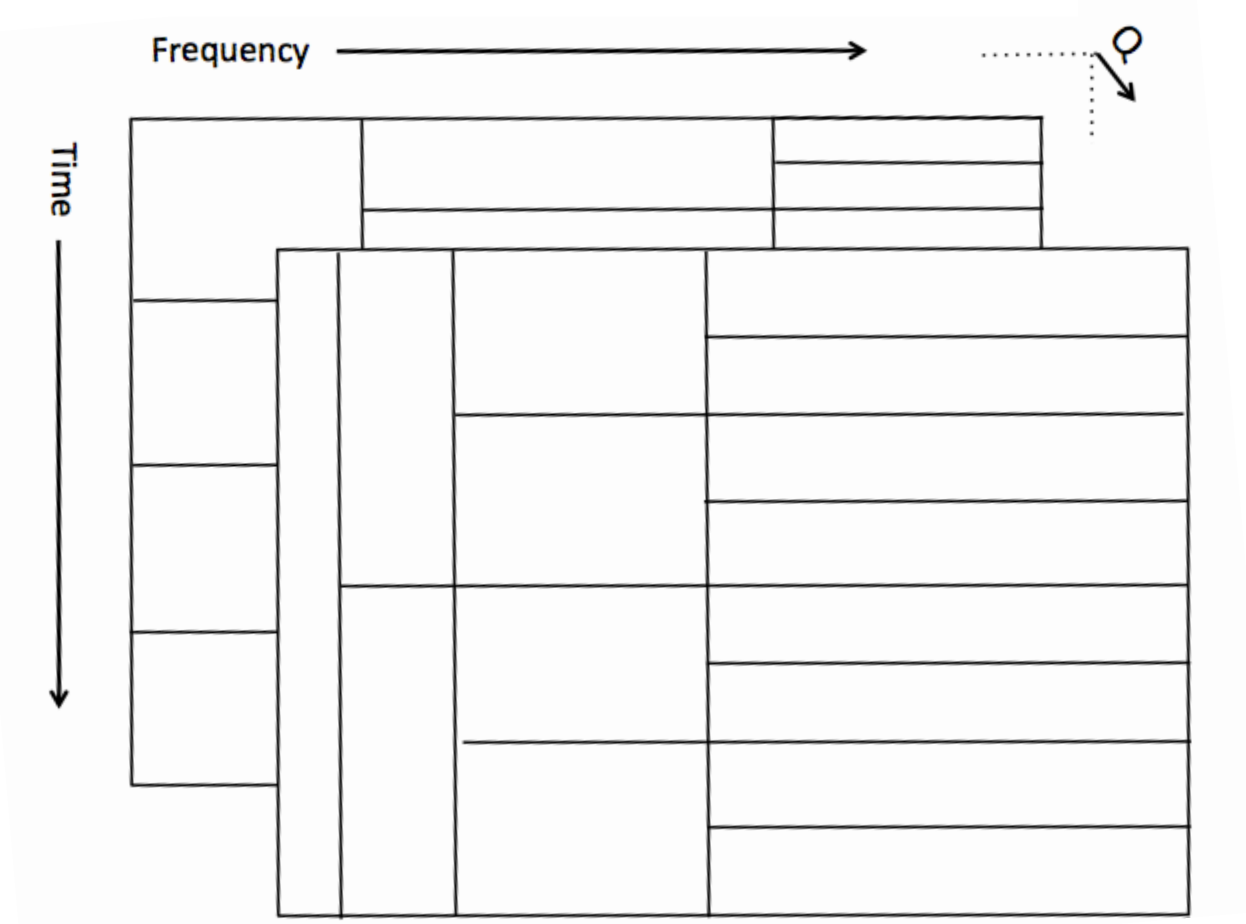
$$\widetilde{Y}(f, t_0, f_0, Q) = \left(\frac{Q^2}{2\pi f_0^2}\right)^{\frac{1}{4}} \exp\left[\frac{-Q^2}{4 f_0^2}(f - f_0)^2\right] \exp\left[-i2\pi t_0(f - f_0)\right]. \quad (3.12)$$



$$\Delta t \Delta f = 1/4\pi$$

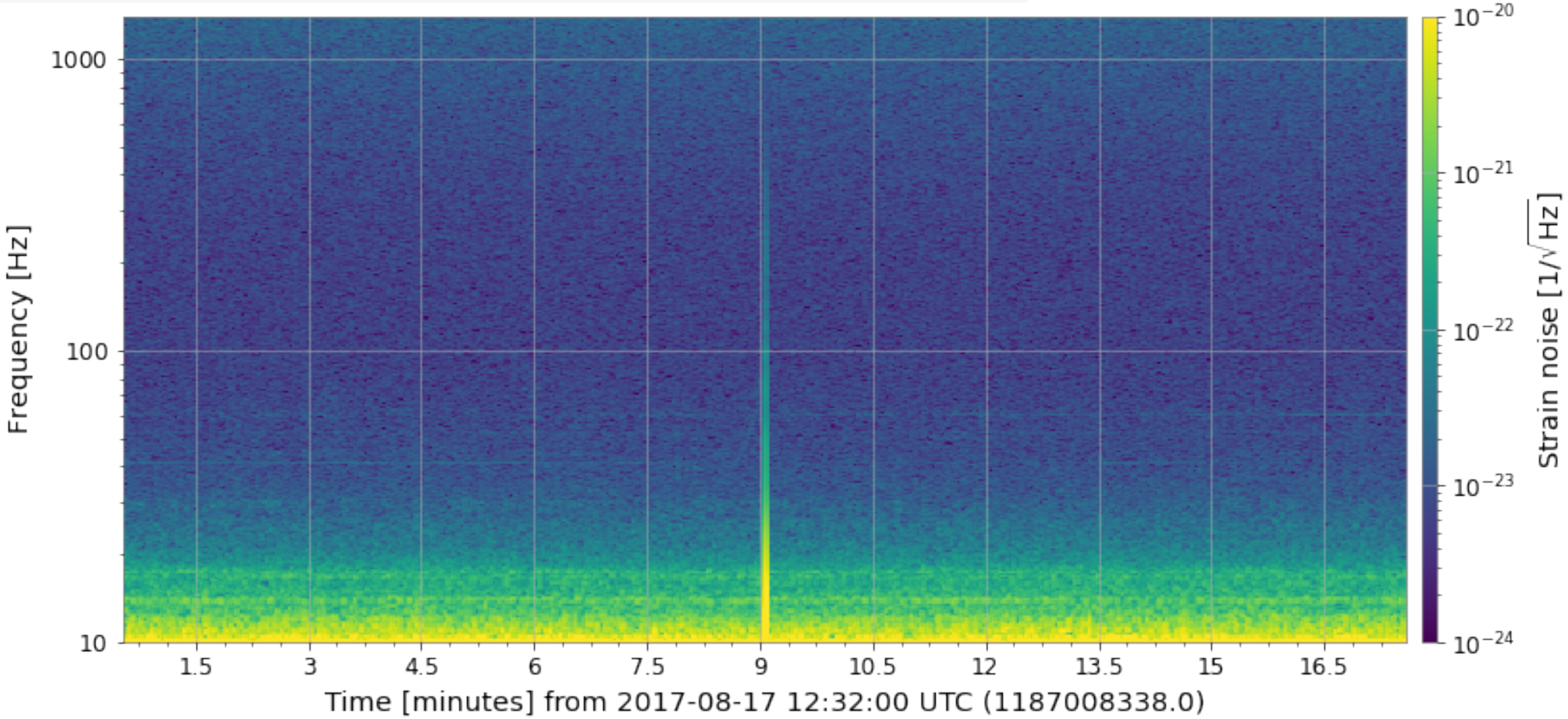
$$Q = f_0/\Delta f \; = \; 4\pi f_0 \Delta t.$$





GW170817: Spectrograms in gwpy

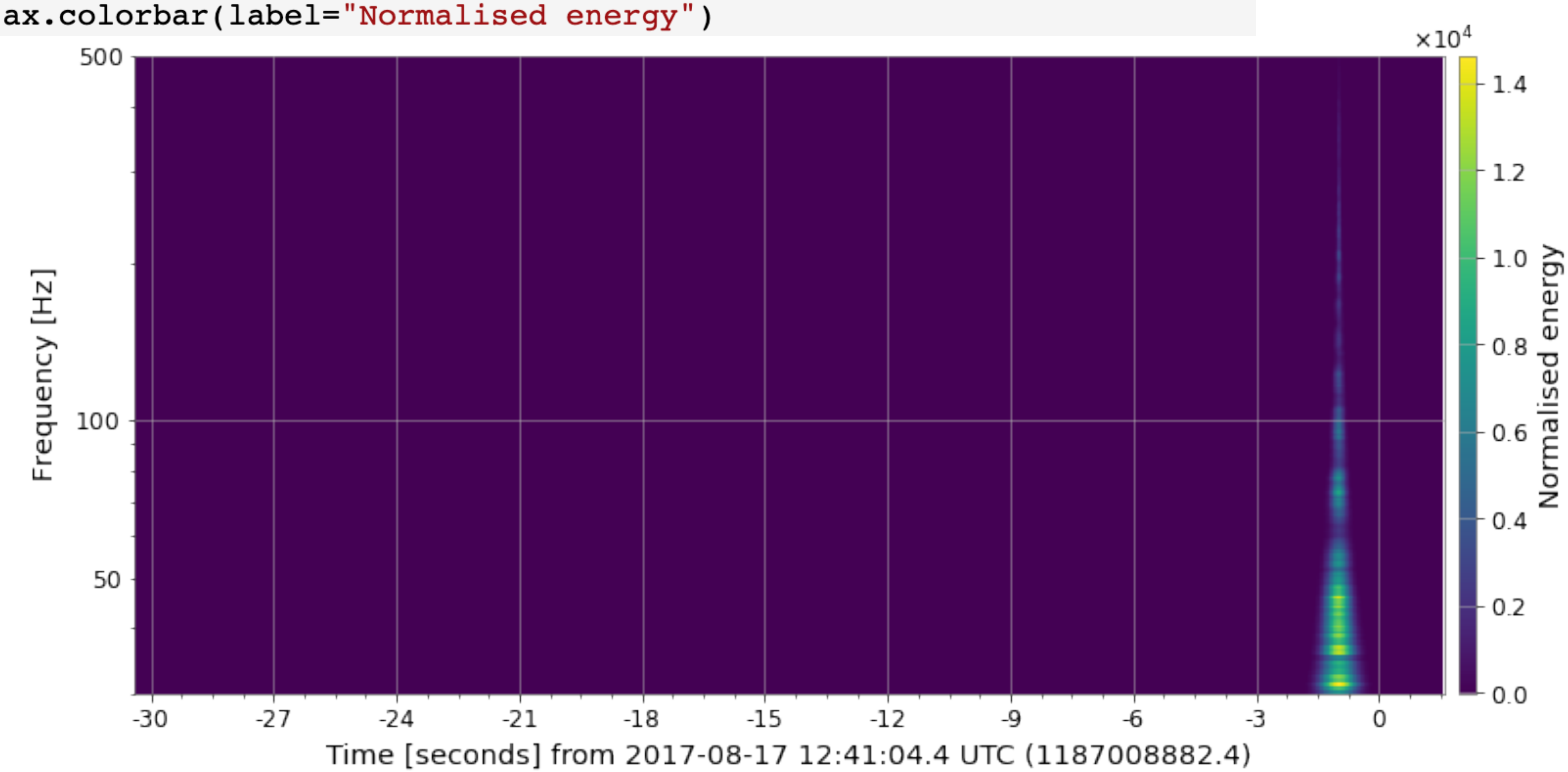
```
ax = plot.gca()
ax.set_yscale('log')
ax.set_ylim(10, 1400)
ax.colorbar(
    clim=(1e-24, 1e-20),
    norm="log",
    label=r"Strain noise [$1/\sqrt{\mathrm{Hz}}$]",
)
plot  # refresh
```



GW170817: Q-transform in gwpy

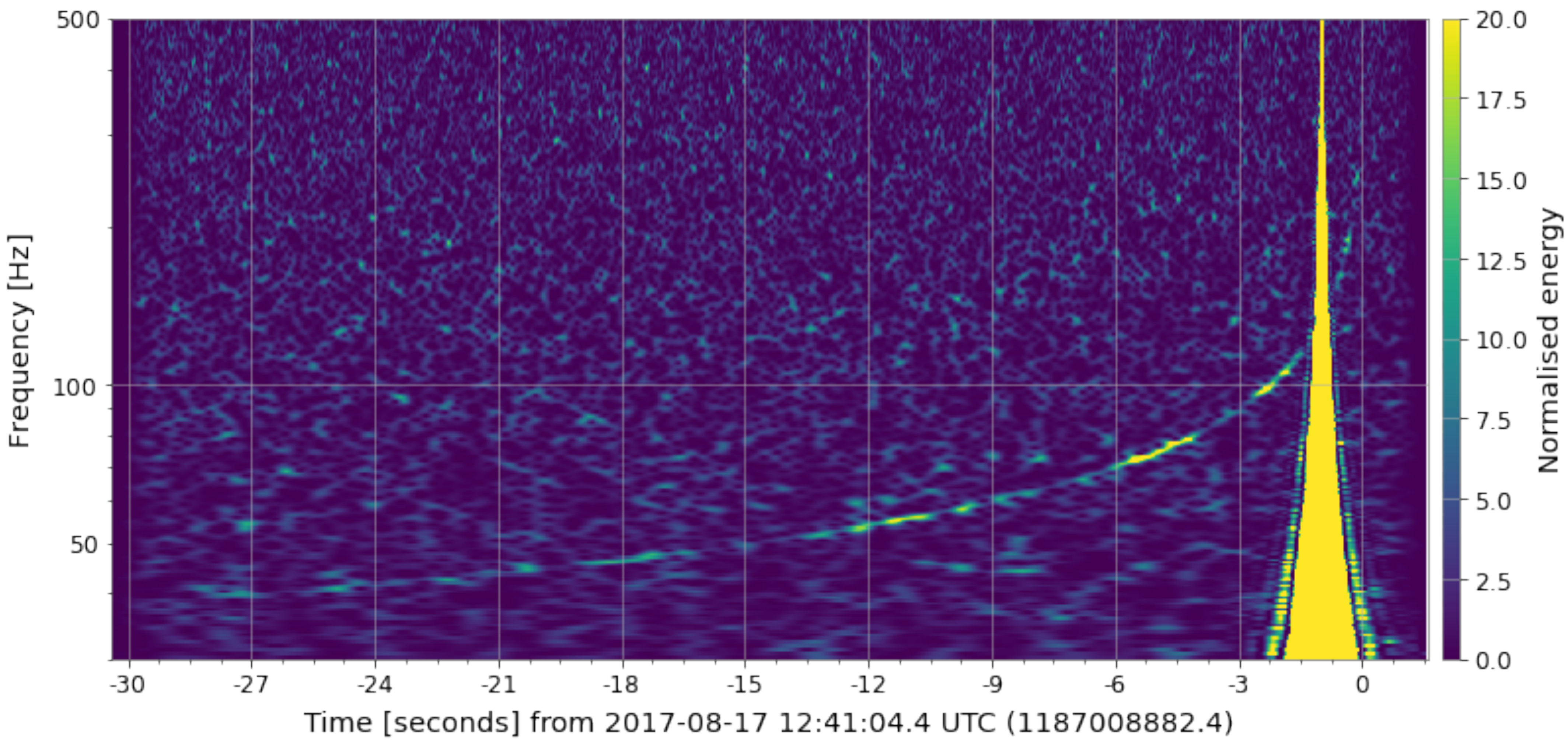
```
ldata = TimeSeries.fetch_open_data('L1', *segment, verbose=True)
```

```
lq = ldata.q_transform(frange=(30, 500), qrange=(100, 110))
plot = lq.plot()
ax = plot.gca()
ax.set_epoch(gps)
ax.set_yscale('log')
ax.colorbar(label="Normalised energy")
```

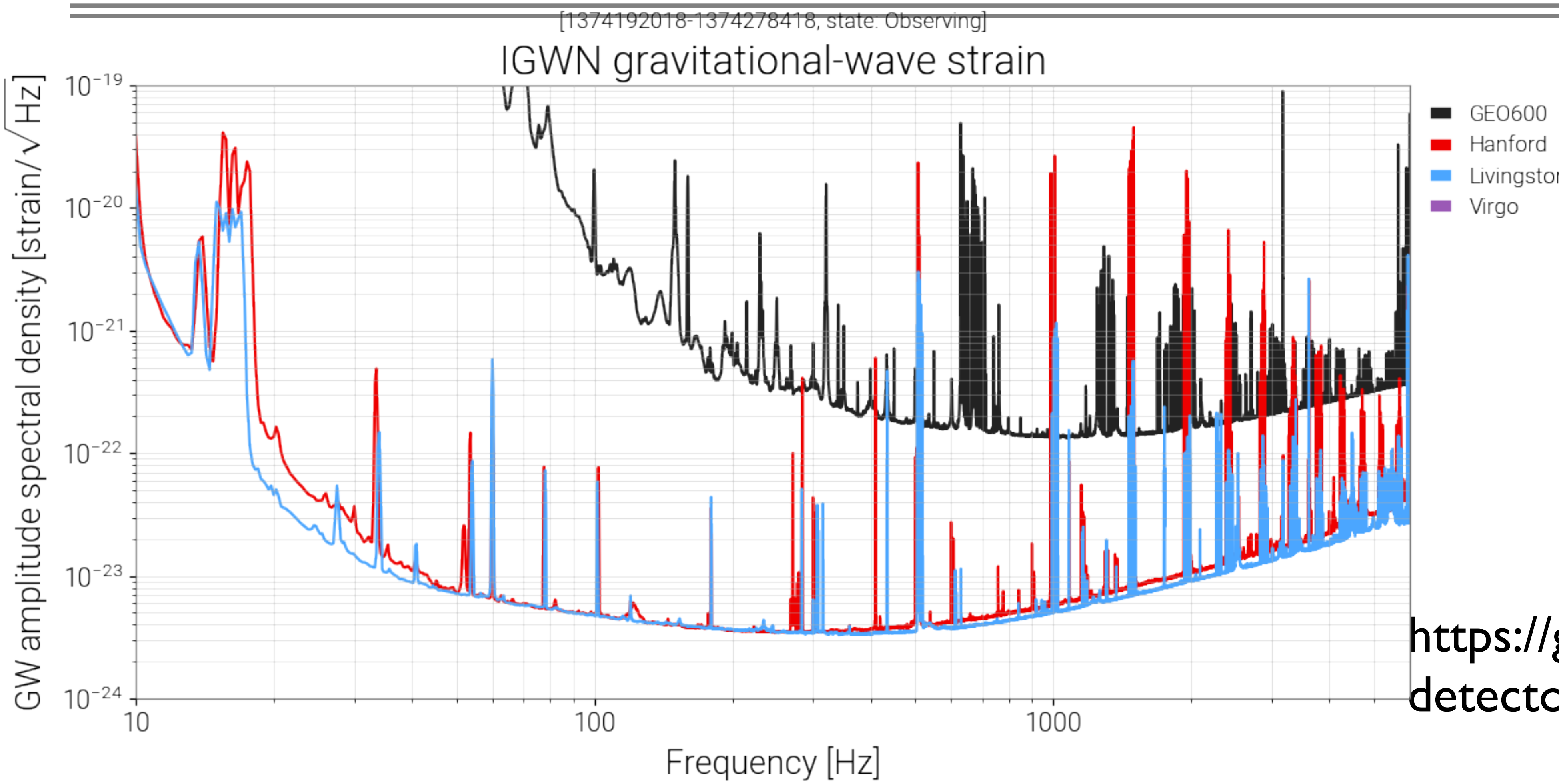


GW170817: Q-transform in gwpy

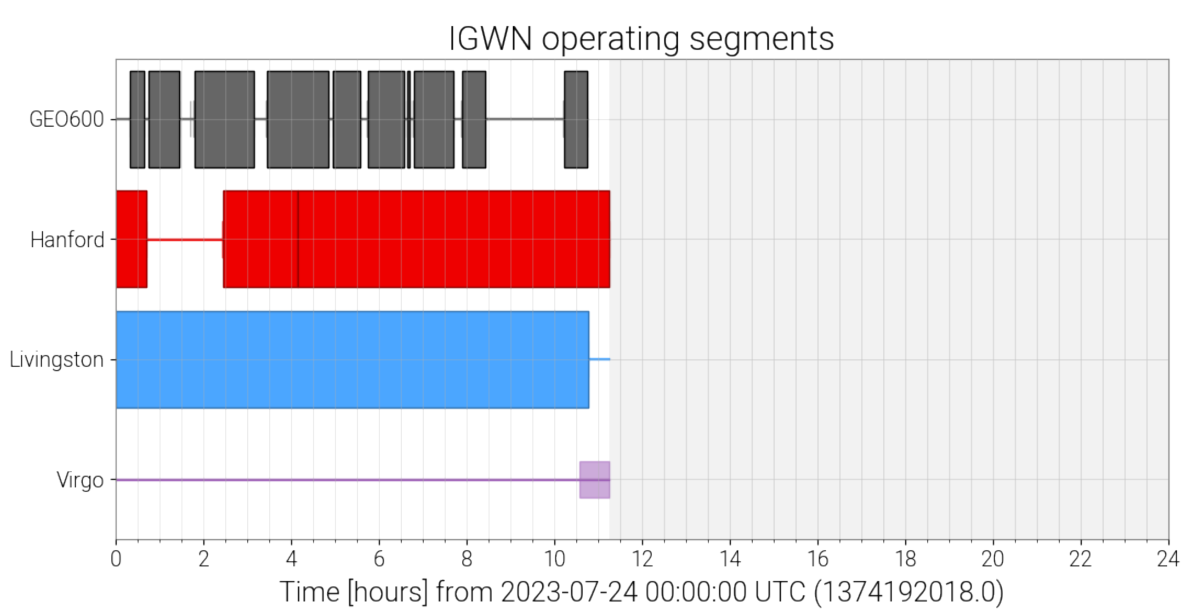
```
plot.colorbars[0].mappable.set_clim(0,20)
plot.refresh()
plot
```

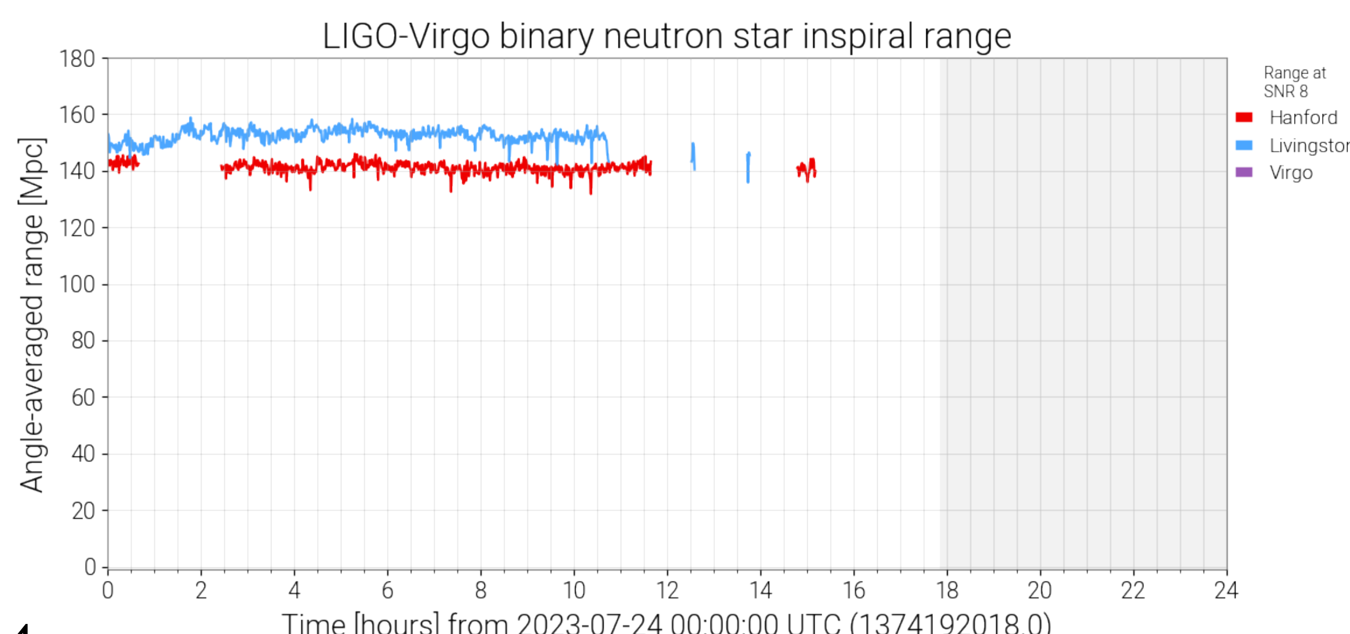


Detector Status in GWOSC



https://gwosc.org/detector_status/day/20230724/





BNS Range

Expected SNR

$$\varrho = \sqrt{4\int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)}df}$$

$$= \left(\frac{1\ \mathrm{Mpc}}{D_{\mathrm{eff}}}\right)\sqrt{4\mathcal{A}^2_{1\ \mathrm{Mpc}}(M,\mu)\int_0^\infty \frac{f^{-7/3}}{S_n(f)}df} \quad \text{(D1)}$$

Horizon distance

$$D_{\mathrm{hor}} = \frac{1\ \mathrm{Mpc}}{\varrho}\sqrt{4\mathcal{A}^2_{1\ \mathrm{Mpc}}(M,\mu)\int_0^\infty \frac{f^{-7/3}}{S_n(f)}df}, \quad \text{(D2)}$$

snr=8, m1=m2=1.4 Msun, mu=0.7 Msun

BNS range
(Sense-monitor range)

R = D_hor * F

1/F = 4/(3 * 1.84)^(1/3) ~ 2.12648

PHYSICAL REVIEW D 85, 122006 (2012)

Example - BNS range by GWPy

First, we need to load some data. We can `fetch` the public data around the GW170817 BNS merger:

```
from gwpy.timeseries import TimeSeries
h1 = TimeSeries.fetch_open_data('H1', 1187006834, 1187010930, tag='C02')
l1 = TimeSeries.fetch_open_data('L1', 1187006834, 1187010930, tag='C02')
```

Then, we can measure the inspiral range directly:

```
from gwpy.astro import range_timeseries
h1range = range_timeseries(h1, 30, fftlength=4, fmin=10)
l1range = range_timeseries(l1, 30, fftlength=4, fmin=10)
```

We can now plot these trends to see the variation in LIGO sensitivity over an hour or so surrounding GW170817:

```
plot = h1range.plot(
    label='LIGO-Hanford', color='gwpy:ligo-hanford', figsize=(12, 5))
ax = plot.gca()
ax.plot(l1range, label='LIGO-Livingston', color='gwpy:ligo-livingston')
ax.set_ylabel('Angle-averaged sensitive distance [Mpc]')
ax.set_title('LIGO sensitivity to BNS around GW170817')
ax.set_epoch(1187008882)  # <- set 0 on plot to GW170817
ax.legend()
plot.show()
```

https://gwpy.github.io/docs/latest/examples/miscellaneous/range-timeseries.html

Example - BNS range by GWPy

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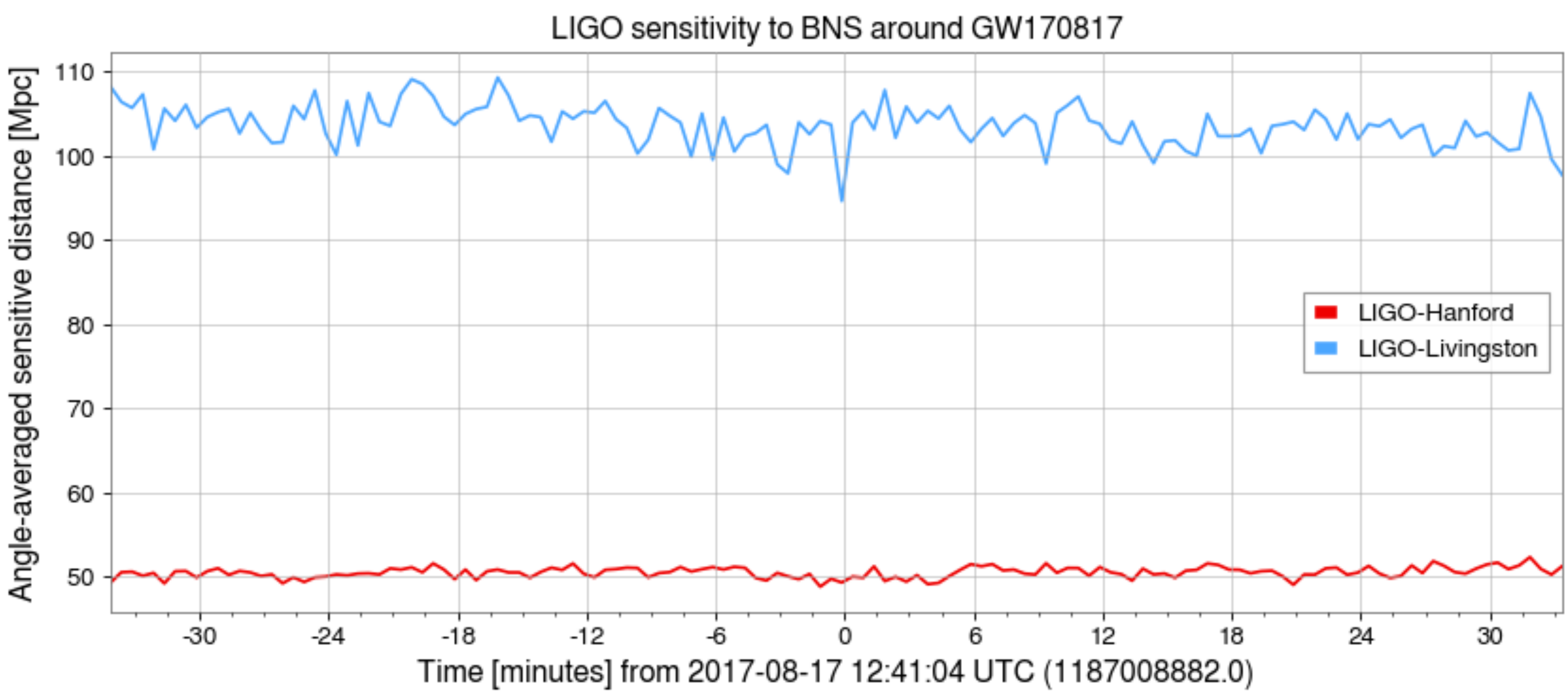
```




```
ax.legend()
plot.show()
```

https://gwpy.github.io/docs/latest/examples/miscellaneous/range-timeseries.html

Noise backgrounds

Complicated noise curves

Many lines in the data, not such an issue for transient searches, but can be an issue for continuous wave searches

To an okay approximation, the detector data is colored Gaussian noise - standard Gaussian noise just with certain frequencies louder than others

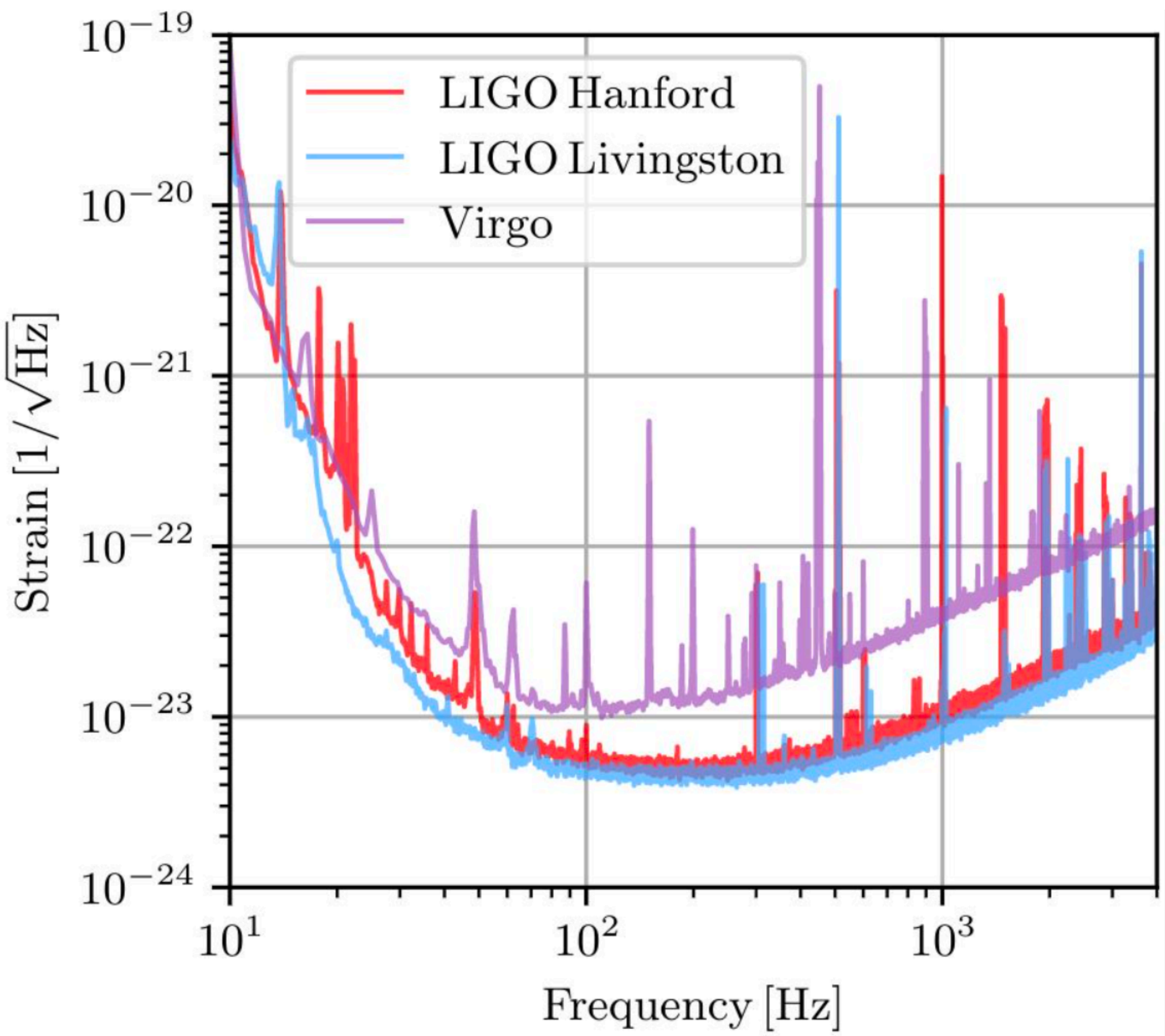
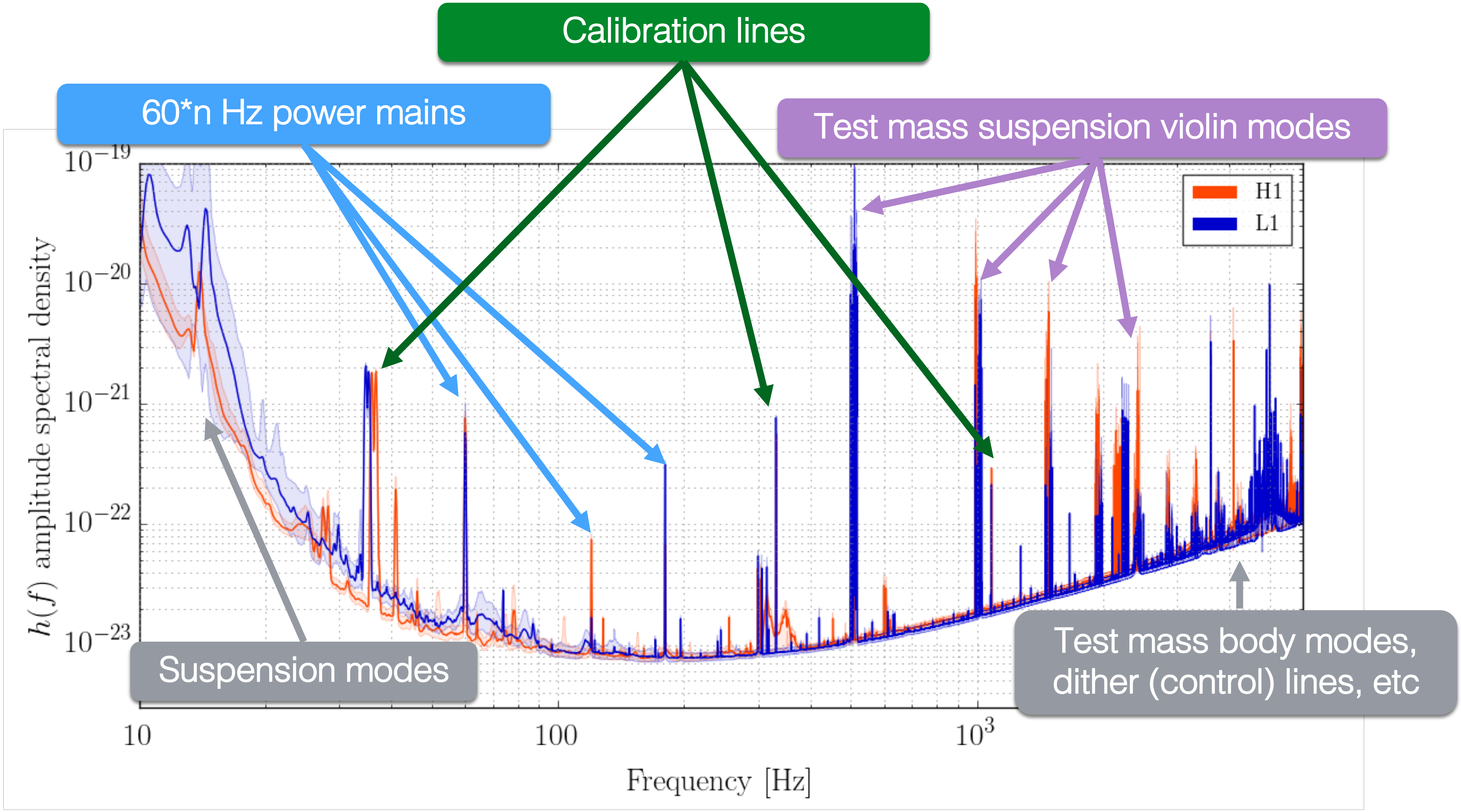


Image from Abbott et al (2020) GWTC-2 2010.14527

Calibrated Strain noise spectral lines



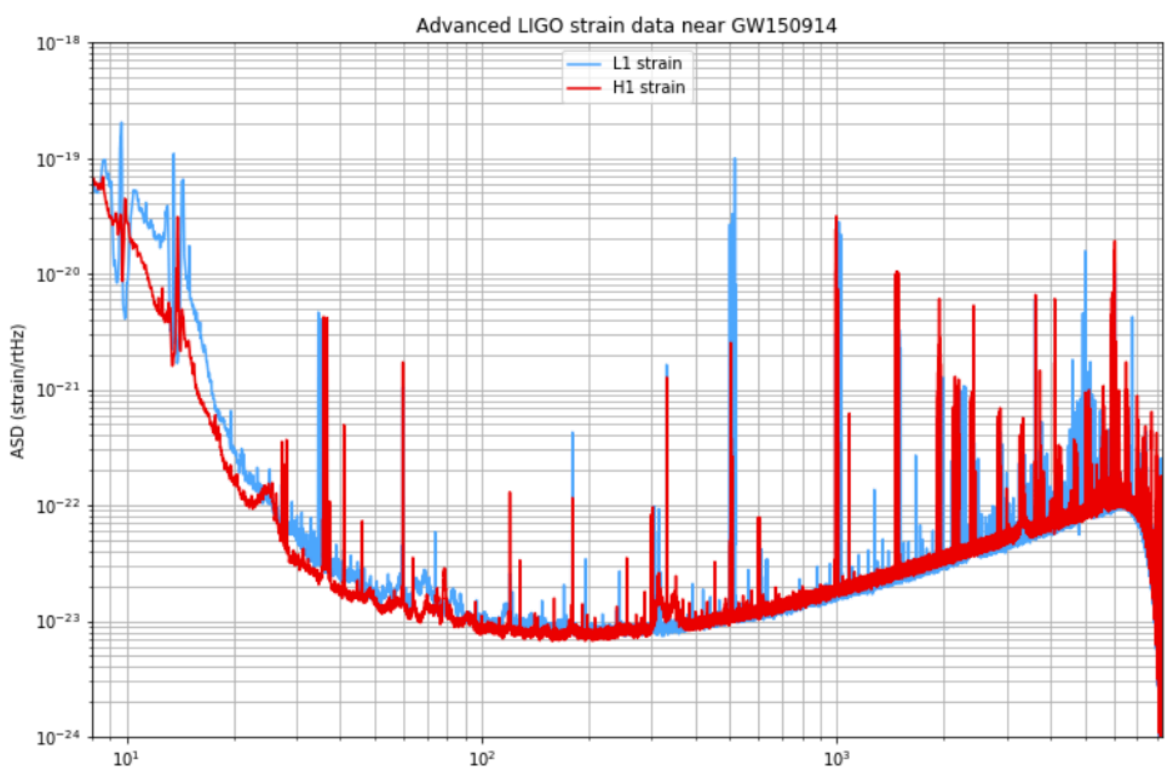
Source: https://losc.ligo.org/events/GW150914/

Spectral Lines - official info.

O1 Instrumental Lines

The plot below shows the amplitude spectral density (ASD) of the strain noise in the H1 and L1 Advanced LIGO detectors, during a "typical" time in the O1 run. The plot shows frequency [Hz] on the X-axis, and the ASD value [1 / sqrt(Hz)] on the y-axis. The first thing to note is that the data are not calibrated or valid below 10 Hz or above 5 kHz (and the data sampled at 4096 Hz are not valid above 2000 Hz).

The spectra reveal a large number of "lines" due to instrumental artifacts:



O1 : https://www.gw-openscience.org/o1speclines/

O2 : https://www.gw-openscience.org/o2speclines/

O3a : https://www.gw-openscience.org/O3/o3aspeclines/

Noise backgrounds

Non-stationarity

The detector sensitivity is not constant, this can happen rapidly or slowly

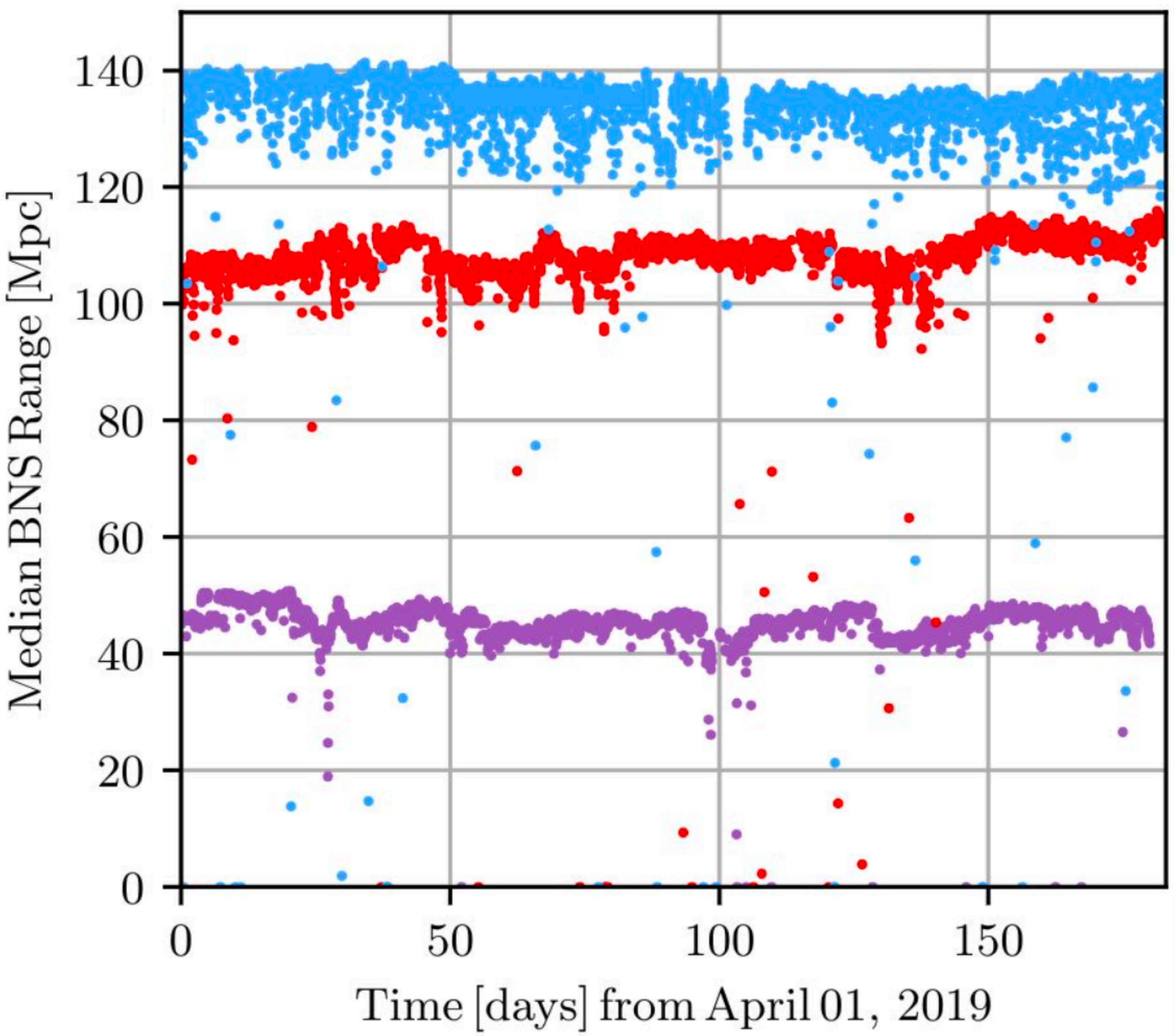
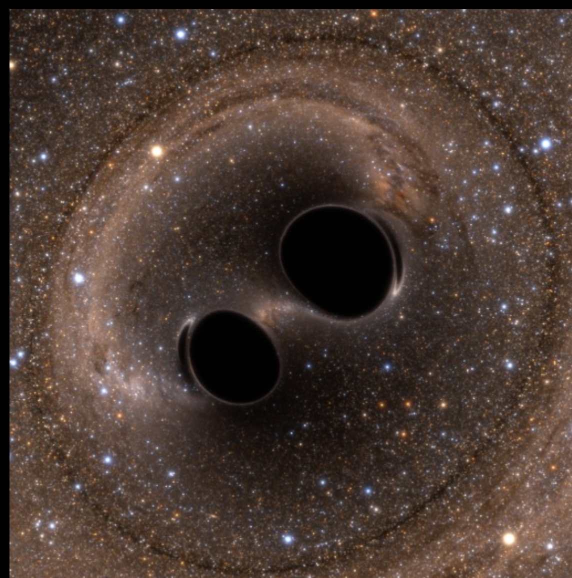


Image from Abbott et al (2020) GWTC-2 2010.14527

Astrophysical GW Sources

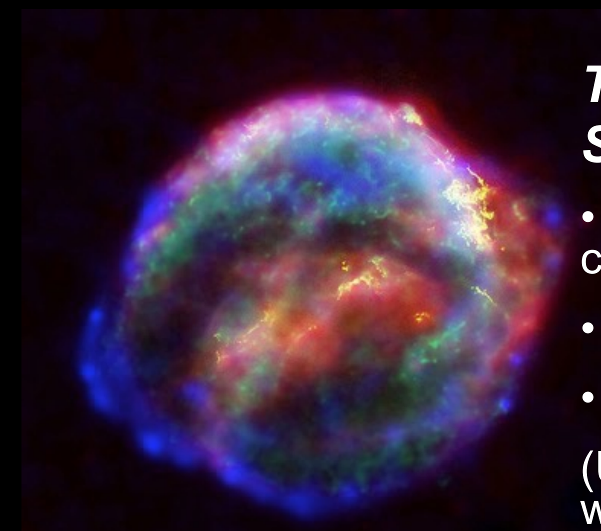


Credit: Bohn, Hébert, Throwe, SXS

Coalescing Binary Systems

- Black hole – black hole
- Black hole – neutron star
- Neutron star – neutron star

(modeled waveform)

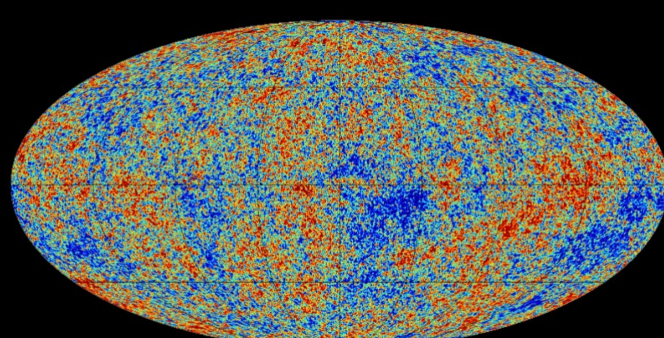


Credit: Chandra X-ray Observatory

Transient 'Burst' Sources

- asymmetric core collapse supernovae
- cosmic strings
- ???

(Unmodeled waveform)



Credit: Planck Collaboration

Stochastic Background

- residue of the Big Bang
- incoherent sum of unresolved 'point' sources

(stochastic, incoherent noise background)

Credit: Casey Reed, Penn State

Continuous Sources

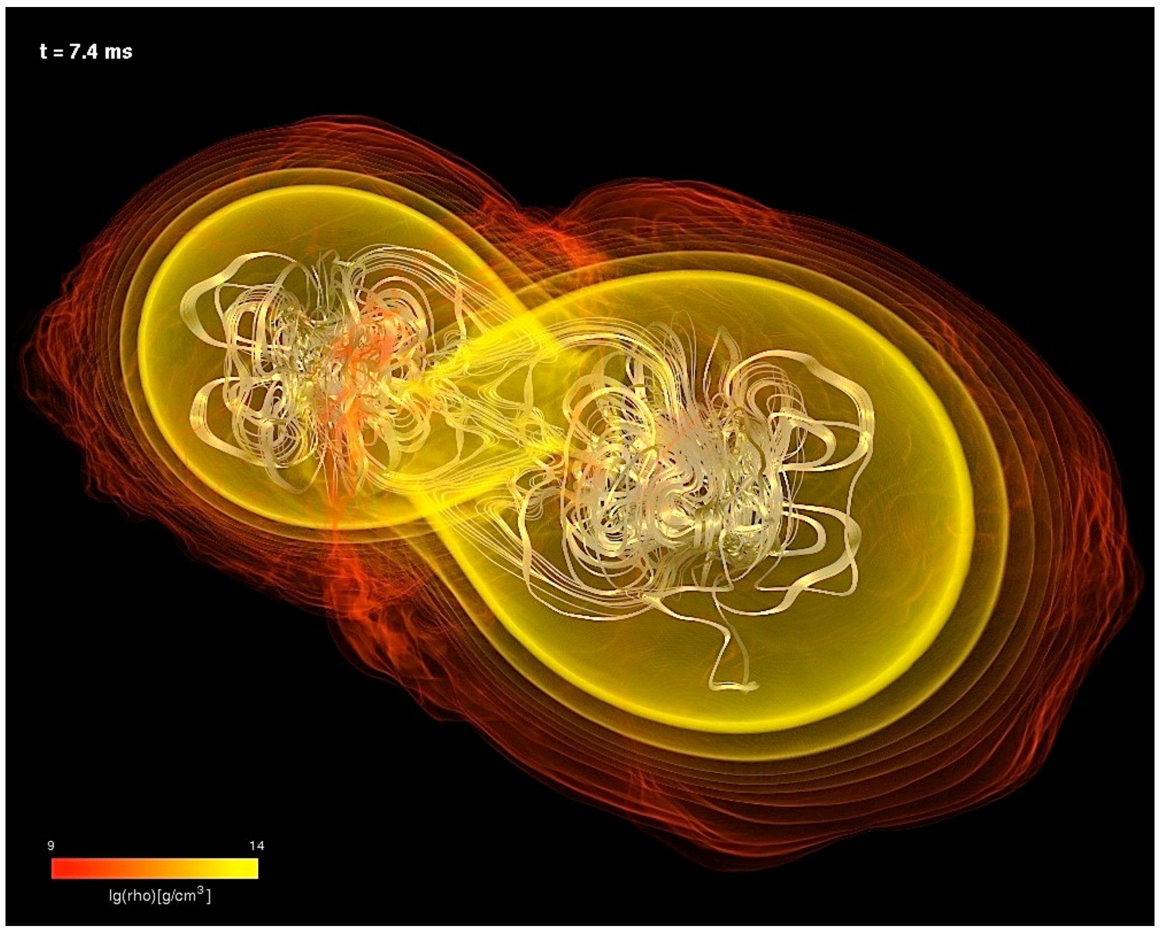
- Spinning neutron stars

(monotone waveform)

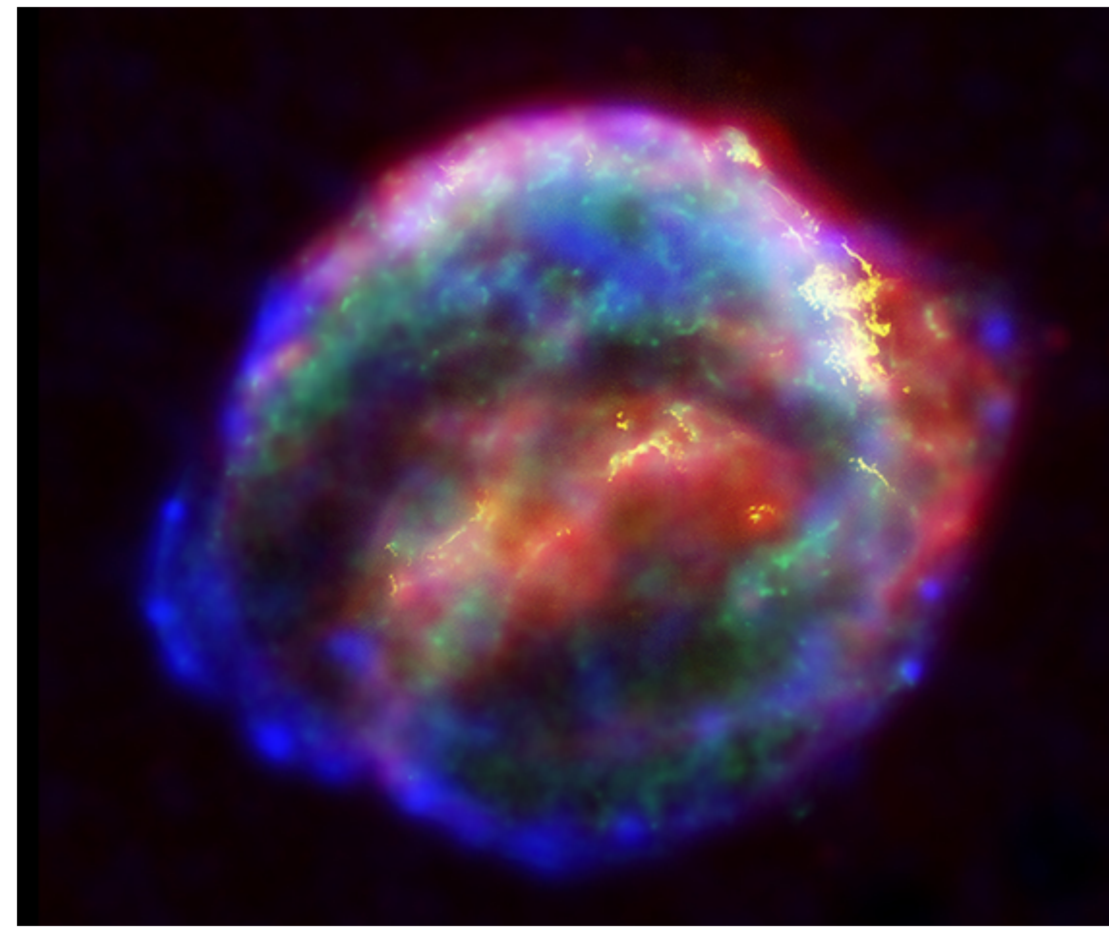
In D. Reitze's presentation in LIGO ODW #1, 2018

The Astrophysical Sources of GWs (1)

Transient sources



Credit: Albert Einstein Institute (AEI)



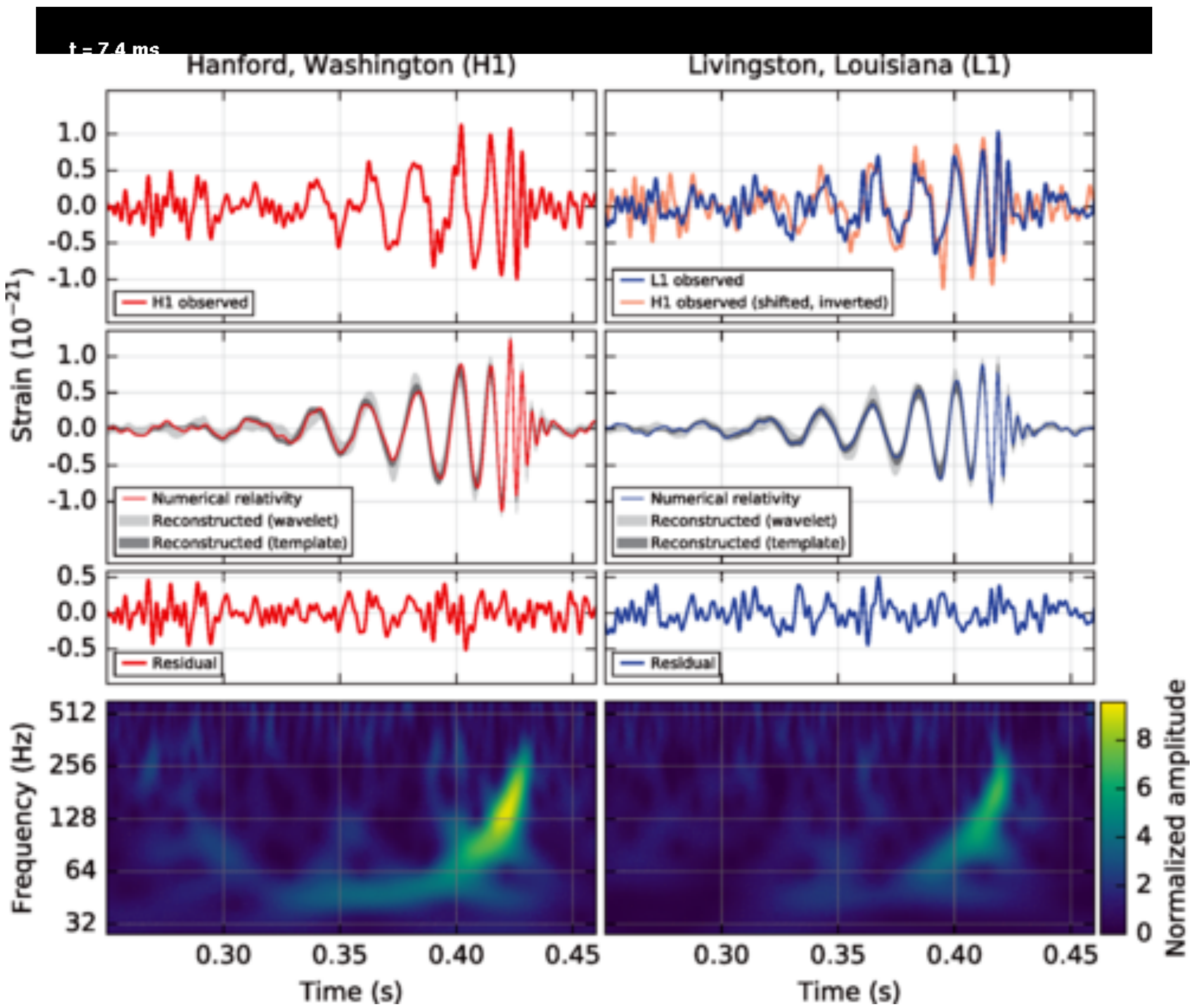
Credit: Chandra X-ray Observatory

Compact Binary Coalescence
(modeled waveform)

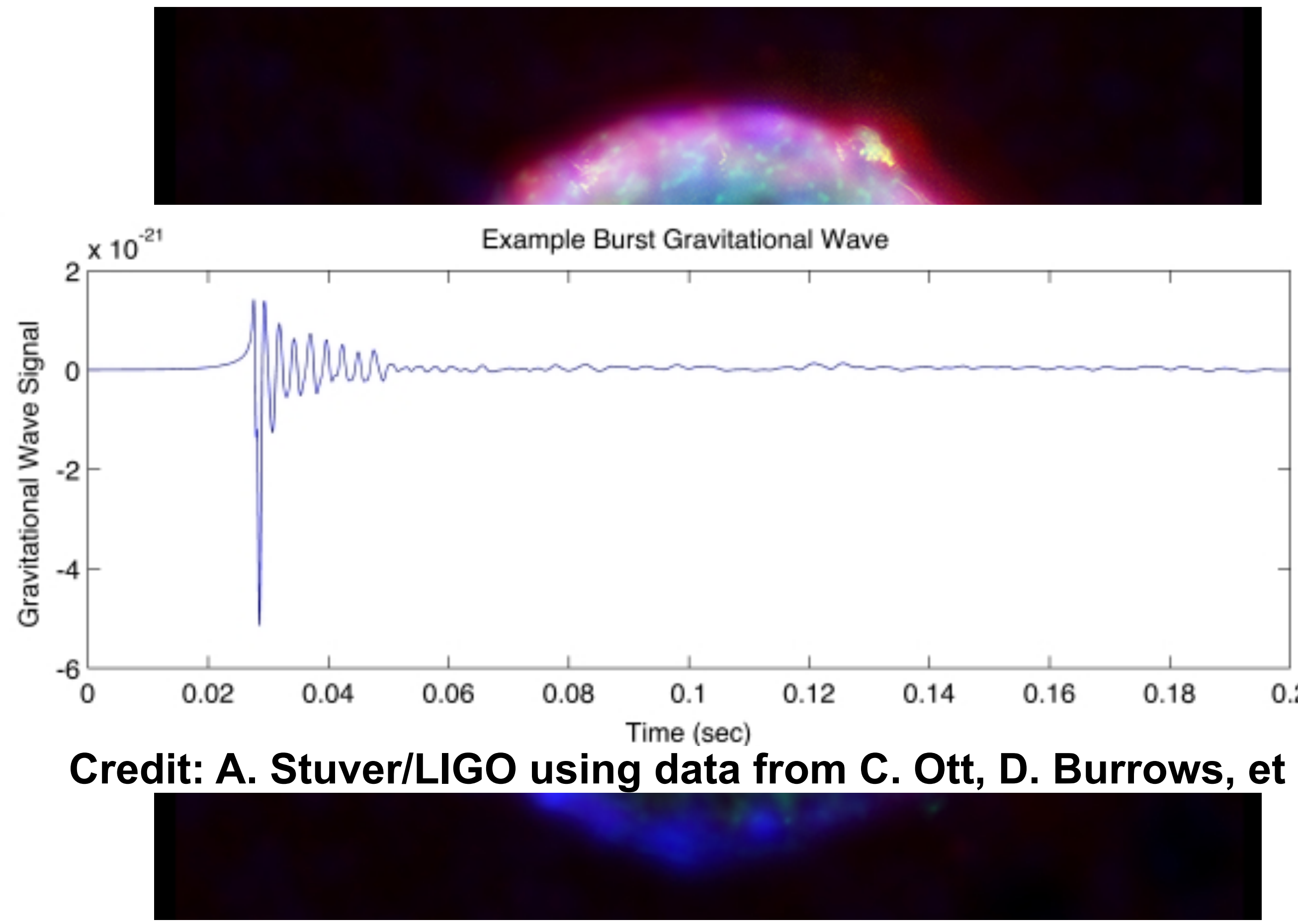
Burst sources
(un-modeled waveform)

The Astrophysical Sources of GWs (1)

Transient sources



PhysRevLett.116.061102



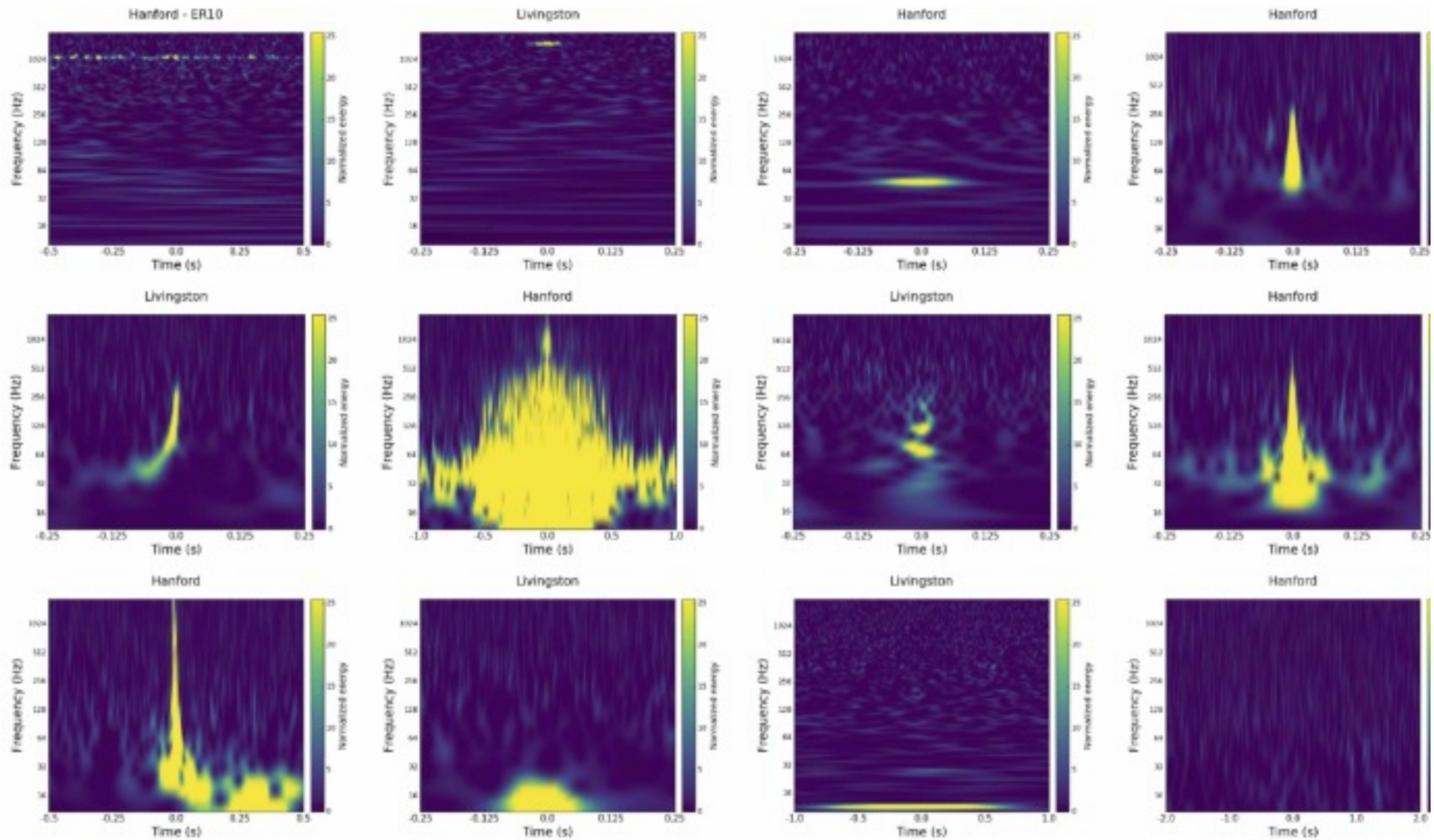
Credit: A. Stuver/LIGO using data from C. Ott, D. Burrows, et al

Credit: Chandra X-ray Observatory

Compact Binary Coalescence
(modeled waveform)

Burst sources
(un-modeled waveform)

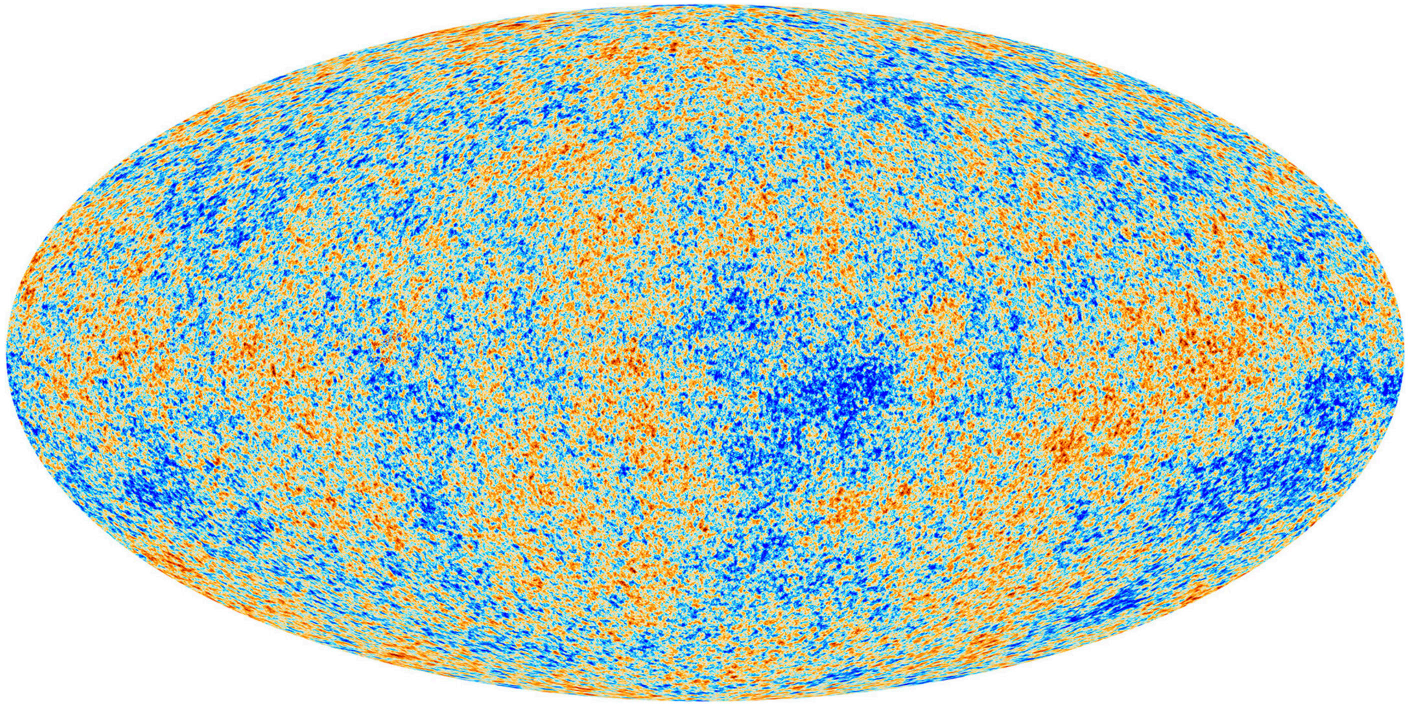
Non-Gaussian Transient Noises



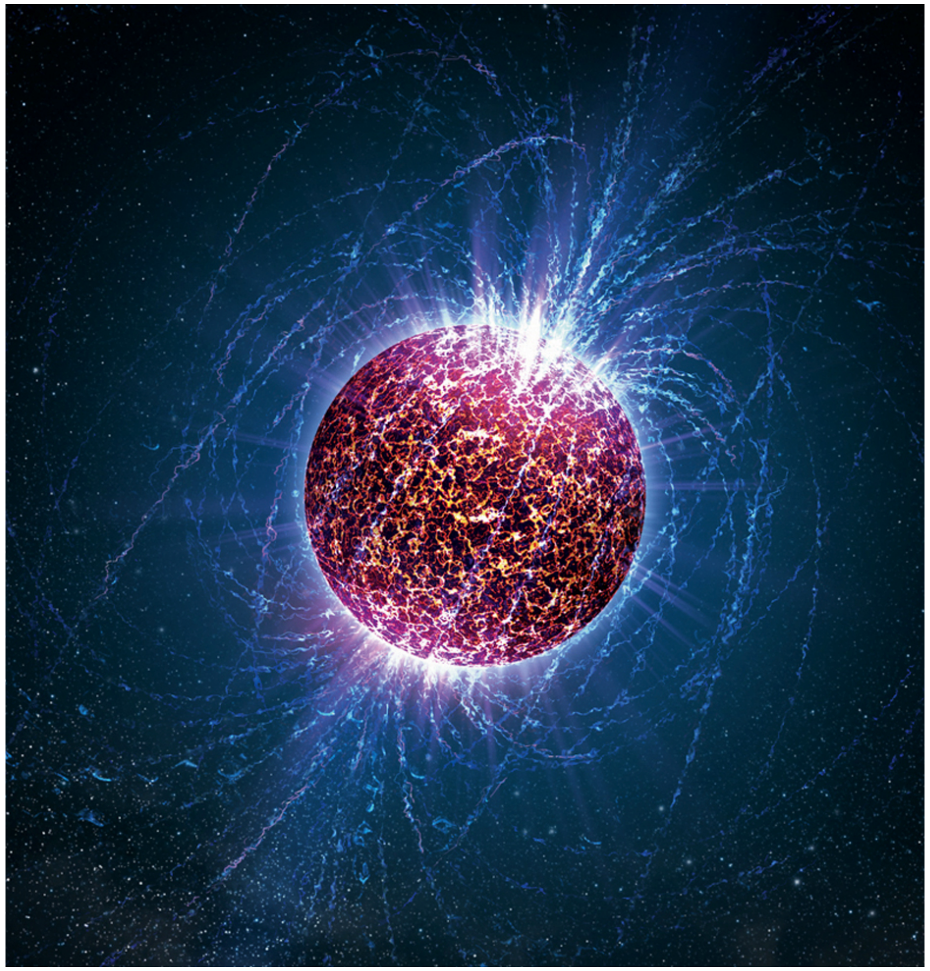
Bahaadini et al. (2018)

The Astrophysical Sources of GWs (2)

non-Transient sources



Credit: Plank Collaboration



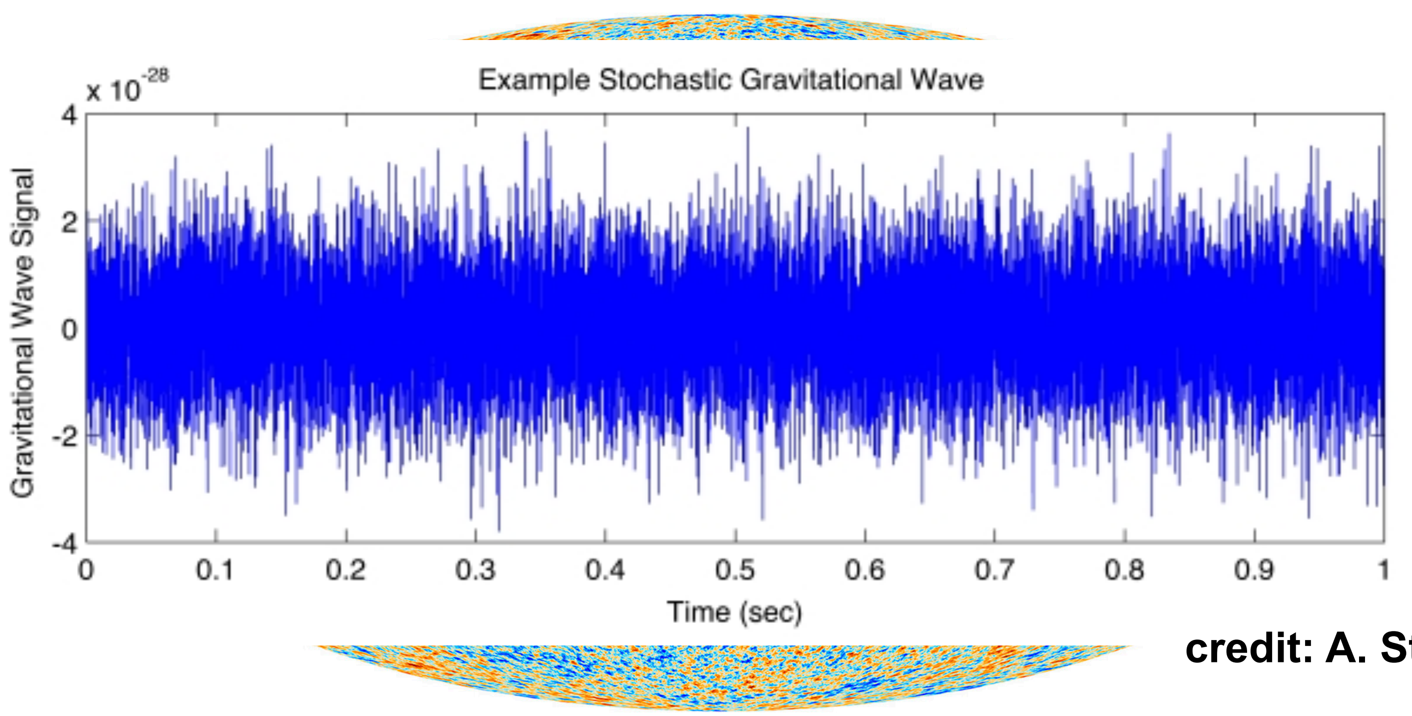
Credit: Casey Reed, Penn State

Stochastic Background

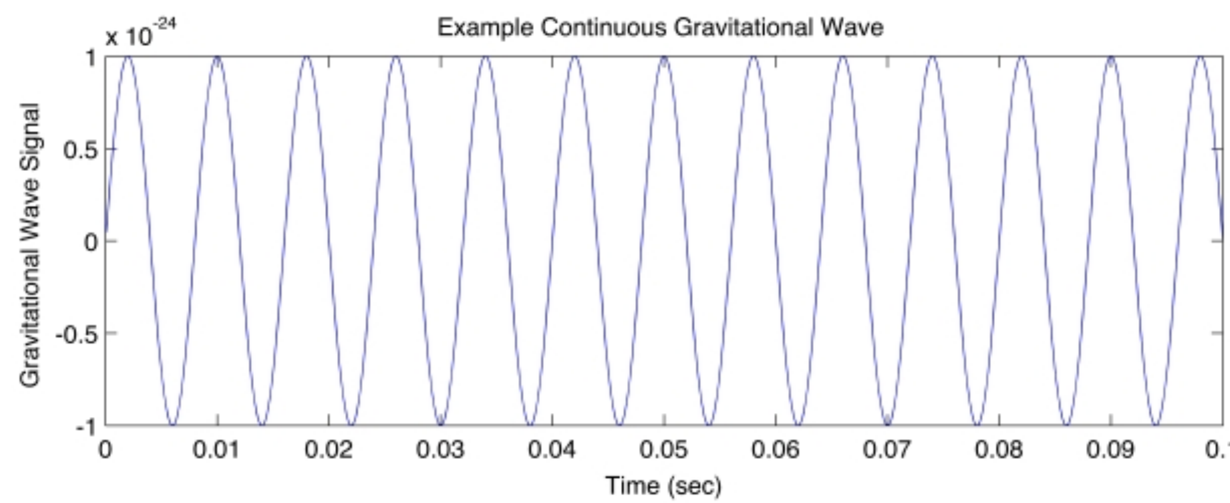
Continuous Sources

The Astrophysical Sources of GWs (2)

non-Transient sources



Credit: Plank Collaboration



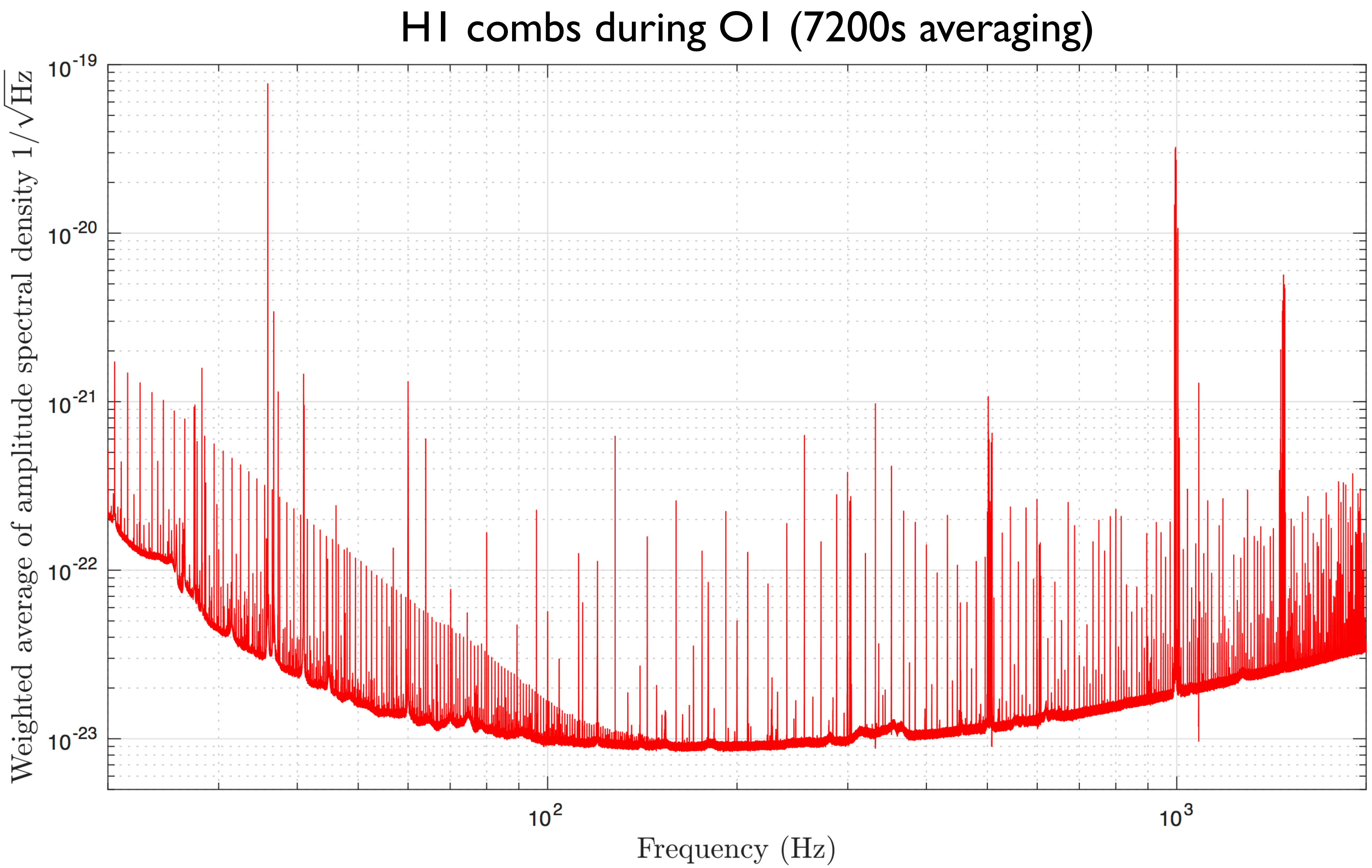
credit: A. Stuver/ LIGO

Credit: Casey Reed, Penn State

Stochastic Background

Continuous Sources

Spectral Lines and Combs



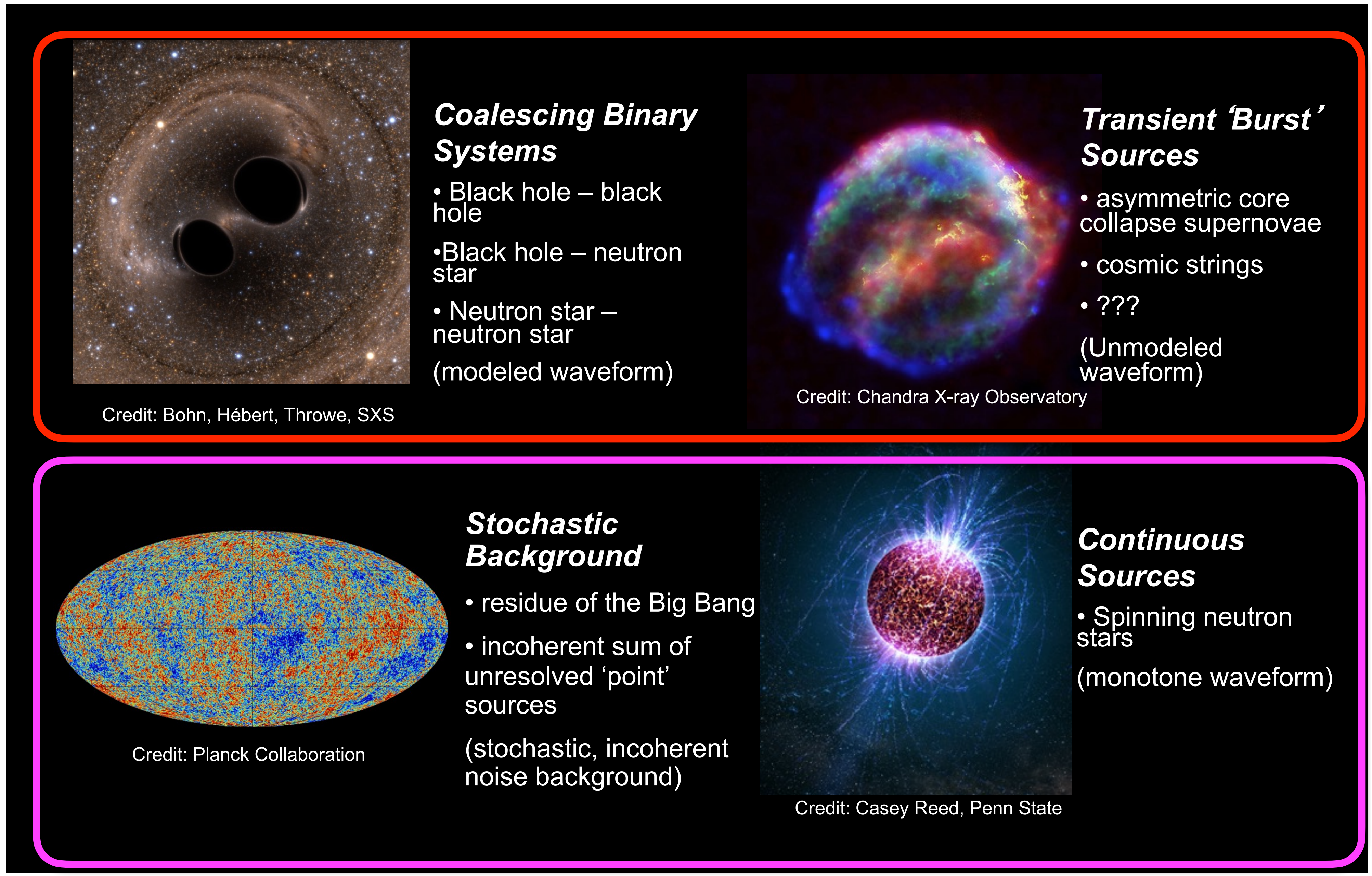
O1 and O2 noise lines paper: Covas et al. (2017) arxiv: 1801.07204

Instrumental Lines catalog: www.gw-openscience.org/o1speclines

Detection limitation by Noises

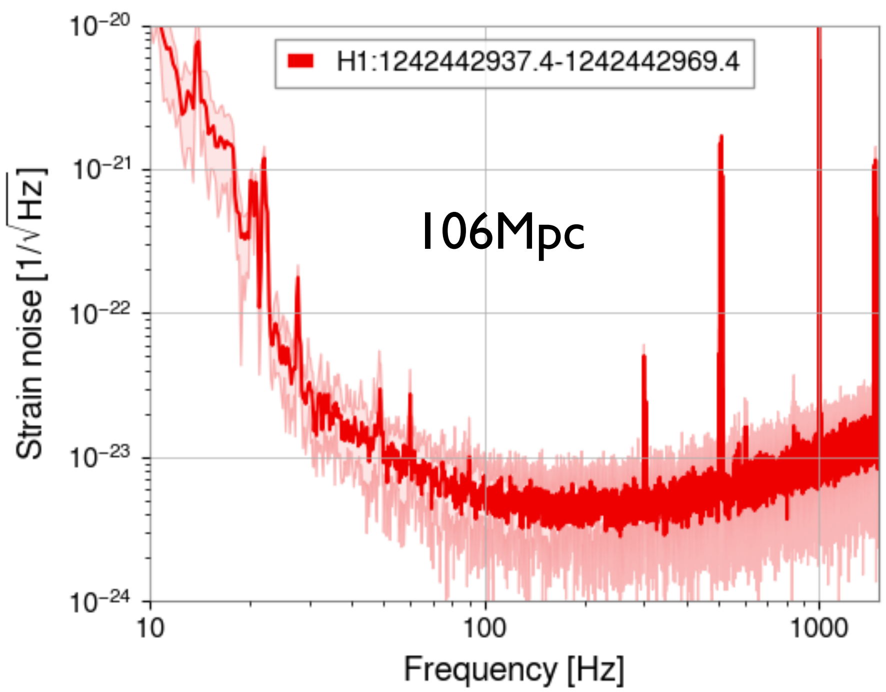
Non-Gaussian Transient Nosies : Glitches

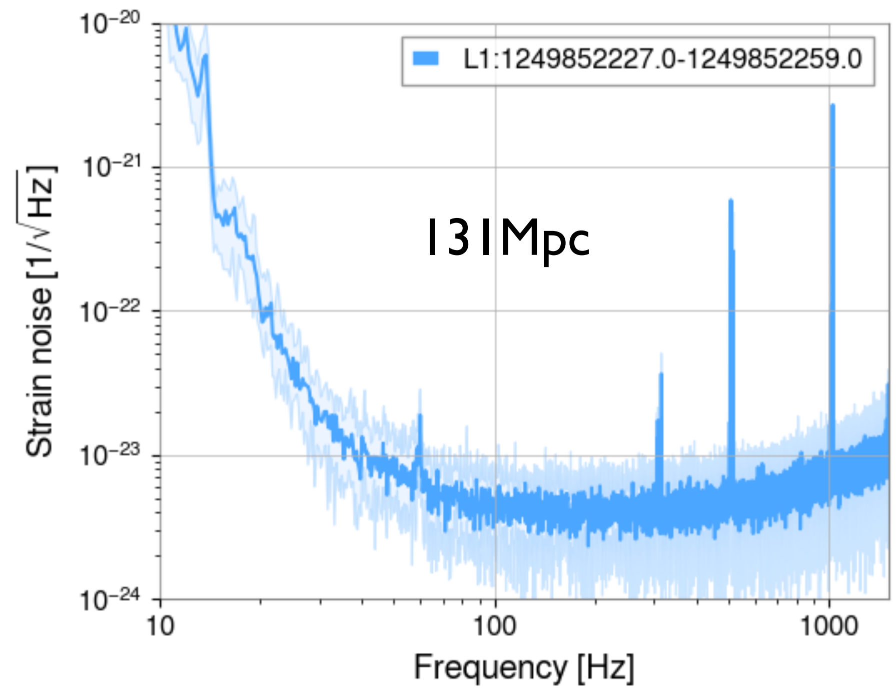
Spectral lines : electrical or mechanical resonances

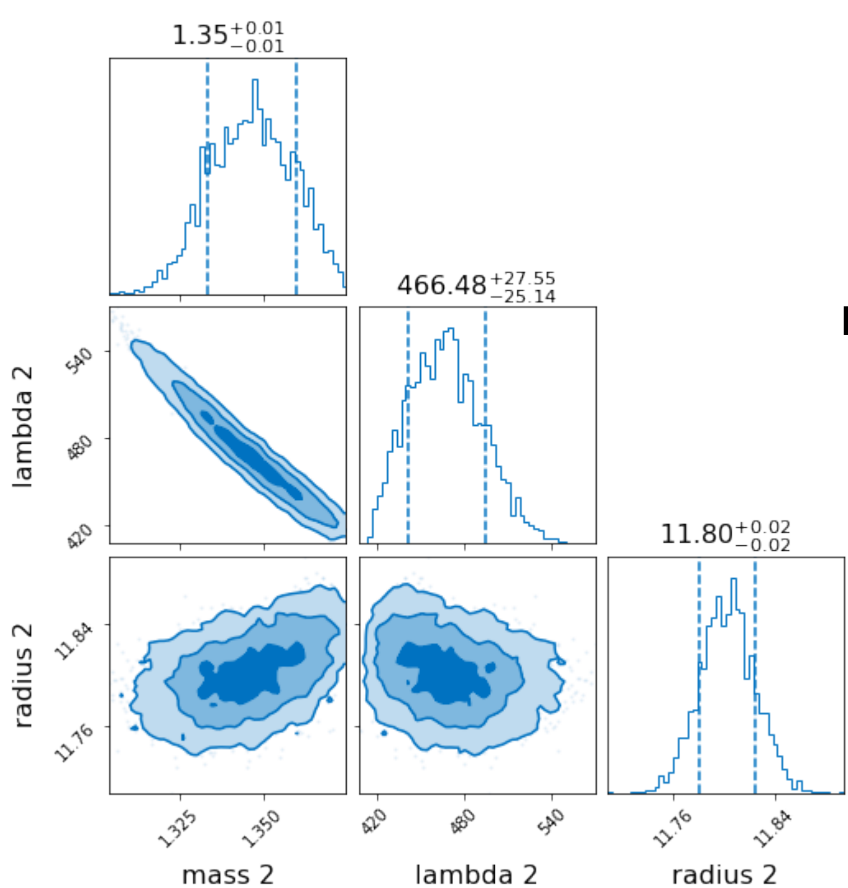


In D. Reitze's presentation in LIGO ODW #1, 2018

Posteriors depending on DET status





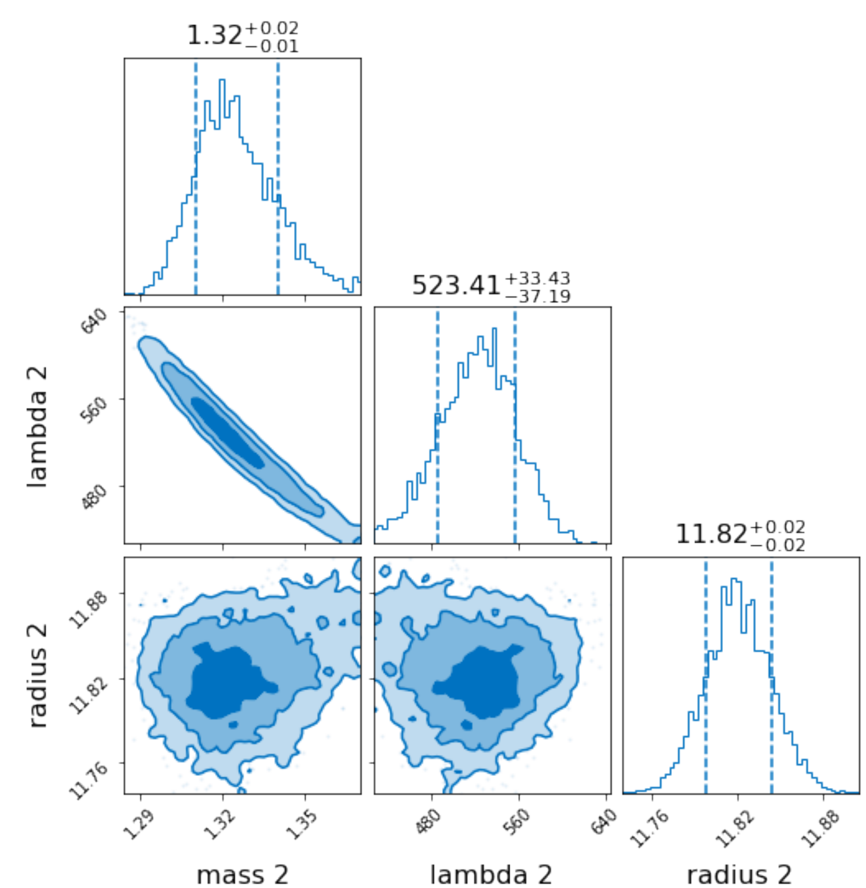


m1=1.4 Msun

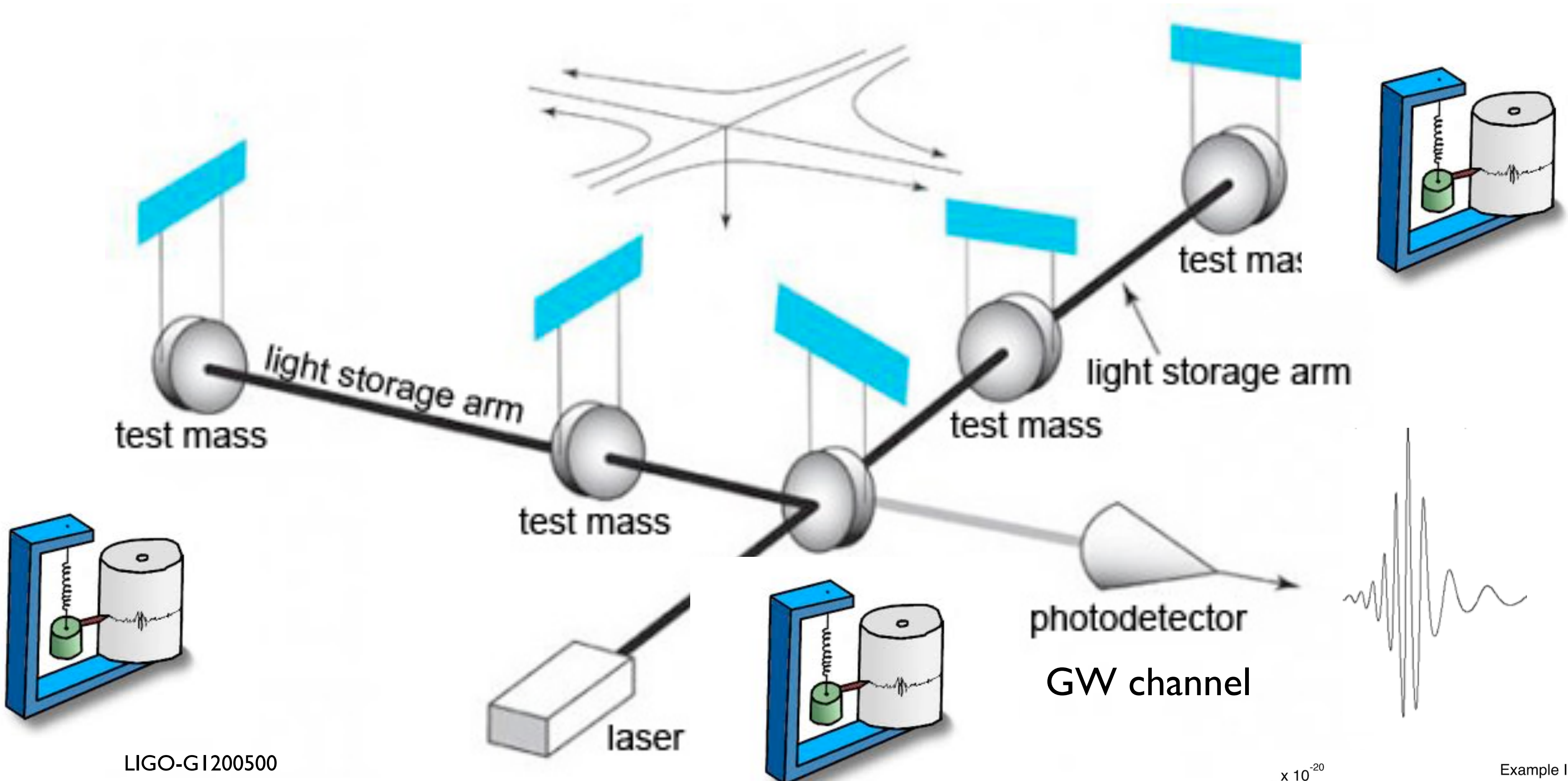
Λ1=400

m2=1.35 Msun

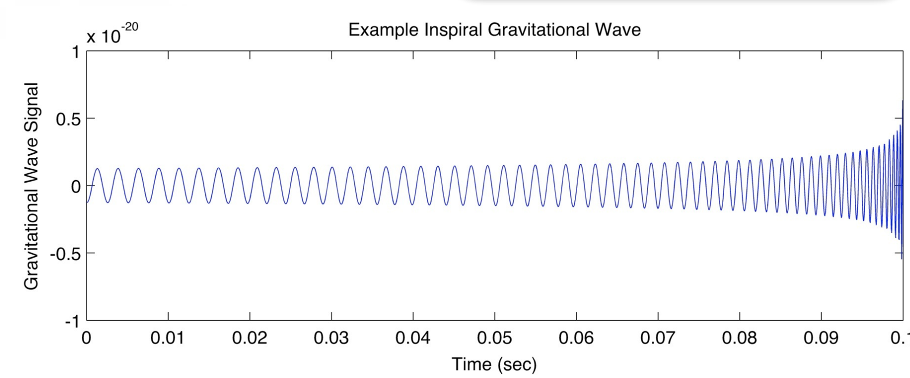
Λ2=450



Auxiliary Channels for DQ

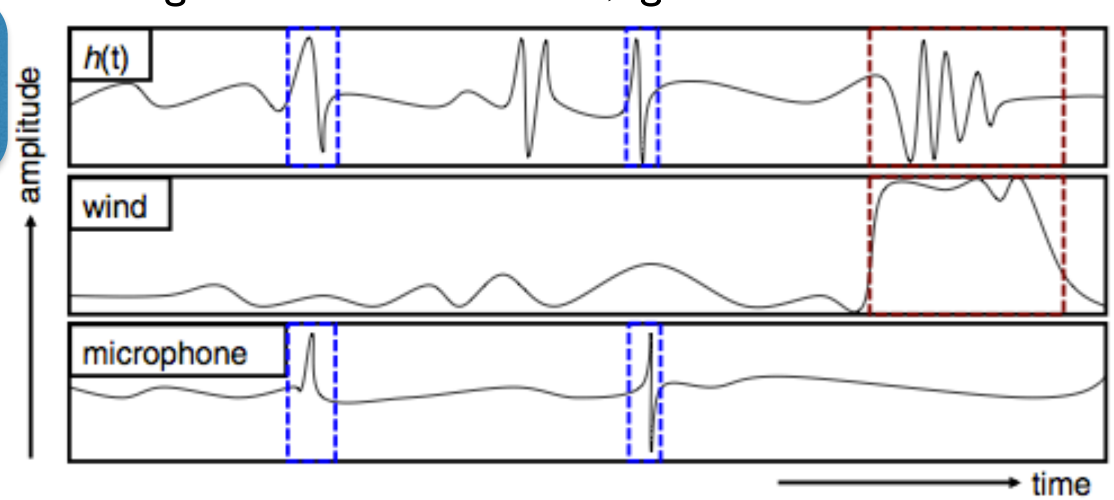


Signal Search

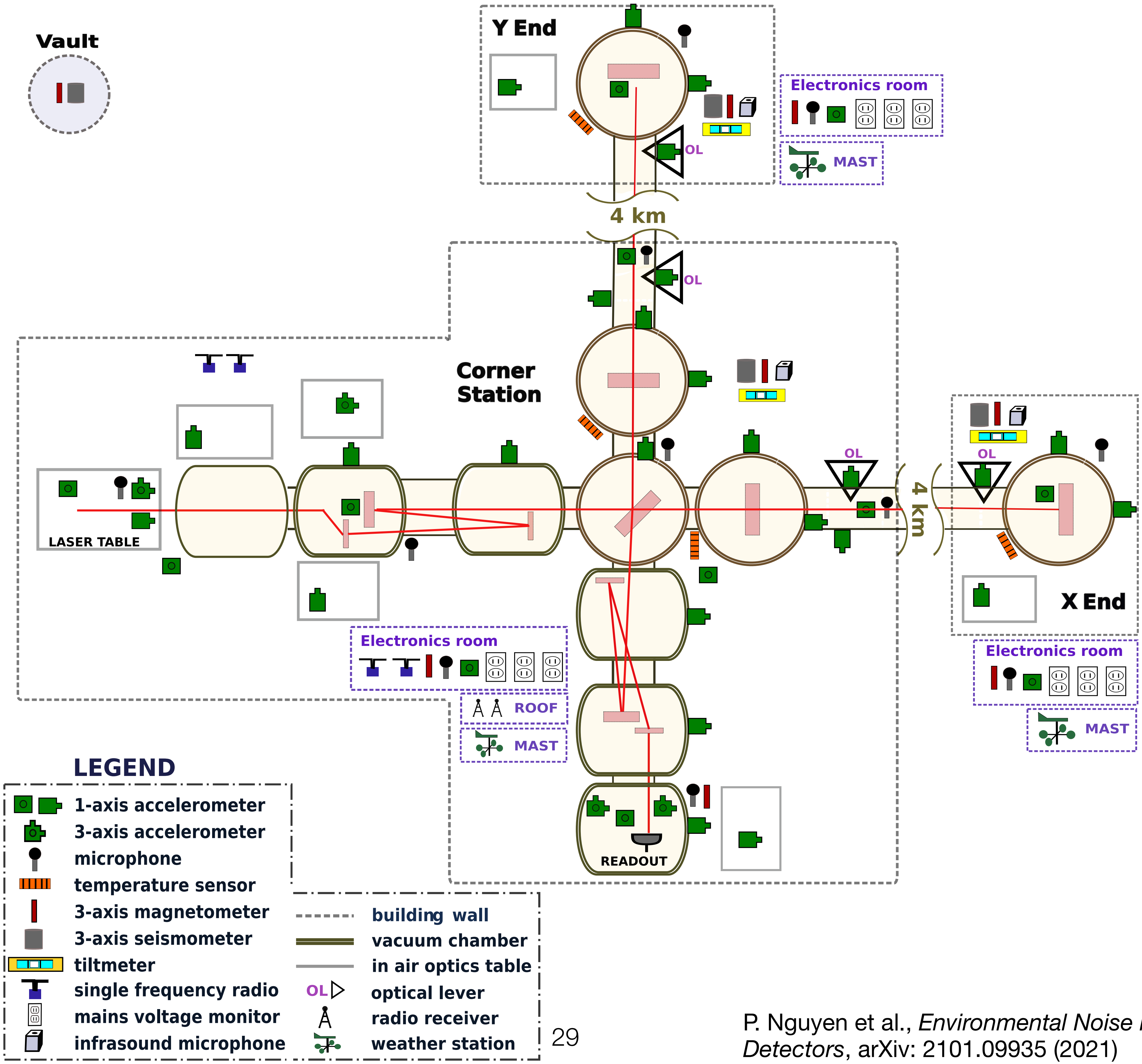


Detector Characterization

non-gaussian noise artifacts, "glitch"



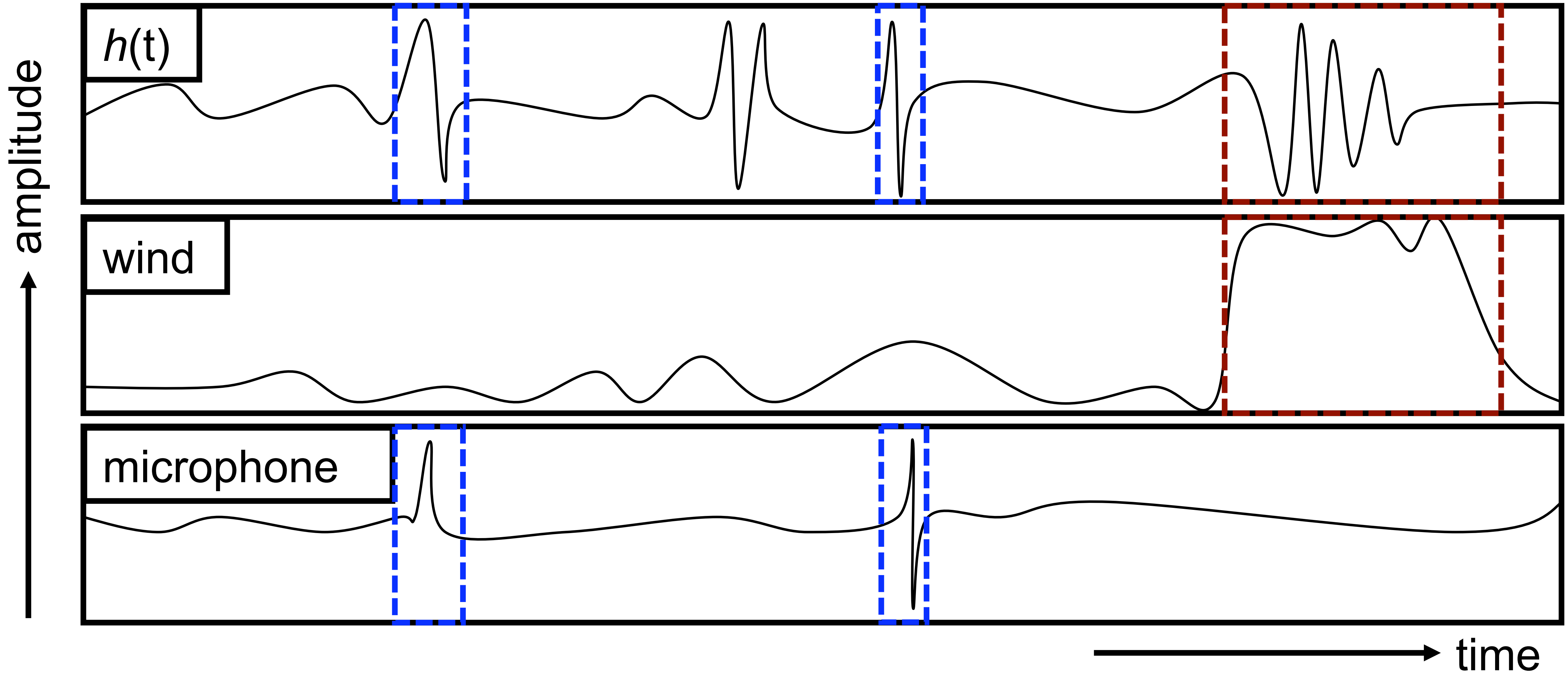
Physical Environment Channels



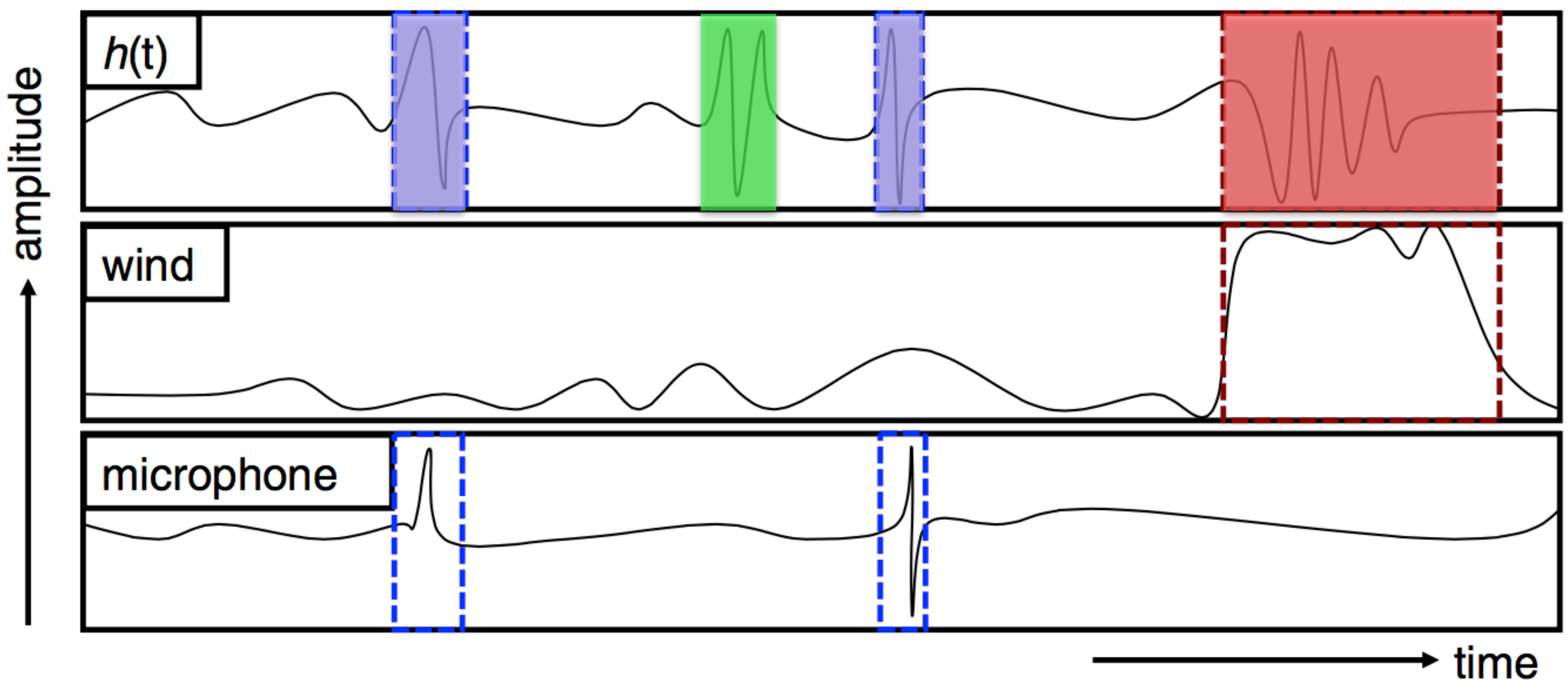
P. Nguyen et al., *Environmental Noise in Advanced LIGO Detectors*, arXiv: 2101.09935 (2021)

Correlations with Auxiliary channels

- We record over 200,000 channels per detector that monitor environment and detector behaviour
- We can use them to help track down and trace instrumental causes of glitches that pollute the searches.



Veto

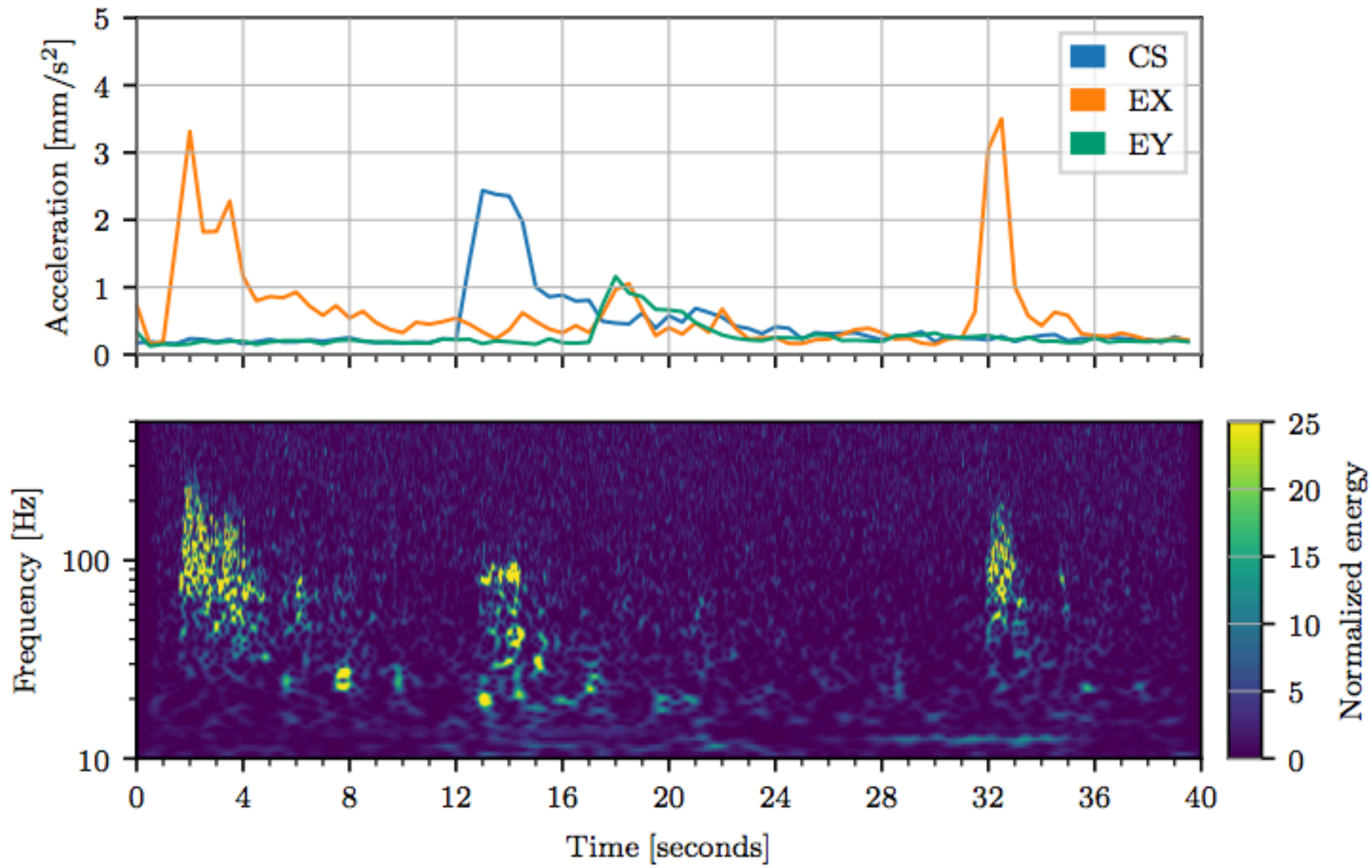


GW channel

Auxiliary channels

Data Quality Flags: exclude periods of data for known noises
Data Quality Triggers: short duration vetoes generated by algorithms that identify significant statistical correlation between a transient in h(t) and transient noise in auxiliary channels

Thunderstorms

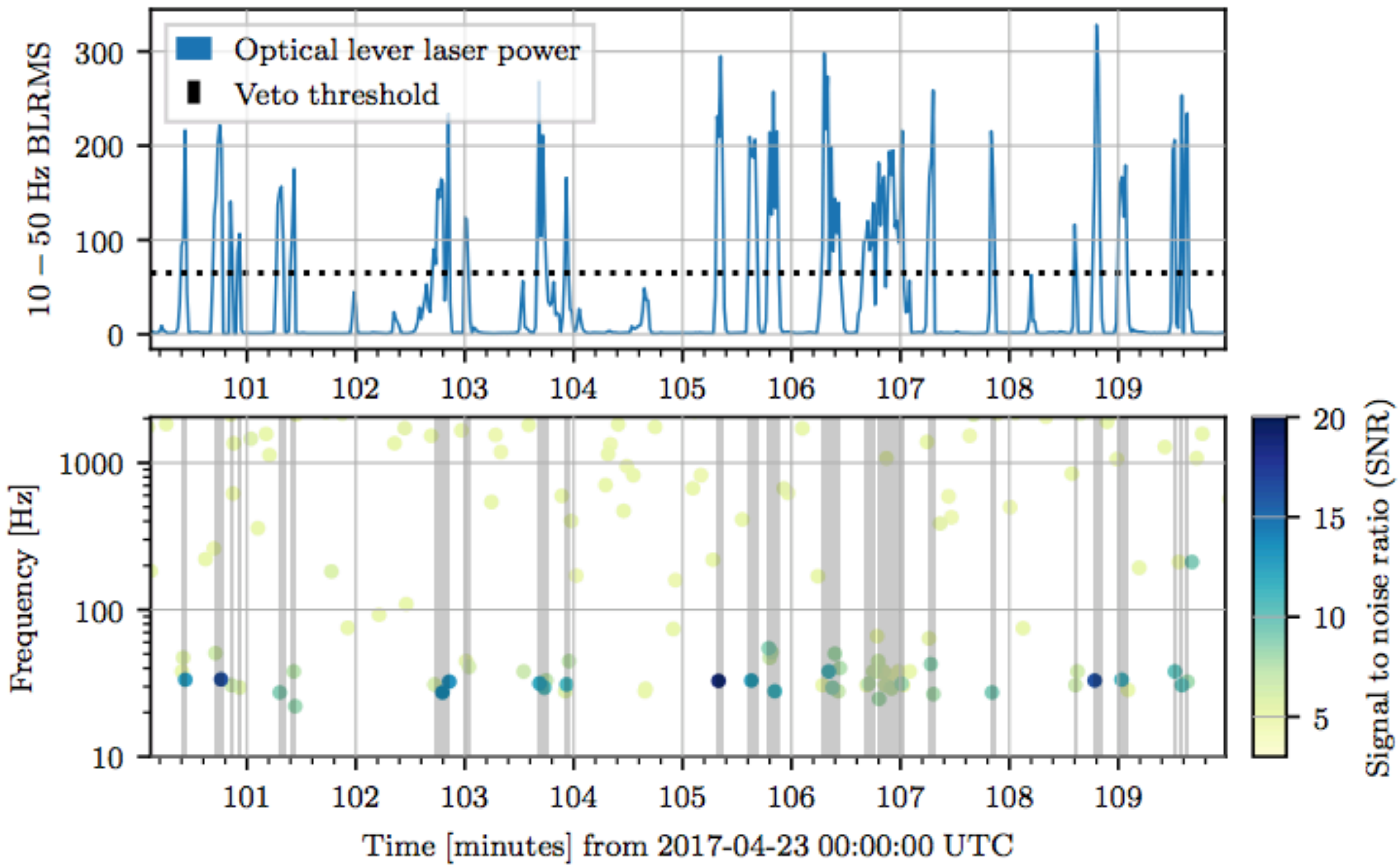


- Top: Data between 10-100 Hz from accelerometers located in the corner station (CS), End X station (EX) and End Y station (EY)

- Bottom: Spectrogram of the GW strain channel at the same time. Excess noise in the frequency range of 20 Hz to 200 Hz coincides with the thunderclaps, with intensity depending on the thunder's location.

D. Davis et al., *LIGO Detector Characterization in the Second and Third Observing Runs*, arXiv: 2101.11673 (2021)

Example of a data quality veto in O2



D. Davis et al., *LIGO Detector Characterization in the Second and Third Observing Runs*, arXiv: 2101.11673 (2021)

Gravitational Wave Open Science Center

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Auxiliary Channel Three Hour Release

Data Set

A large number of sensors are used to record the state of the LIGO instruments and their enviornment. This data release contains sensor data recorded in around 500 channels at each LIGO site. These data represent three hours of time centered on GW170814 (GPS 1186736512 — 1186747264). Strain data from the same period are available in the O2 Data Release.

500 ch.

~3hr

Download Data

The data are available as down-sampled HDF5 files [19 GB], or full sample rate GWF files [68 GB]:

HDF5 Data GWF Data

Data may also be accessed from a network data server (NDS2) using the NDS2 client or GWpy:

```
from gwpy.timeseries import TimeSeries
data = TimeSeries.fetch('L1:LSC-DARM_OUT_DQ', start=1186741850, end=1186741870, host='losc-nds.ligo.org')
```

See the NDS2 Example Code for details.

Example Software

Example software is available in an associated git repo. To work with GWF files, see the software page.

Channel Descriptions

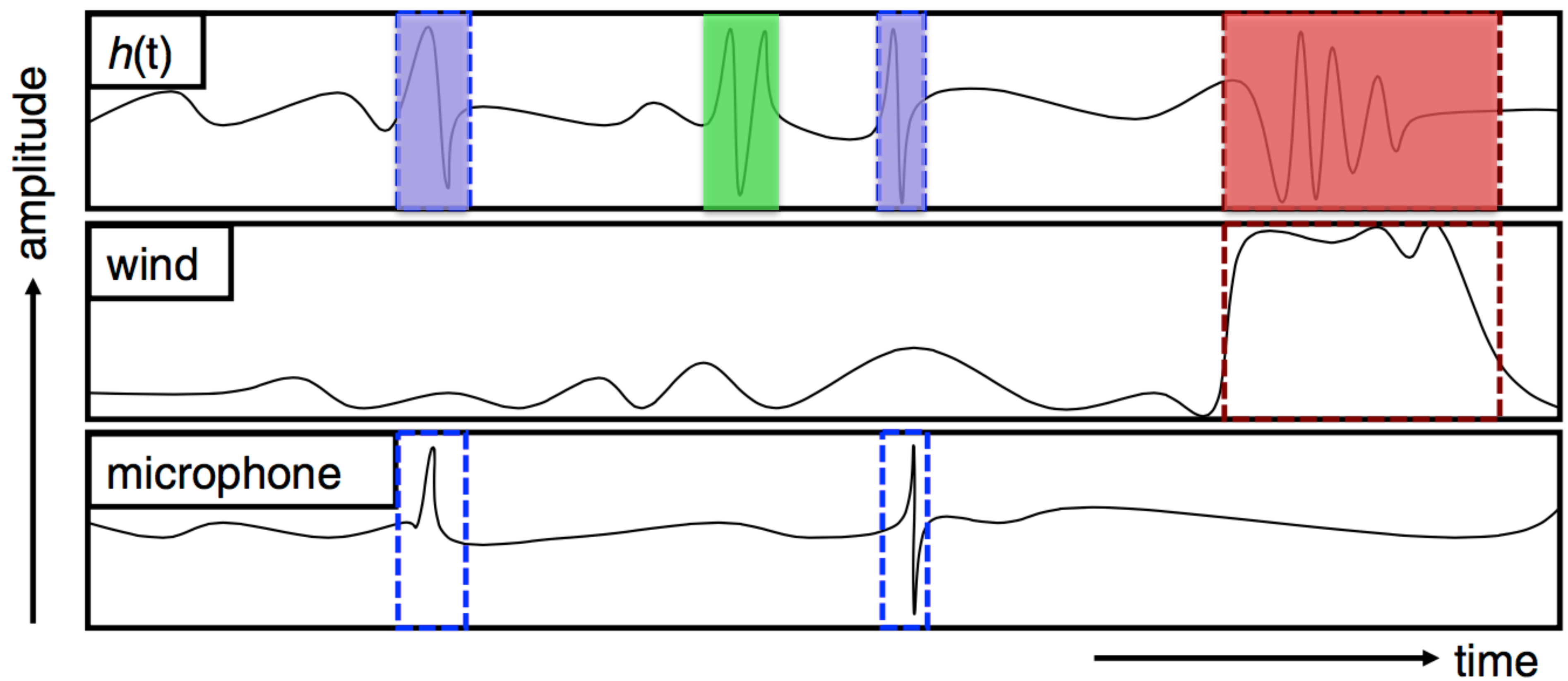
This data set is designed to be used for subtracting noise sources - especially controls noise - from LIGO data. Channels included in this set are those most likley to include a coupling to the gravitational wave strain channel, and so are possible sources of noise.

The Channel List shows each channel with a few properties:

- Channel name
- Desired sample rate: The sampling rate in the down-sampled, HDF5 data
- Notes: A brief note explaining the meaning of the data in the channel
- Calibration: Where available, a calibration factor is included. Most channels are not calibrated.
- Units: Where available, the units corresponding to the calibration factor

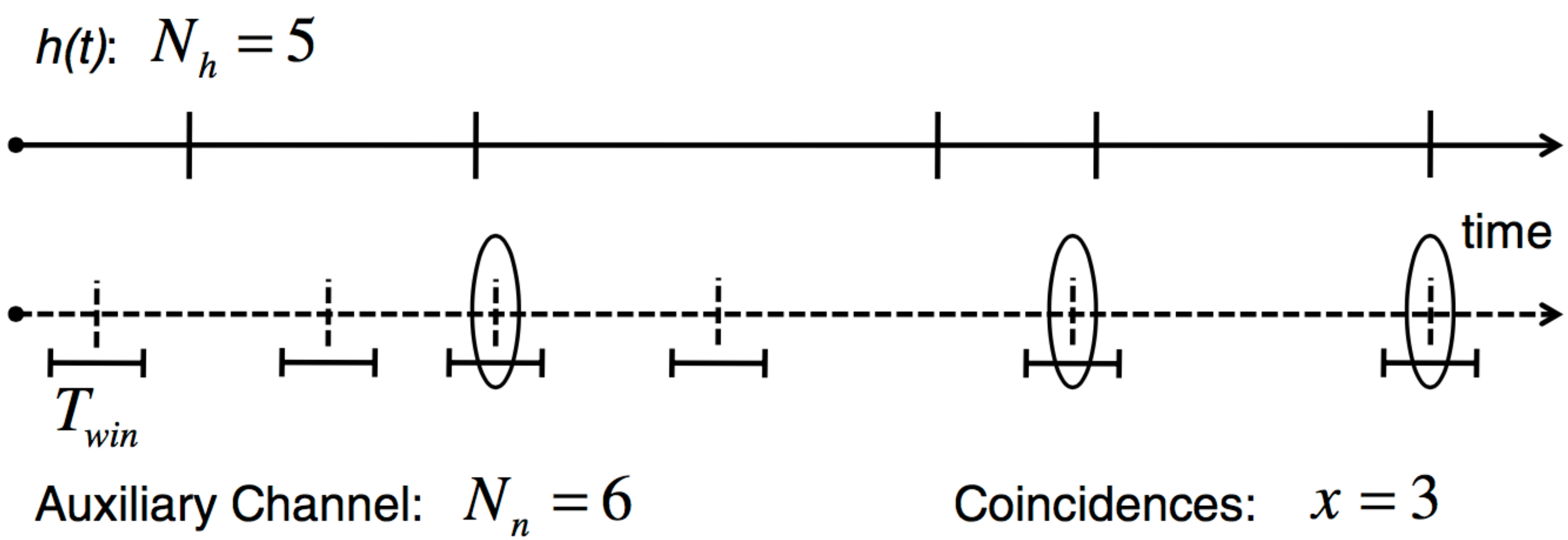
In some cases, data for a given channel may not be available. These are marked "invalid" in the HDF5 files, and the corresponding channel may be absent from the GWF files. Unavailable channels may correspond to sensors that are not present at a particular site or not operational at a particular time.

Veto



Data Quality Flags: exclude periods of data for known noises
Data Quality Triggers: short duration vetoes generated by algorithms that identify significant statistical correlation between a transient in h(t) and transient noise in auxiliary channels

Counting Experiment



Poisson Statistics

Poisson statistics

- Poisson distribution expresses probability of a number of independent events occurring in a given time period
- apply to coincidence
- Definitions
  - N_{de} = **number** of triggers in DARM ERR channel
  - N_n = number of triggers in auxilliary channel n
  - T_{win} = full time window centered on auxilliary channel trigger
  - T_{tot} = total live-time analyzed
- From these calculate mean number of expected coincidences

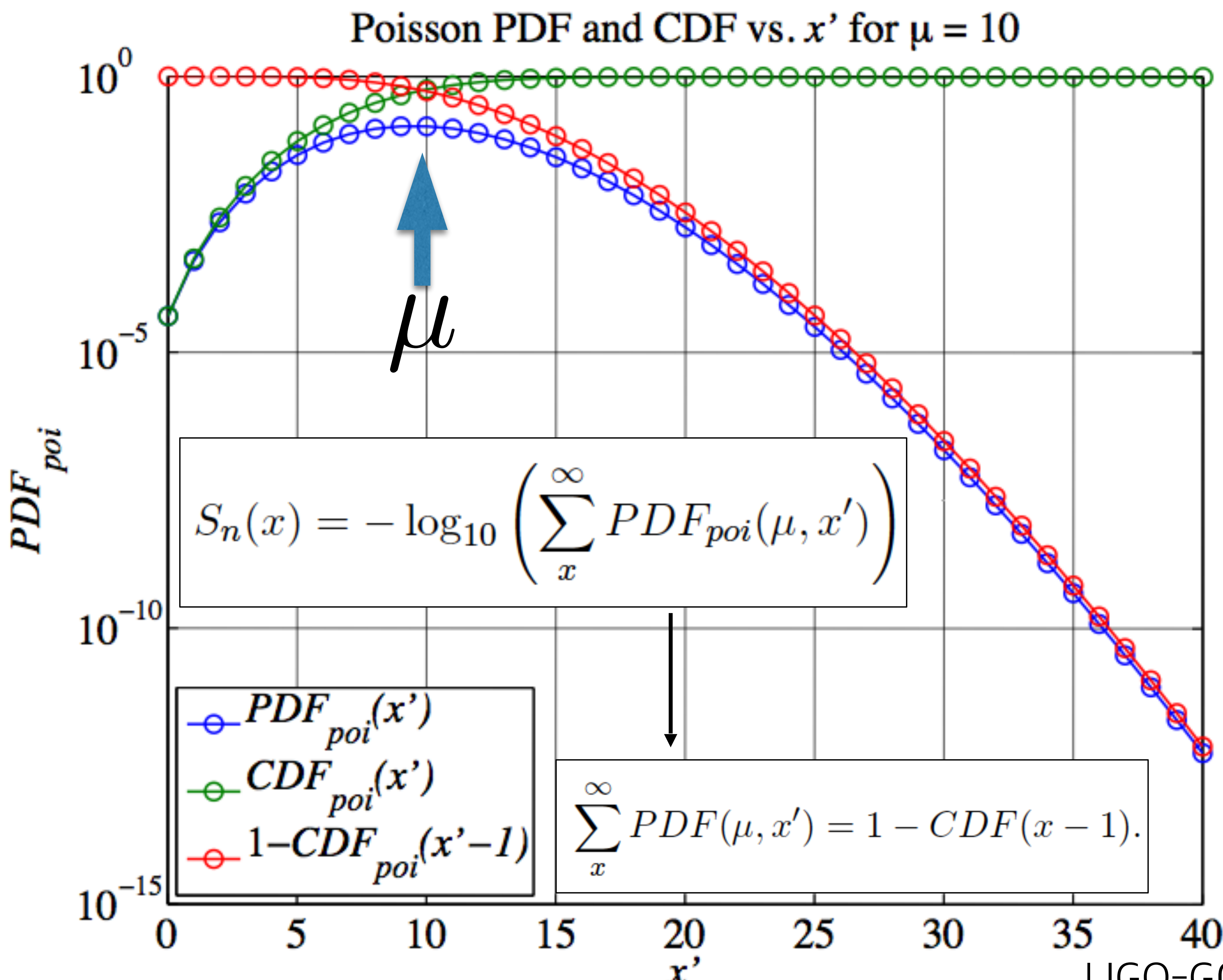
Probability Density Function

$$PDF_{poi}(\mu, x') = \frac{\mu^{x'} e^{-\mu}}{x'!},$$

Mean number of coincidence

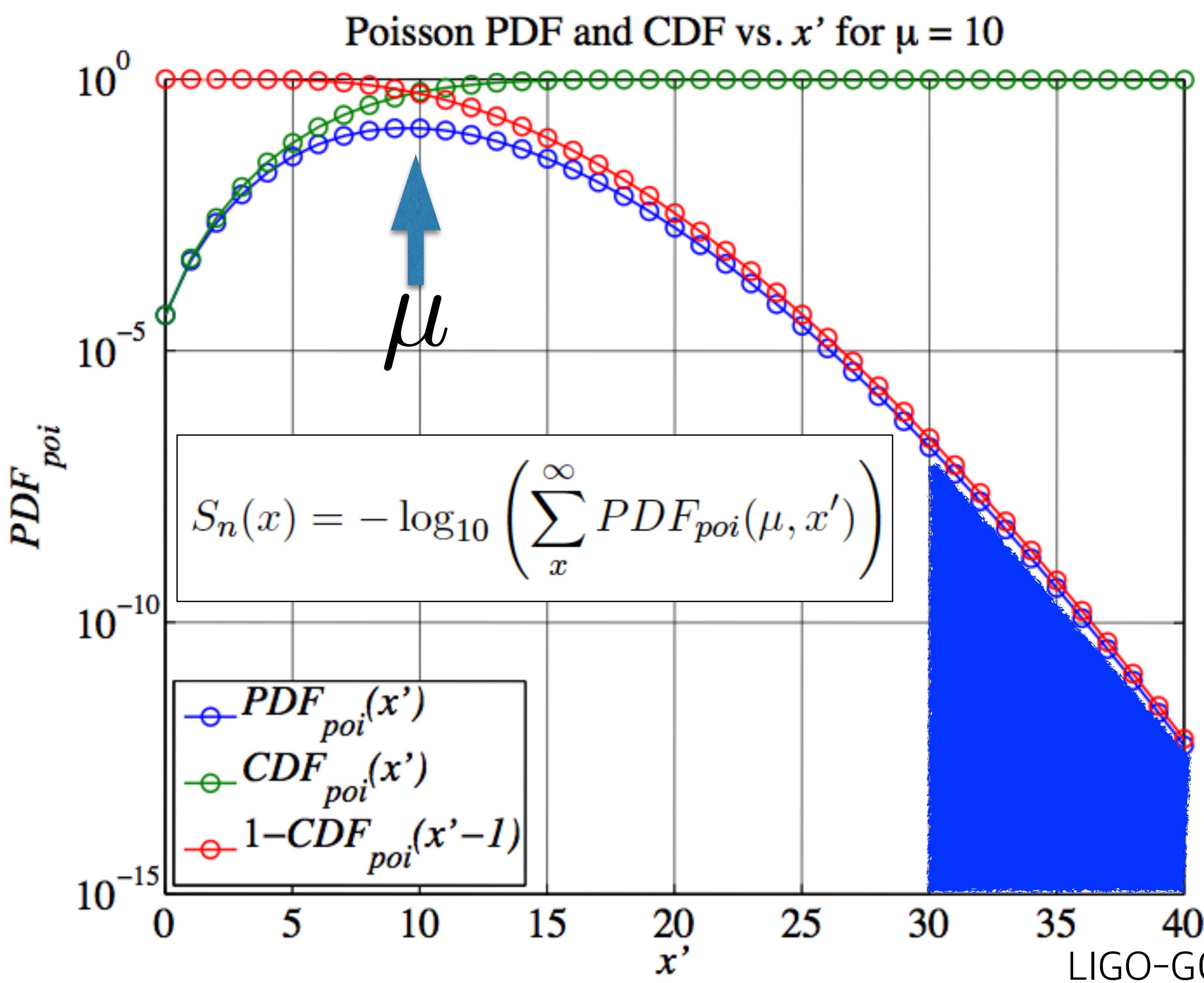
$$\mu = \frac{N_{de} N_n T_{win}}{T_{tot}}$$

Statistical Significance



LIGO-G0900878

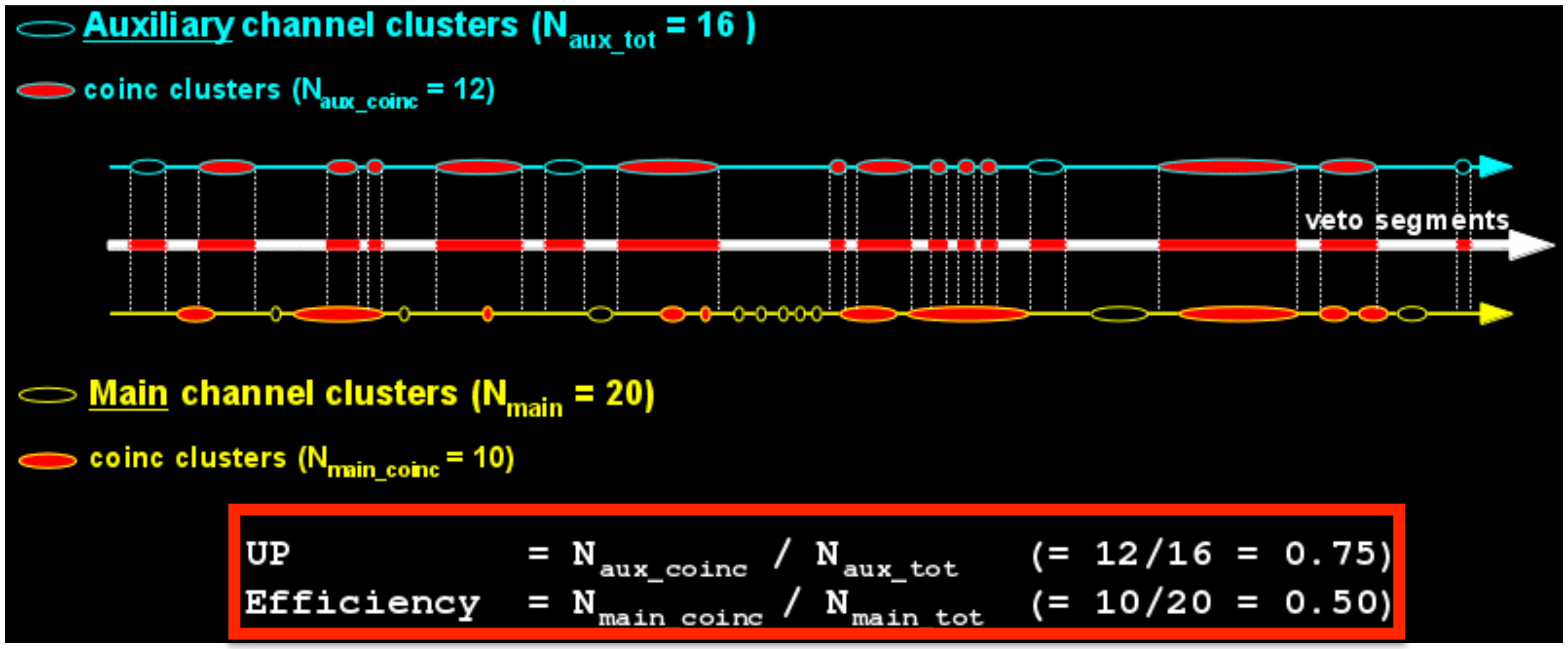
Statistical Significance



LIGO-G0900878

Veto Algorithms (1)

1. Use-Percentage Veto (UPV)



Journal of Physics: Conference Series 243, 012005 (2010); 14th GWDAW

2. Hierarchical Veto (Hveto)

$$S = -\log_{10}\Sigma_{k=n}^{\infty}[\frac{\mu^k e^{-\mu}}{k!}])$$

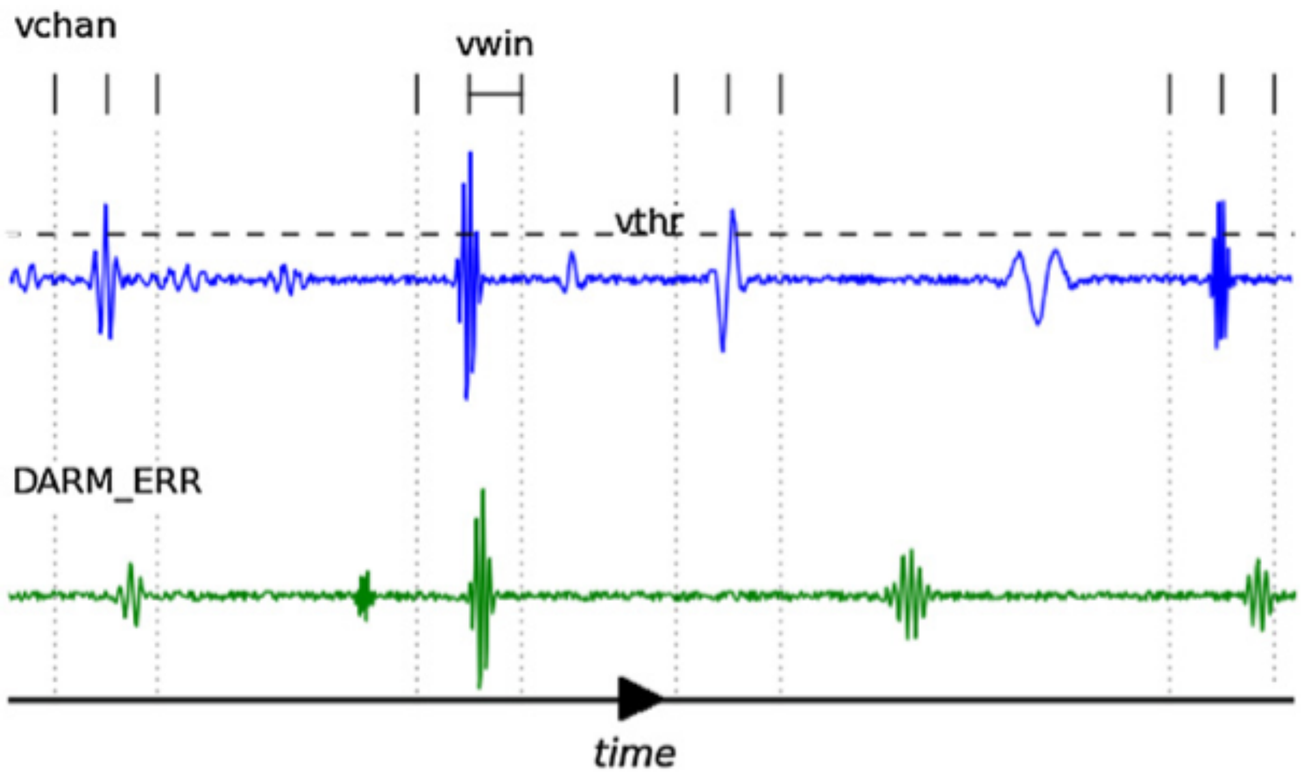
n : the number of coincidences
T_win : full width of coincidence time window
T_tot : a given total analysis time

$$\mu = \frac{N_{main\_tot} N_{aux\_tot} T_{win}}{T_{tot}}$$

Class. Quantum. Gav. 28, 235005 (2011)

Veto Algorithms (2)

Ordered-Veto List (OVL) - used in iDQ



veto efficiency

$$e = n_c / N_{GW}$$

fractional dead time

$$f = t/T$$

$$e/f = \frac{n_c}{t(N_{GW}/T)} \sim \frac{n_c}{t\lambda_{GW}}$$

$$t\lambda_{GW} \sim < n_c >$$

$$p = \sum_{k=n_c}^{\infty} \frac{\langle n_c \rangle^k}{k!} \mathrm{e}^{-\langle n_c \rangle} = \sum_{k=n_c}^{\infty} \frac{(n_c(f/\varepsilon))^k}{k!} \mathrm{e}^{-n_c(f/\varepsilon)}$$

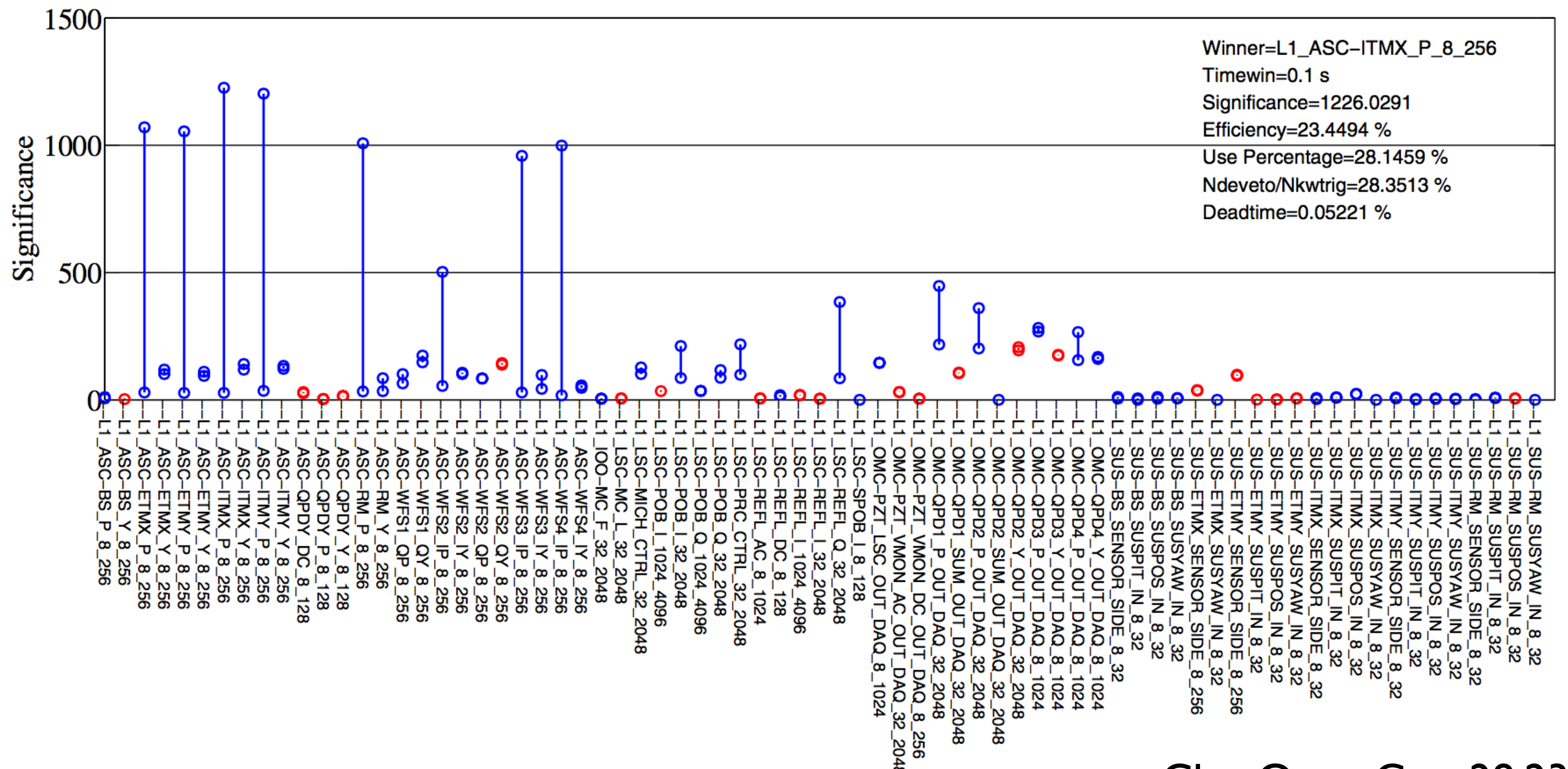
Class. Quantum. Gav. 30, 155010 (2013)

hVeto

$$S = -\log_{10}\Sigma_{k=n}^{\infty}[\frac{\mu^k e^{-\mu}}{k!}])$$

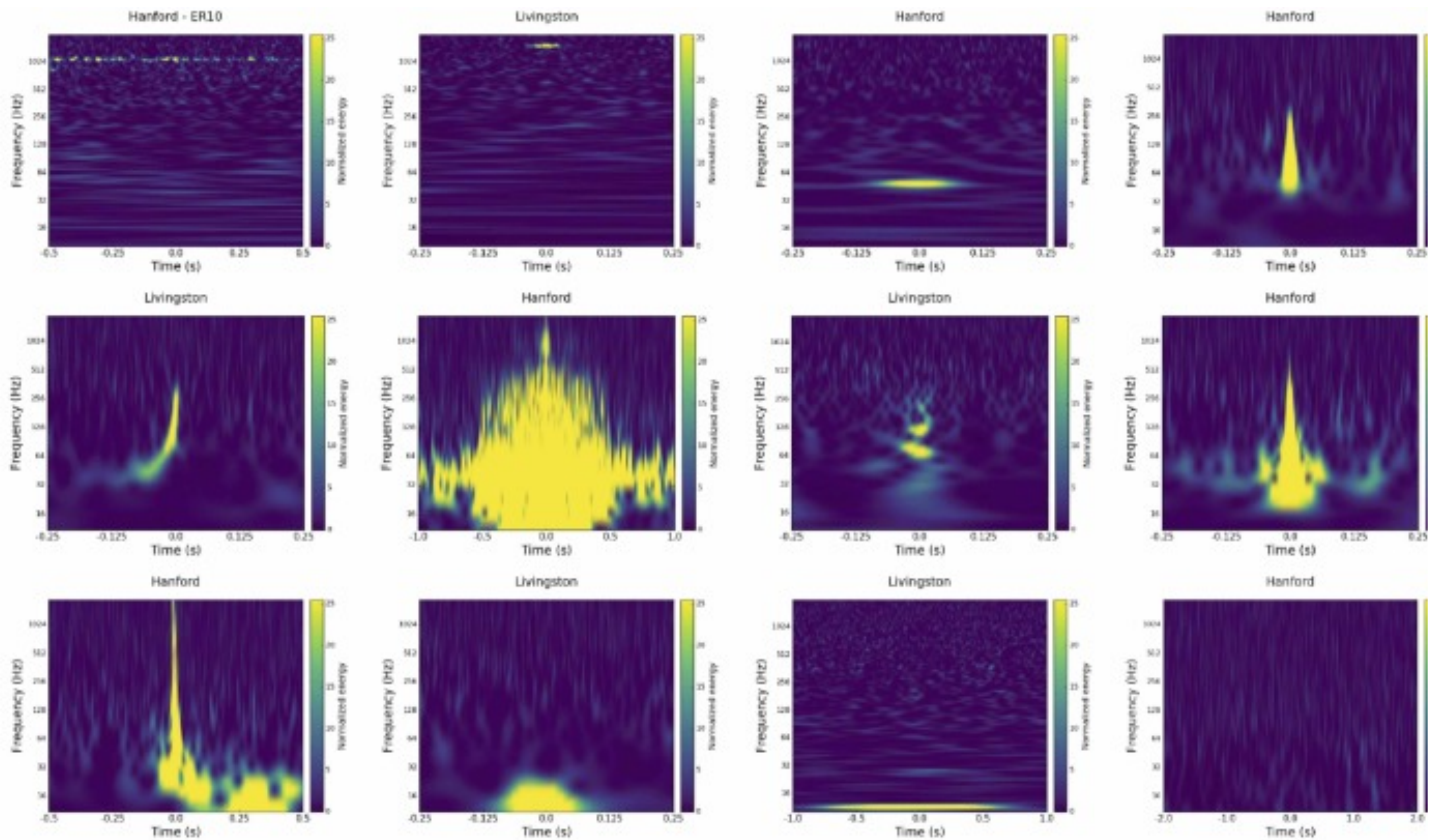
$$\mu = \frac{N_{main\_tot} N_{aux\_tot} T_{win}}{T_{tot}}$$

n : the number of coincidences
T_win : full width of coincidence time window
T_tot : a given total analysis time



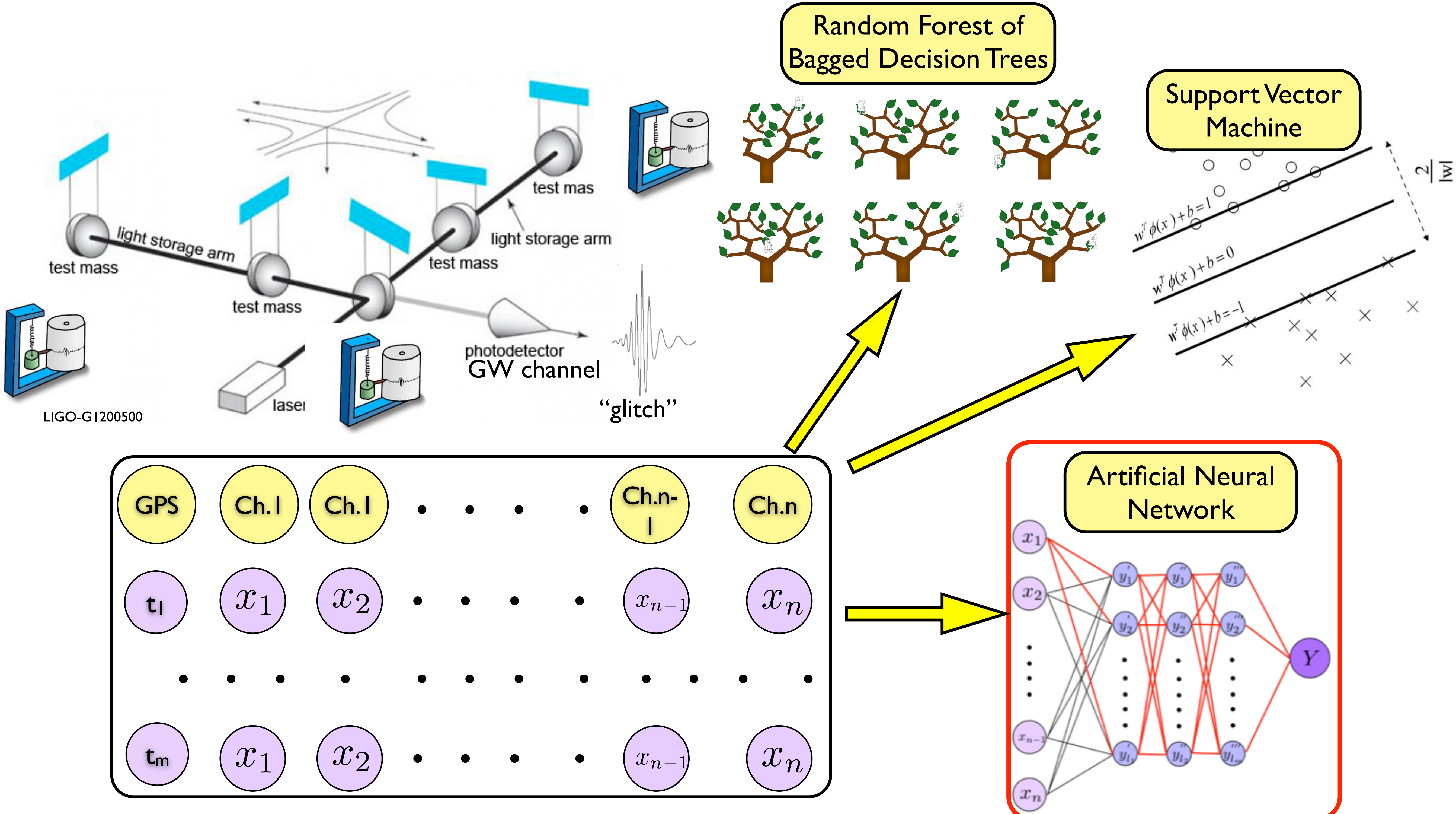
ClassQuantGrav.28.235005(2011)

Non-Gaussian Transient Noises



Bahaadini et al. (2018)

Glitch Classification by ML



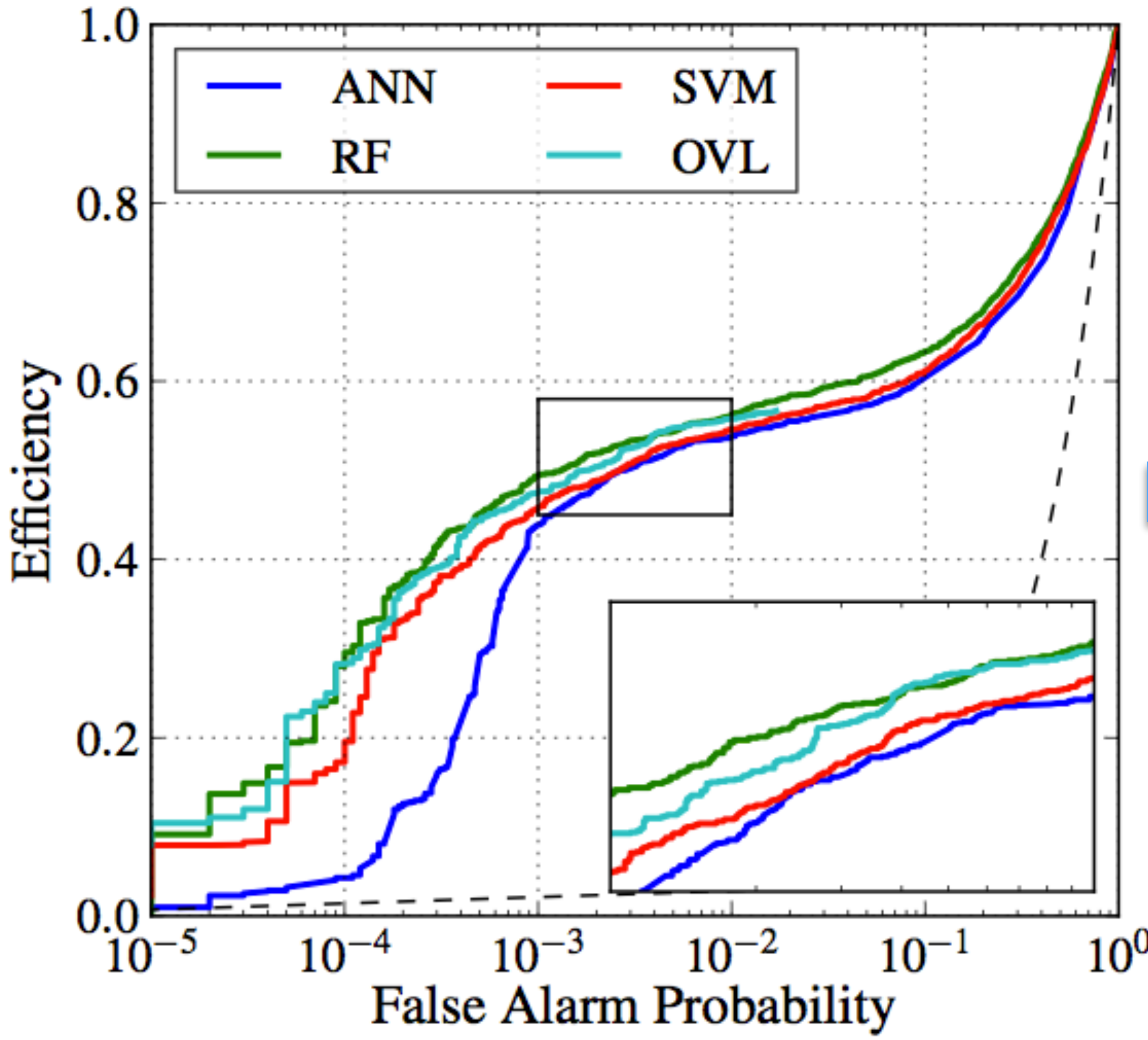
Vectorized information

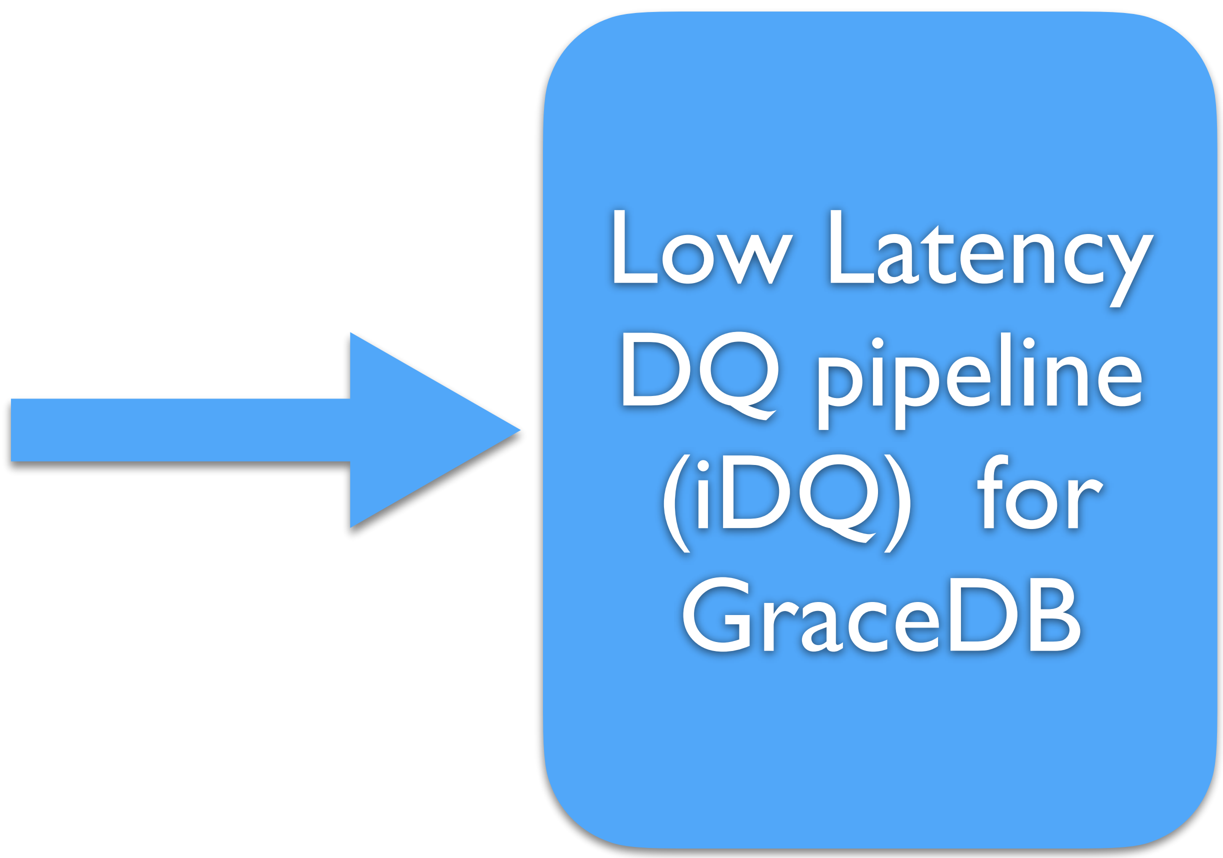
MLA application to DQ

1. Ordered Veto List (OVL) + 3 Machine Learning Algorithms

   - application to hundreds of channels among 200,000 auxiliary channels

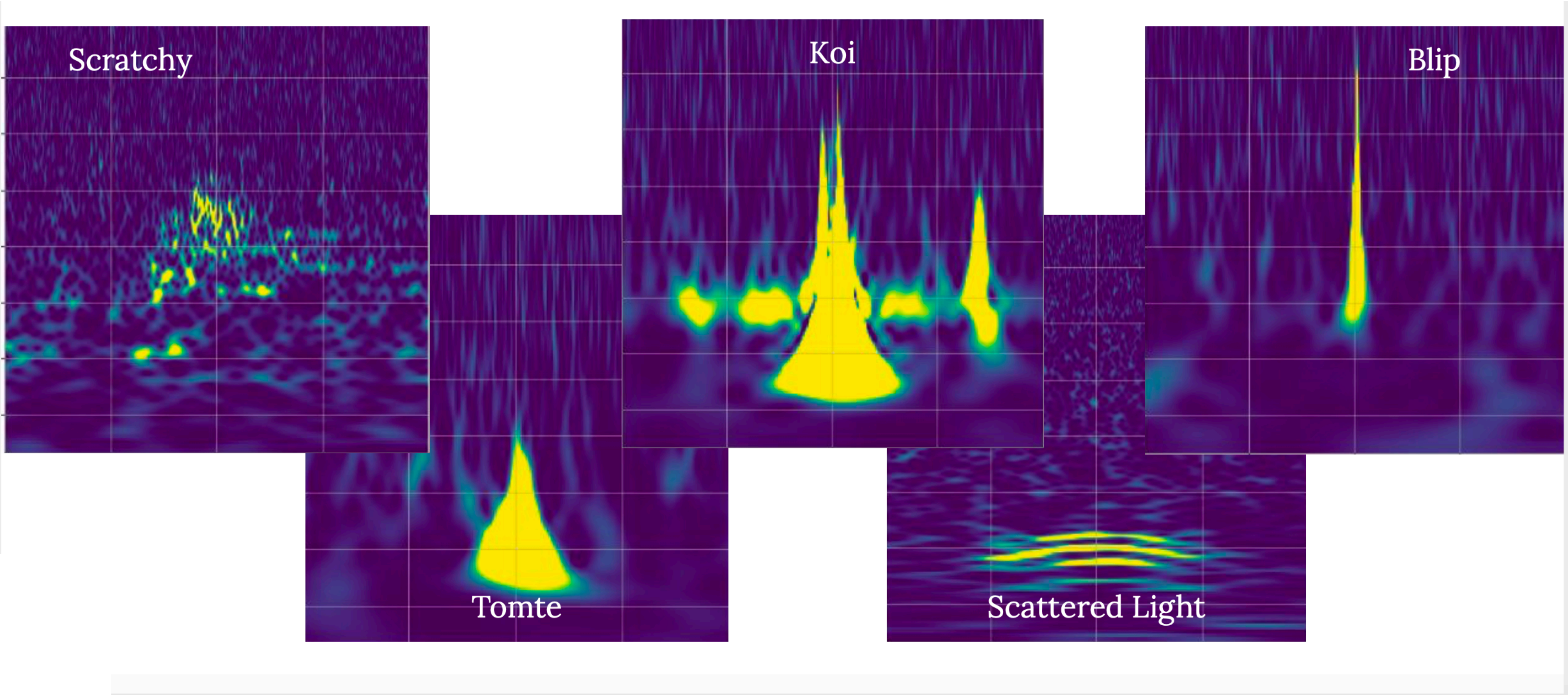
Phys. Rev. D 88, 062003 (2013)





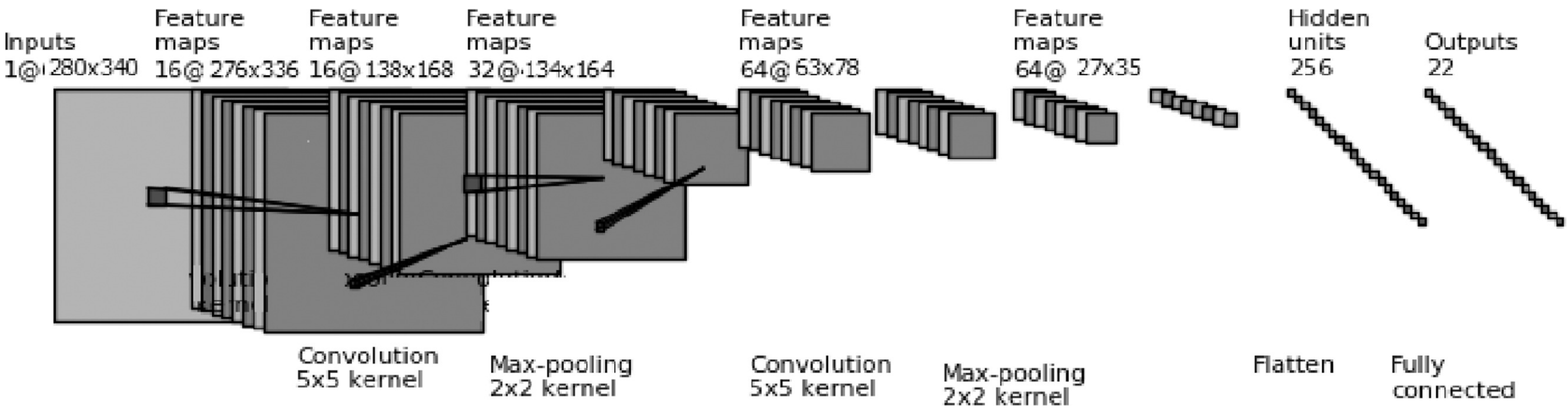
Gravity Spy

Non-Gaussian Glitches



Gravity Spy

downsample: 140*170 —> merged view images (0.5, 1.0, 2.0, 4.0s)



+

Support Vector Machine (SVM)

Ensemble Learning

samples: 8583

train: 6008

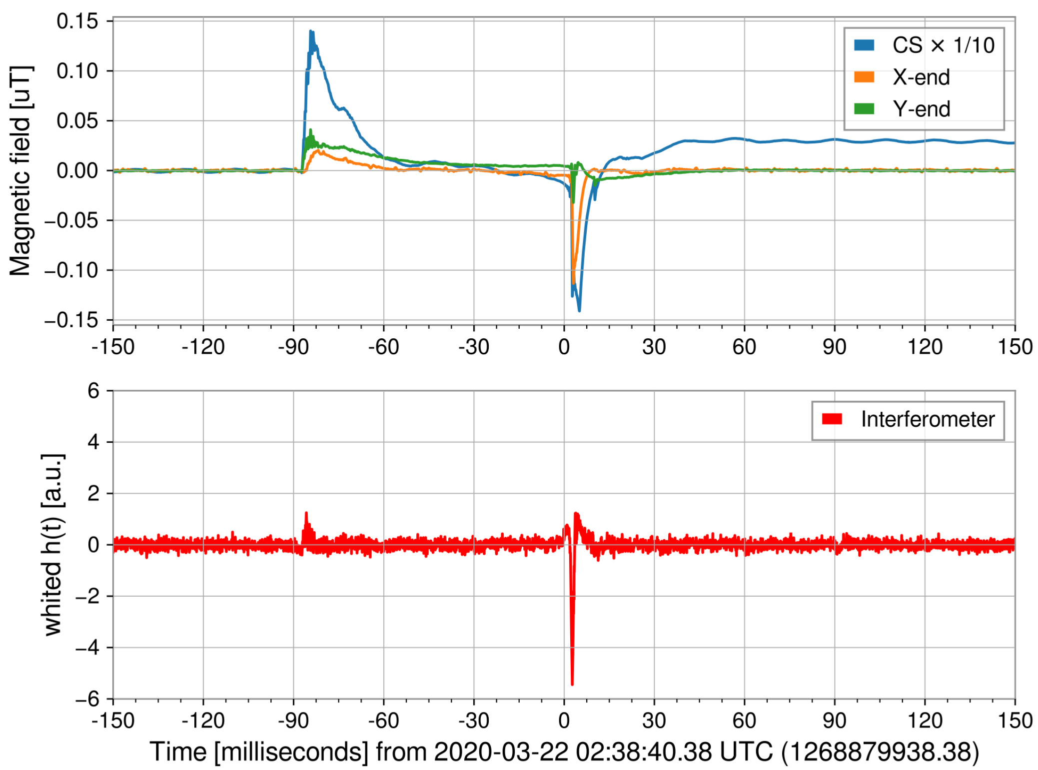
validation: 1288

Test: 1287

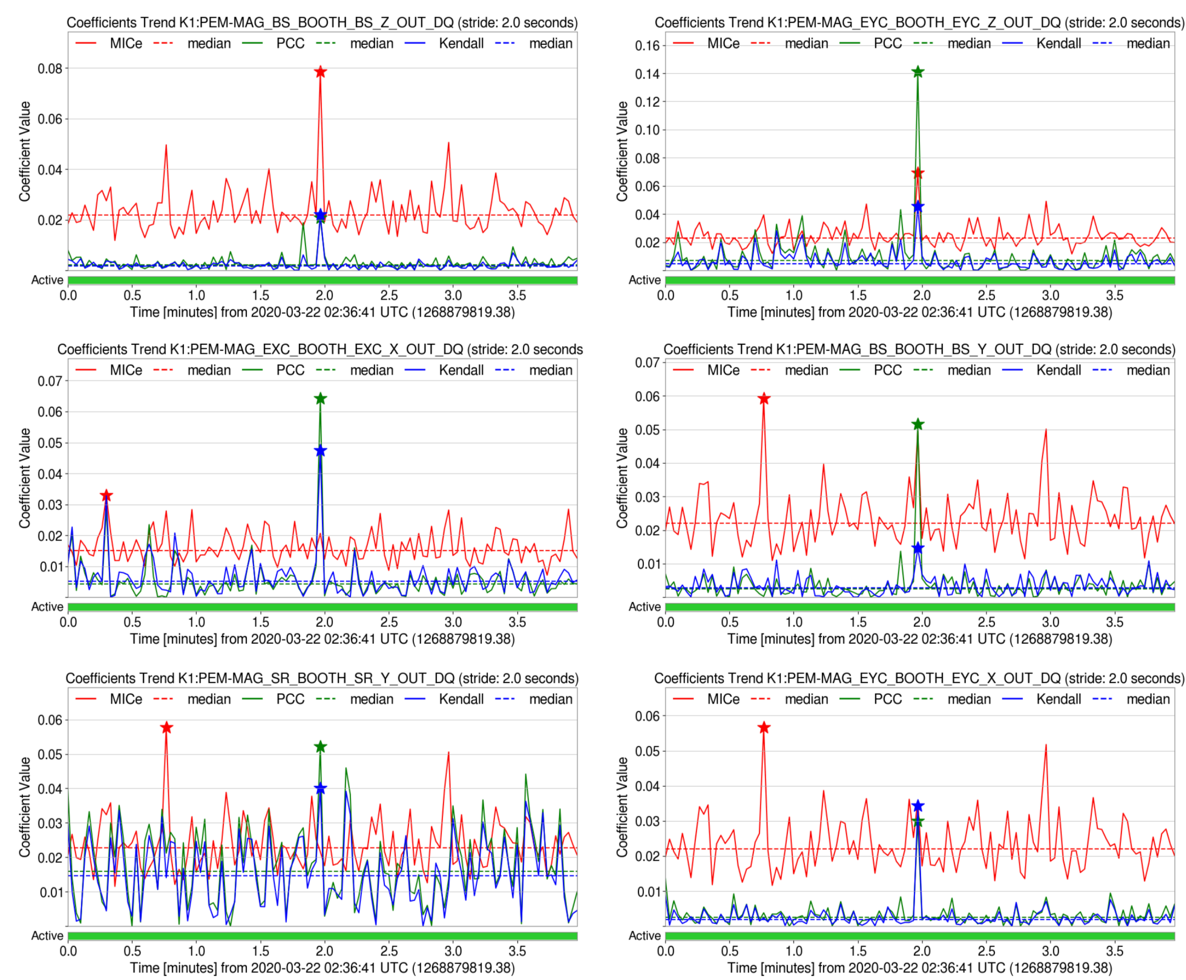
Bahaadini et al. (2018)

CAGMon

1. Developers : J. J. Oh (오정근), P. J. Jung (정필종)
2. Wiki: https://kgwg.nims.re.kr/wiki/DetChar/CAGMon
3. Code : https://github.com/pjjung/cagmon



T. Washimi *et al* 2021 *JINST* **16** P07033



P.J. Jung et al. , arxiv:2204.00370, published in PRD

Data Quality Information

DATA (Data Available): Failing this level indicates that LIGO/Virgo data are not publicly available because the instruments or data calibration were not operating in an acceptable condition.

CAT1 (Category 1): Failing a data quality check at this category indicates **a critical issue with a key detector component not operating in its nominal configuration**.

- These times are identical for each data analysis group.
- *Times that fail CAT1 flags are not available.*

CAT2 (Category 2): Failing a data quality check at this category indicates times when there is a **known, understood physical coupling to the gravitational wave channel**. For example, high seismic activity.

CAT3 (Category 3):
- Burst: Failing a data quality check at this category indicates times when there is **statistical coupling to the gravitational wave channel** which is not fully understood.
- CBC: Category not used

Data quality levels are defined in a cumulative way: a time which fails a given category automatically fails all higher categories.

Data quality categories are defined independently for different analysis groups: if something fails at CAT2_BURST, it could pass CAT2_CBC.

DQ Category

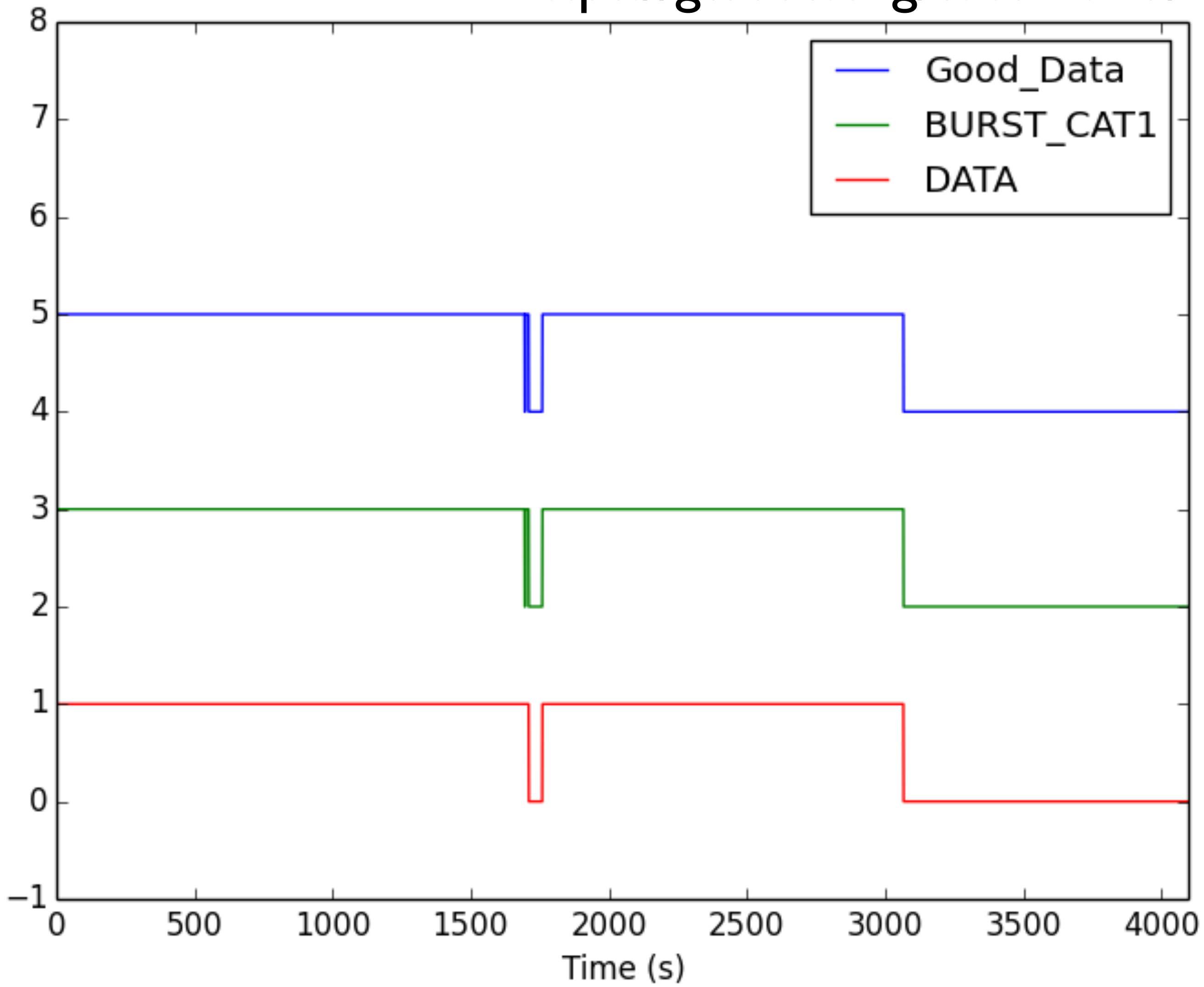
Bit	Short Name	Description
Data Quality Bits		
0	DATA	data present
1	CBC_CAT1	passes the cbc CAT1 test
2	CBC_CAT2	passes cbc CAT2 test
3	CBC_CAT3	passes cbc CAT3 test
4	BURST_CAT1	passes burst CAT1 test
5	BURST_CAT2	passes burst CAT2 test
6	BURST_CAT3	passes burst CAT3 test
Injection Bits		
0	NO_CBC_HW_INJ	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

https://gwosc.org/archive/dataset/O3a_16KHZ_R1/

DQ Category

Bit	Short Name	Description
Data Quality Bits		
0	DATA	
1	CBC_CAT1	
2	CBC_CAT2	
3	CBC_CAT3	
4	BURST_CAT1	
5	BURST_CAT2	
6	BURST_CAT3	
Injection Bits		
0	NO_CBC_HW_INJ	
1	NO_BURST_HW_INJ	
2	NO_DETCHAR_HW_INJ	
3	NO_CW_HW_INJ	
4	NO_STOCH_HW_INJ	

https://gwosc.org/tutorial03/



https://gwosc.org/archive/dataset/O3a_16KHZ_R1/

Gravitational Wave Open Science Center

Data Software Online Tools About GWOSC

Strain Data

O3a Data Release

O3 Time Range: April 1, 2019 through October 1, 2019
Detectors: H1, L1 and V1

4 kHz Data | 16 kHz Data | Documents | Timeline

O2 Data Release

O2 Time Range: November 30, 2016 through August 25, 2017
Detectors: H1, L1 and V1

4 kHz Data | 16 kHz Data | Documents | Timeline

O1 Data Release

O1 Time Range: September 12, 2015 through January 19, 2016
Detectors: H1 and L1

4 kHz Data | 16 kHz Data | Documents | Timeline

Gravitational Wave Open Science Center

Data▾ Software▾ Online Tools▾ About GWOSC▾

Strain Data

f_{GW}: Up to 2kHz

O3a Data Release

O3 Time Range: April 1, 2019 through October 1, 2019
Detectors: H1, L1 and V1

4 kHz Data | 16 kHz Data | Documents | Timeline

O2 Data Release

O2 Time Range: November 30, 2016 through August 25, 2017
Detectors: H1, L1 and V1

4 kHz Data | 16 kHz Data | Documents | Timeline

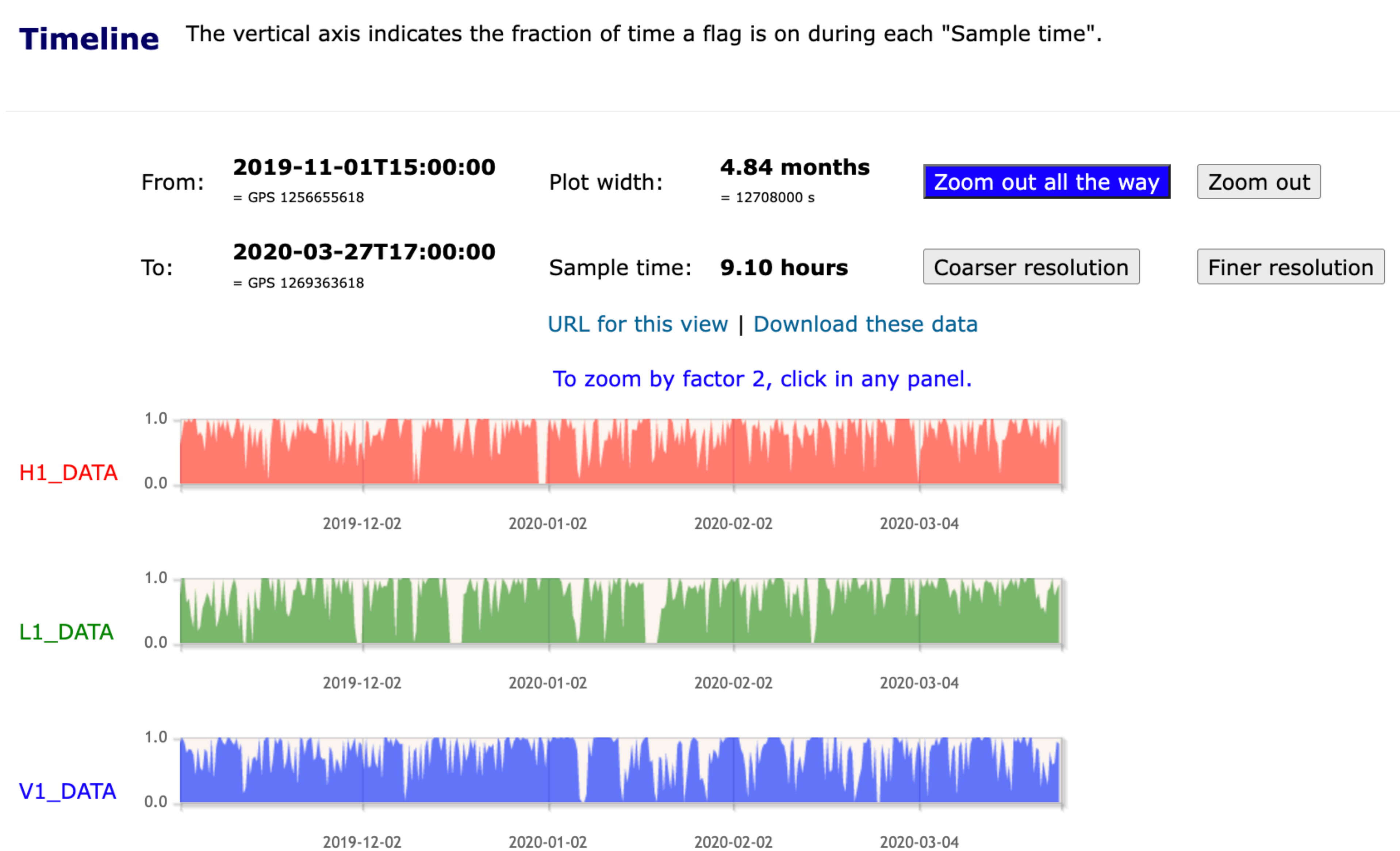
O1 Data Release

O1 Time Range: September 12, 2015 through January 19, 2016
Detectors: H1 and L1

4 kHz Data | 16 kHz Data | Documents | Timeline

Segment Information

1. segment DB : https://segments.ligo.org
   - query an available segment to segment DB
2. Public segment information in GWOSC (www.gwosc.org)



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Timeline The Timeline App provides information on times when data are available, as well as

Timeline Queries

- Use the **Run Timeline Query Form** to request any of the Run Timeline or Segment Lists.
- Use the **Event Portal** to access individual Events and request any of the Event Timeline or Seg

Timeline Examples

Science Mode History

- Five detectors since 2005

Timelines from the O3a run, 2019

- Data available over the O3a run
- Passes O3a Burst checks for H1, L1, V1
- Passes O3a CBC checks for H1, L1, V1
- Times with no Continuous-Wave injections

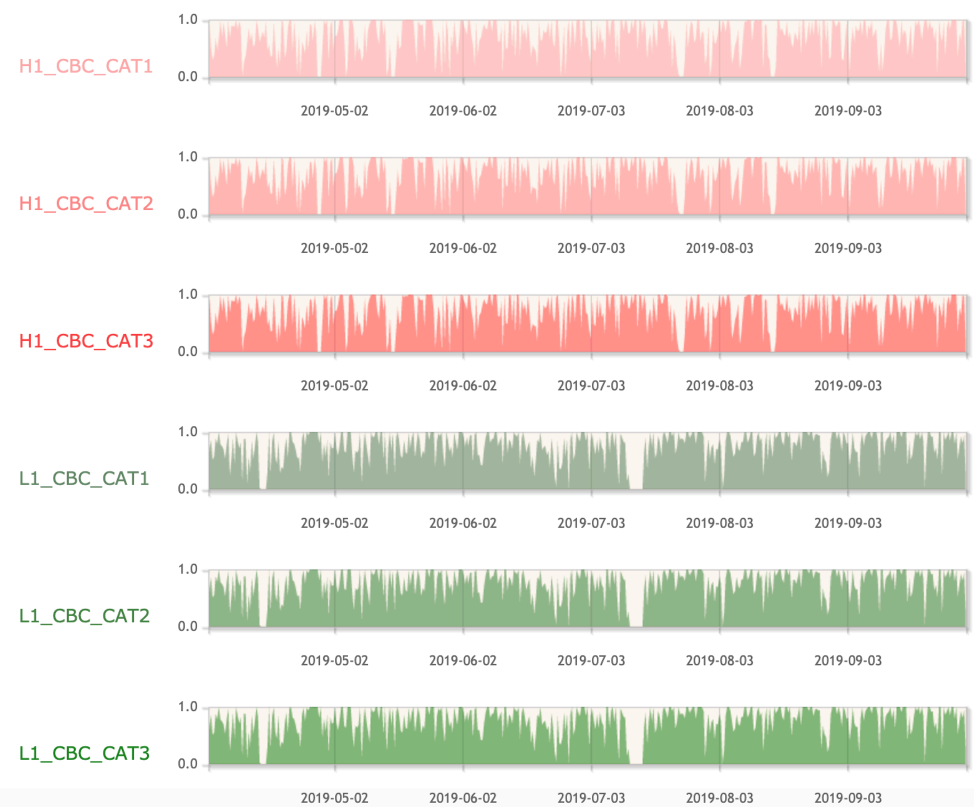
Timeline The vertical axis indicates the fraction of time a flag is on during each "Sample time".

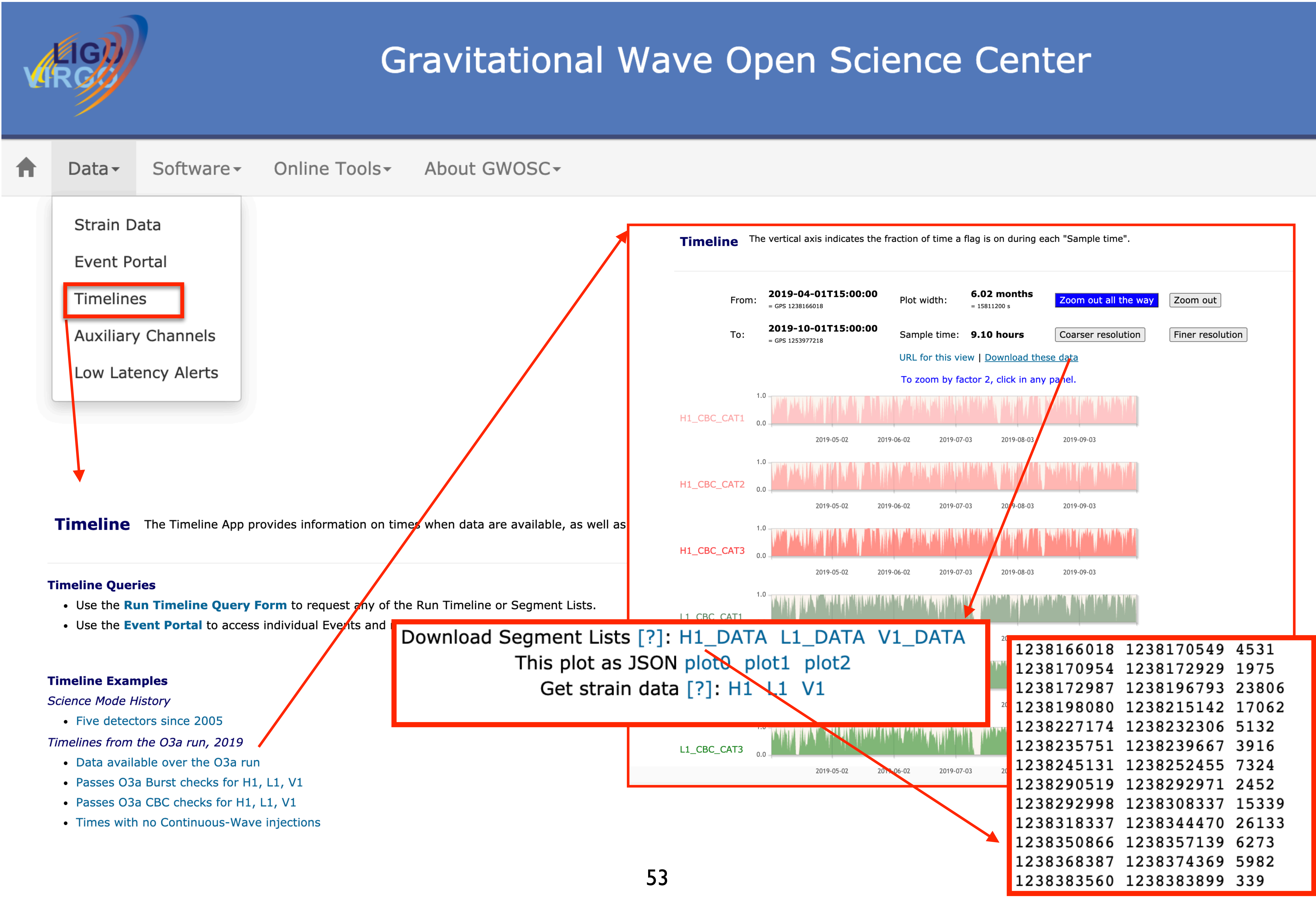
From: **2019-04-01T15:00:00** = GPS 1238166018 Plot width: **6.02 months** = 15811200 s [Zoom out all the way] [Zoom out]

To: **2019-10-01T15:00:00** = GPS 1253977218 Sample time: **9.10 hours** [Coarser resolution] [Finer resolution]

URL for this view | Download these data

To zoom by factor 2, click in any panel.

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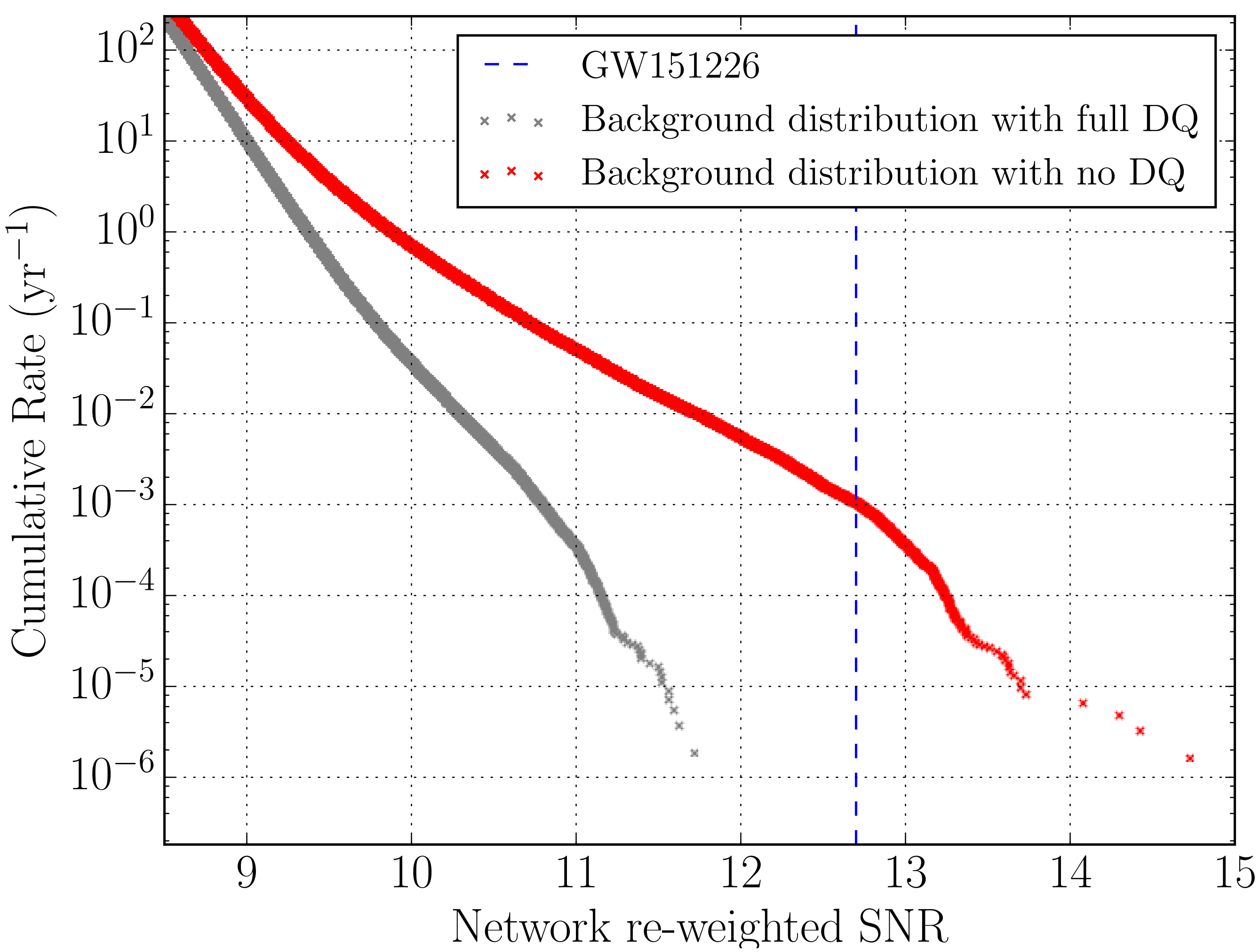
Timeline The vertical axis indicates the fraction of time a flag is on during each "Sample time".
From: 2019-04-01T15:00:00
= GPS 1238166018
Plot width: 6.02 months
= 15811200 s
Zoom out all the way
Zoom out
To: 2019-10-01T15:00:00
= GPS 1253977218
Sample time: 9.10 hours
Coarser resolution
Finer resolution
URL for this view | Download these data
To zoom by factor 2, click in any panel.
H1_CBC_CAT1
H1_CBC_CAT2
H1_CBC_CAT3
L1_CBC_CAT1
L1_CBC_CAT3
1.0
0.0
2019-05-02
2019-06-02
2019-07-03
2019-08-03
2019-09-03
Download Segment Lists [?]: H1_DATA L1_DATA V1_DATA
This plot as JSON plot0 plot1 plot2
Get strain data [?]: H1 L1 V1
1238166018 1238170549 4531
1238170954 1238172929 1975
1238172987 1238196793 23806
1238198080 1238215142 17062
1238227174 1238232306 5132
1238235751 1238239667 3916
1238245131 1238252455 7324
1238290519 1238292971 2452
1238292998 1238308337 15339
1238318337 1238344470 26133
1238350866 1238357139 6273
1238368387 1238374369 5982
1238383560 1238383899 339

Data Quality Impact on GW searches



LIGO-Virgo collaboration (2017) - arXiv 1710.02185

The false alarm rate of GW151226 **improves by a factor of 567**, from 1 in 320 years to 1 in 183000 years, **with interferometer data quality information!**


Thank you for your attention.