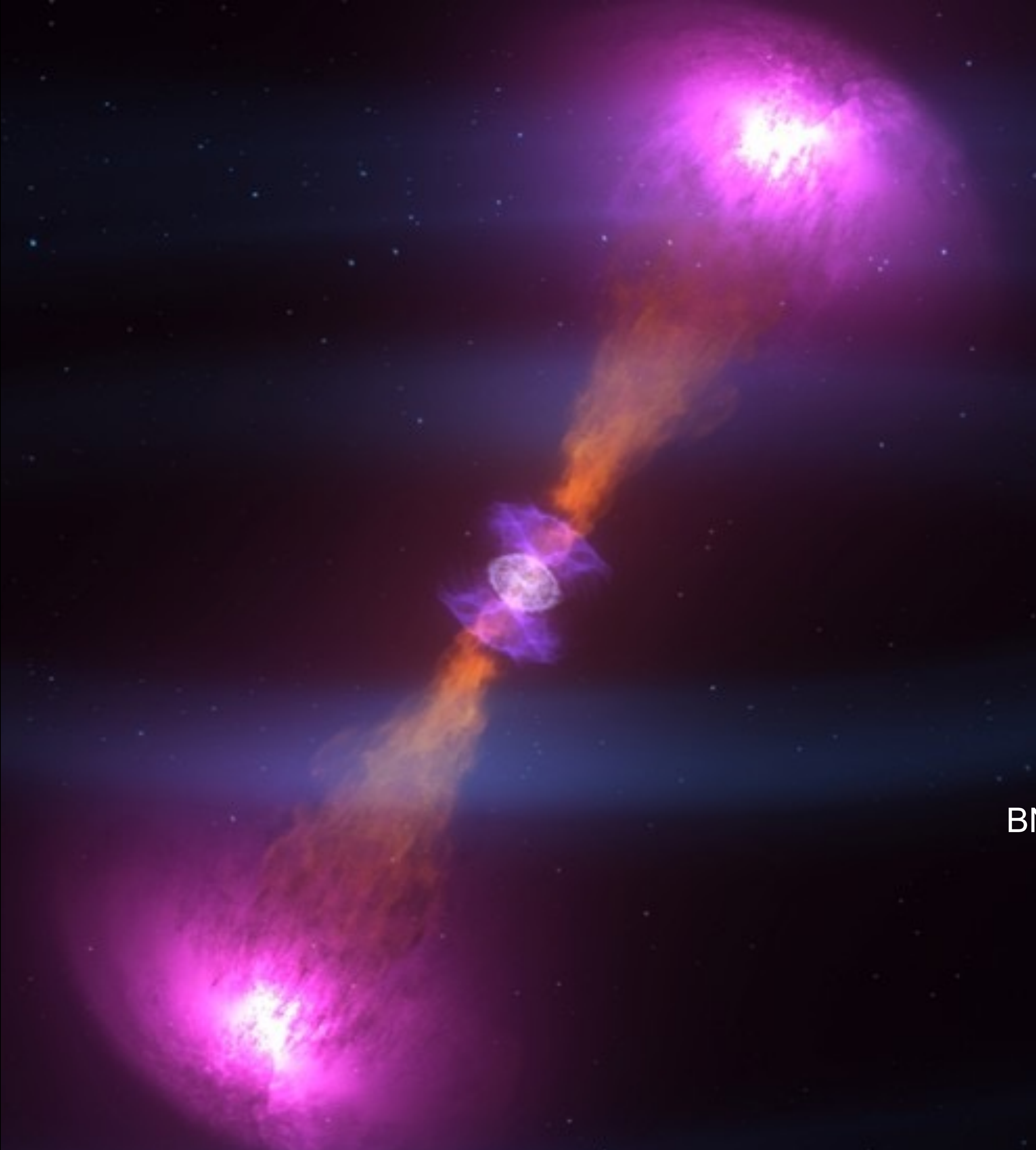

Gravitational Wave Data Manipulation

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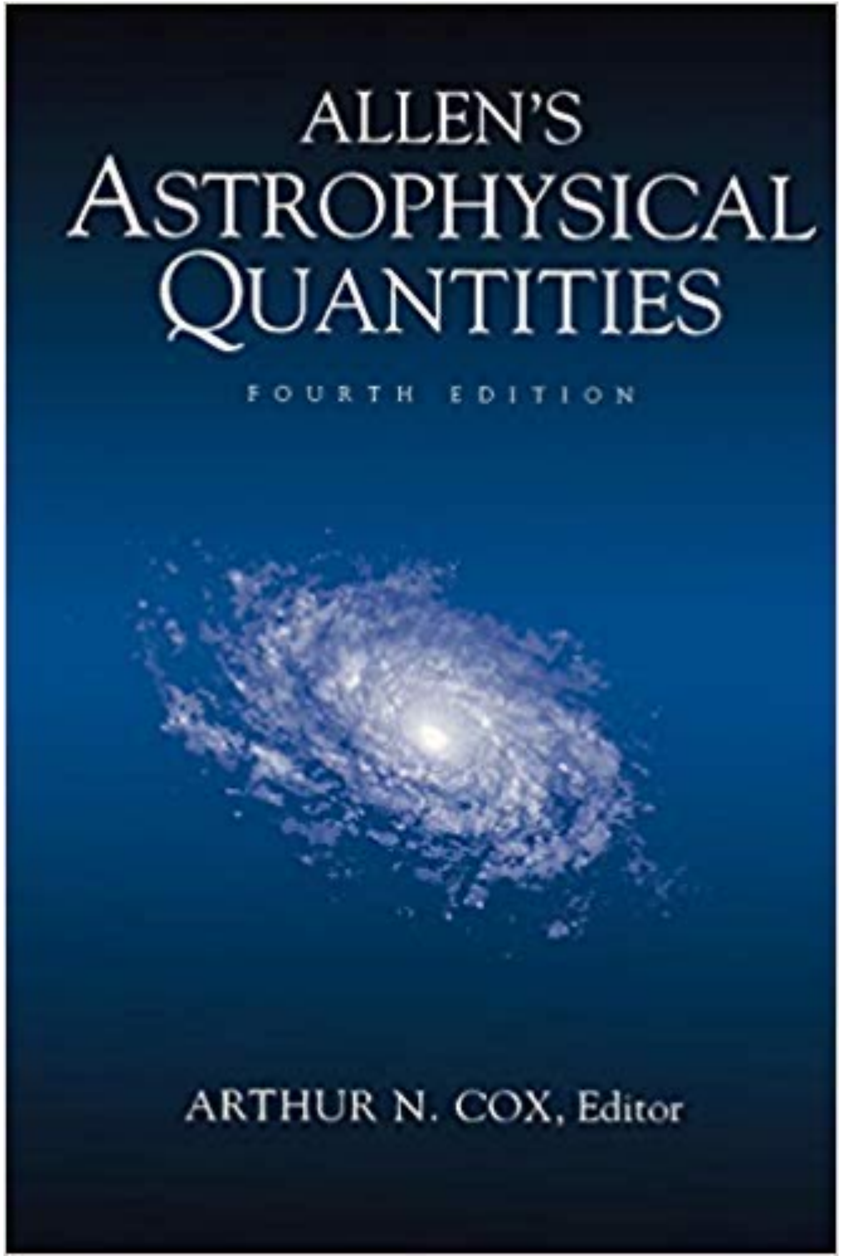
BND School 2024 - Blankenberge, Belgium 2 – 12 Sep 2024

A quick recap on astrophysical quantities

- Useful not just for Gravitational Waves, but also for multimessenger analysis
- Time→ use case: How can I convert the time of a GW event from UTC ?
- Sky Coordinates → use case: Can I find all galaxies within the 95% LIGO-Virgo-KAGRA localization ?
- Lots of calculations (ephemeris table, spherical astronomy…)

…but…



Credits: Springer

The Astropy project

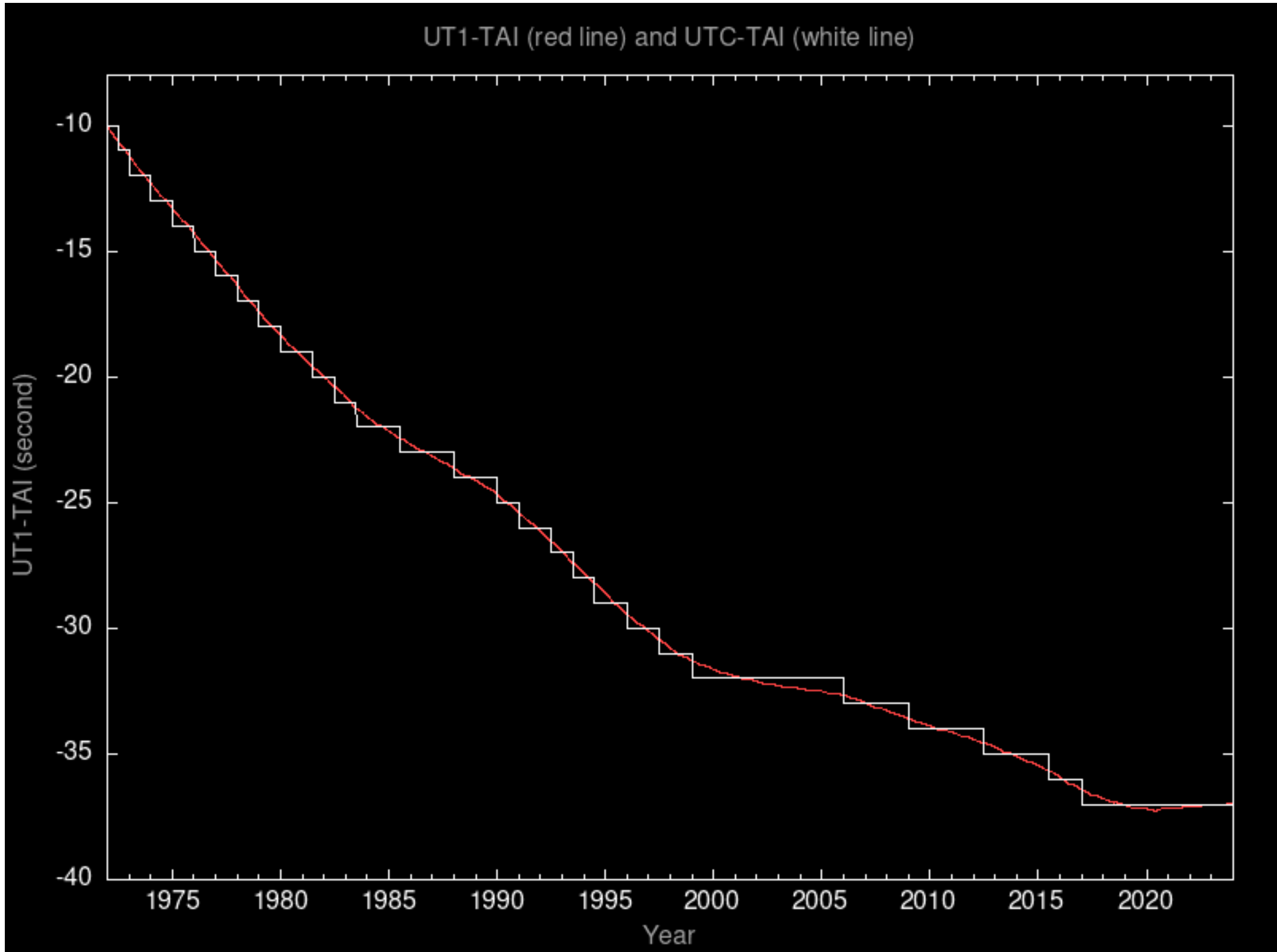
www.astropy.org

- Python-based library for astronomy
- Based on many previous separate projects
- From basic stuff to most advanced methods

Some useful time systems

From Earth rotation to Atomic Clocks

- **International Atomic Time (TAI) – 1958**
  - Uniform scale, based on atomic clocks
  - Synch with Earth Time in Jan 1,1977 = 32.184 s
- **Universal Coordinated Time – 1960**
  - Uniform and based on TAI
  - Offset to keep it close to previous UT1 (within 0.9 s.)
  - Offset adjusted periodically with leap seconds (UTC = TAI – leap seconds)
  - 27 leap seconds from 1972
- **Barycentric Dynamic Time (TDB) - 1976**
  - Time at the Solar System Barycenter
  - Relativistic corrections
  - More uniform, used for planetary ephemeris
  - Fundamental for pulsars



Credits: iers

Julian Date and Modified Julian Date

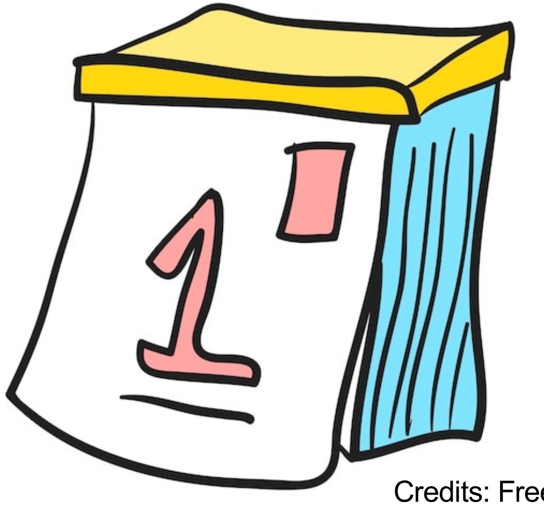
Classic astronomy problem: What if you need to count days between 2 dates?

- **Continous count of days from a starting point**
  - Starting point chosen in Jan 1 4713 BC noon UT
    - Julian day starts at noon UT
    - Suggested by J. Scaliger in 1543, adopted by J. Herschel in 1849

- **Reference point is the start date of 3 calendars:**
    - Metonic (Lunar Phases) – 19 yrs
    - Solar (calendar) – 28 yrs
    - Indiction (hystorians) – 15 yrs

- **Can be referred to UTC, TAI, UT, etc**
  - E.g. 1 Feb 2019 12:00 UT = 2458516.0 JD

- **Julian date is a looong number, so…Modified Julian Date (MJD)**
  - Introduced in 1957 by Smithsonian Astronomical Observatory to track Sputnik orbit
  - Zero point is Nov 17, 1858
  - MJD = JD - 2400000.5



Credits: Freepik

What about Gravitational Waves?

- **No UTC, No JD, we use GPS Time**

- **GPS time**
  - Seconds since Jan 6, 1980, 00:00:00 UTC
  - No leap seconds
  - Other variants: Galileo System Time (GST)
  - Also used in other fields of modern physics (e.g. neutrinos)

- **Quick note on date format**
- We use the ISO 8601 (1988) format

  - YYYY-MM-DD hh:mm:ss” format, or with a T in between (ISOT
  - YYYY-MM-DDThh:mm:ss

A practical example: GW170817

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)

Phys. Rev. Lett. **119**, 161101 – Published 16 October 2017

Physics See Viewpoint: Neutron Star Merger Seen and Heard

Article | References | Citing Articles (6,208) | PDF | HTML | Export Citation

What is the corresponding GPS Time?

ABSTRACT

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and $2.26\,M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–$1.60\,M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01}M_\odot$. The source was localized within a sky region of $28\,\mathrm{deg}^2$ (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

A practical example: GW170817

[4]:
```python
#Basic imports
import numpy as np
from astropy.time import Time
```

[5]:
```python
# Available scales?
Time.SCALES
```

[5]:
```
('tai', 'tcb', 'tcg', 'tdb', 'tt', 'ut1', 'utc', 'local')
```

[6]:
```python
#Available formats?
Time.FORMATS
```

[6]:
```
{'jd': astropy.time.formats.TimeJD,
 'mjd': astropy.time.formats.TimeMJD,
 'decimalyear': astropy.time.formats.TimeDecimalYear,
 'unix': astropy.time.formats.TimeUnix,
 'unix_tai': astropy.time.formats.TimeUnixTai,
 'cxcsec': astropy.time.formats.TimeCxcSec,
 'gps': astropy.time.formats.TimeGPS,
 'plot_date': astropy.time.formats.TimePlotDate,
 'stardate': astropy.time.formats.TimeStardate,
 'datetime': astropy.time.formats.TimeDatetime,
 'ymdhms': astropy.time.formats.TimeYMDHMS,
 'iso': astropy.time.formats.TimeISO,
 'isot': astropy.time.formats.TimeISOT,
 'yday': astropy.time.formats.TimeYearDayTime,
 'datetime64': astropy.time.formats.TimeDatetime64,
 'fits': astropy.time.formats.TimeFITS,
 'byear': astropy.time.formats.TimeBesselianEpoch,
 'jyear': astropy.time.formats.TimeJulianEpoch,
 'byear_str': astropy.time.formats.TimeBesselianEpochString,
 'jyear_str': astropy.time.formats.TimeJulianEpochString}
```

A practical example: GW170817

[17]:
```python
#Define a time in UTC date iso format
t_gw170817_utc = Time("2017-08-17T12:41:04", format='isot', scale='utc')
t_gw170817_utc
```

[17]:
```
<Time object: scale='utc' format='isot' value=2017-08-17T12:41:04.000>
```

[18]:
```python
#Print the value
print(t_gw170817_utc)
```

```
2017-08-17T12:41:04.000
```

[19]:
```python
#Access scale or value of this Time object
print(t_gw170817_utc.scale)
print(t_gw170817_utc.value)
print(t_gw170817_utc.format)
```

```
utc
2017-08-17T12:41:04.000
isot
```

[21]:
```python
#Print different formats
print("ISO is %s " % t_gw170817_utc.iso)
print("JD is %f " % t_gw170817_utc.jd)
print("MJD is %f " % t_gw170817_utc.mjd)
print("GPS is %f " % t_gw170817_utc.gps)
```

```
ISO is 2017-08-17 12:41:04.000
JD is 2457983.028519
MJD is 57982.528519
GPS is 1187008882.000000
```

[22]:
```python
#Change the scale to Barycentric Dynamic Time (TDB)
t_gw170817_tdb = t_utc.tdb
t_gw170817_tdb
```

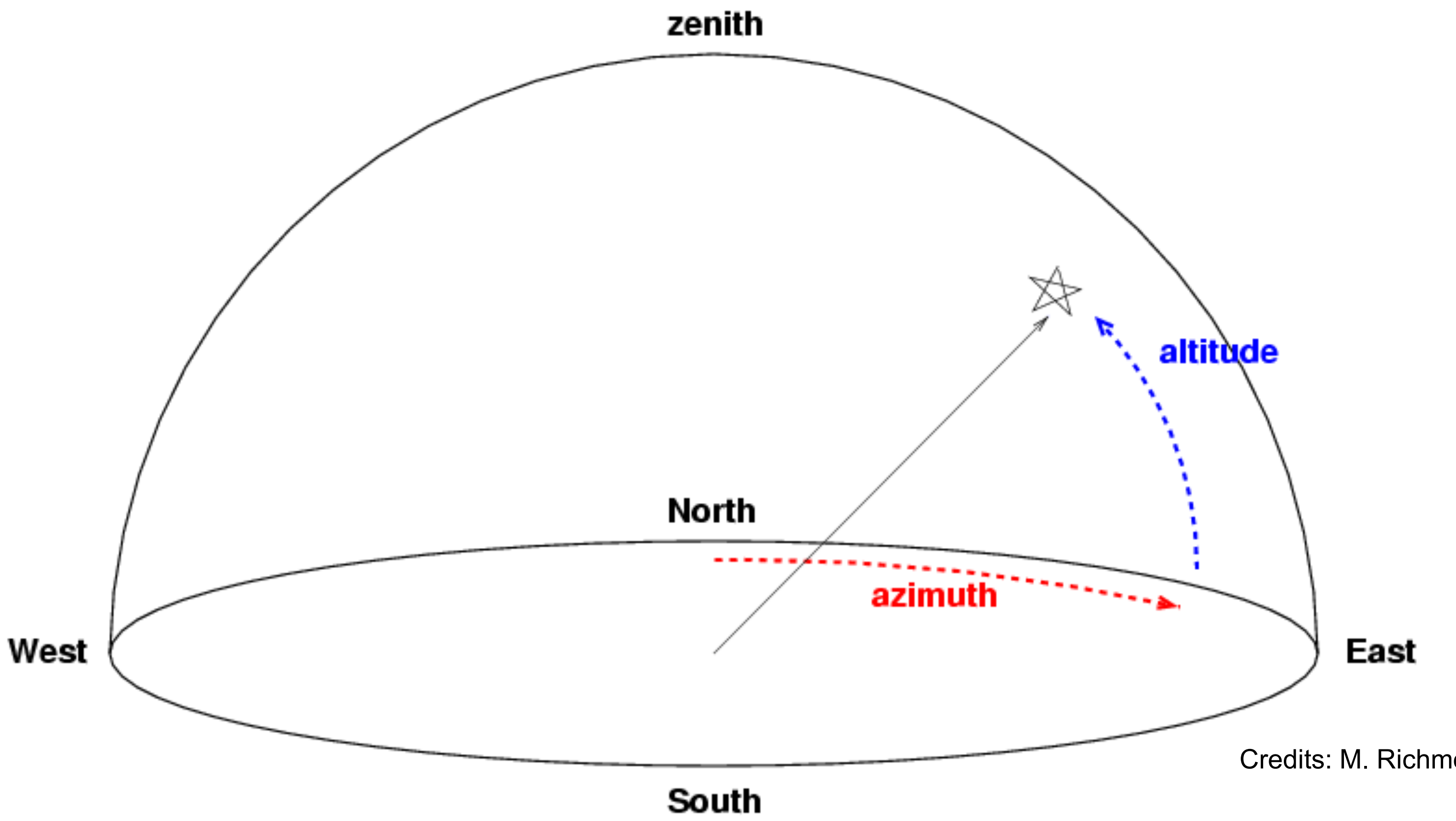
A practical example: GW170817

```
[24]: #How many days from the first GWevent?
      #Lets introduce the time of the GW150914 event (from the PRL paper, Abbot et al. 2016, Phys. Rev. Lett. 116, 061102)
      t_gw150914=Time("2015-09-14T09:50:45", format='isot', scale='utc')

[27]: # Compute the delta using JD
      dt_days = t_gw170817_utc.jd - t_gw150914.jd
      print("Difference is %.6f days" % dt_days)

      Difference is 703.118275 days

[28]: #We can do in a different way
      dt = t_gw170817_utc - t_gw150914

[33]: dt

[33]: <TimeDelta object: scale='tai' format='jd' value=703.118287037037>

[35]: print("DT is %.6f days" % dt.value)

      DT is 703.118287 days

[37]: print("DT is %.2f seconds" % dt.sec)

      DT is 60749420.00 seconds
```

Recap on Coordinate Systems

	Alt-azimutal	Equatorial	Galactic
Centered on	Observer	Center of Earth	Sun
Fundamental plane	Local horizon	Celestial Equator	approx Galactic plane
Advantages	rise/culmination/set	observer-independent	Galactic structure
for Gravitational Wave research	for multimessenger observations (e.g. follow-up)	event coordinates	event coordinates

Astronomical Coordinates – Alt-azimuth



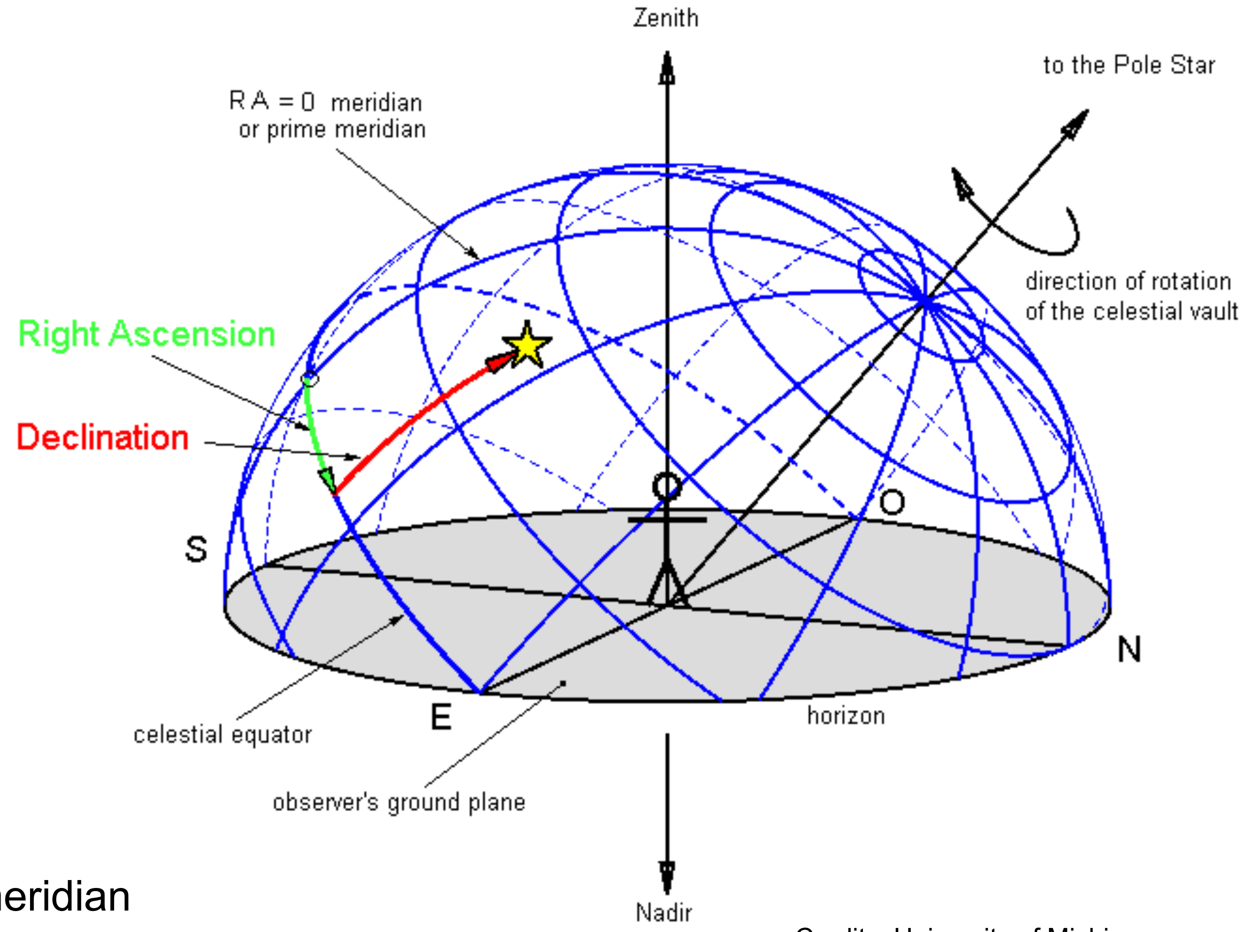
Credits: M. Richmond/rit.edu

- **Altitude (0-90)**
  - horizon is 0°

- **Azimuth:**
  - 0° at North
  - 0°-360° Eastward (sometime from South westward)

Very pratical, but location-dependent!

Astronomical Coordinates - Equatorial

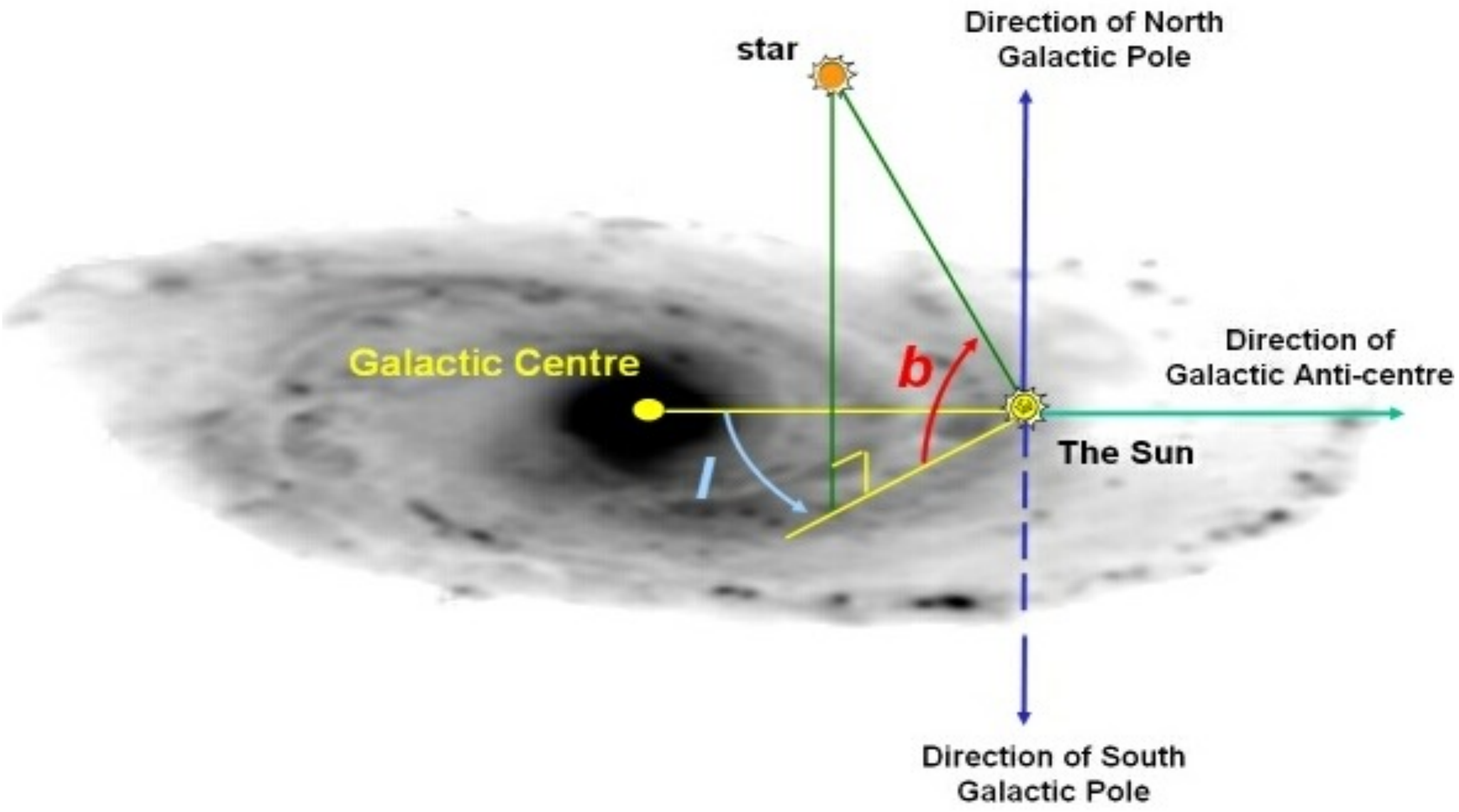


Credits: University of Michigan

- **Declination (-90° - + 90°)**
  - Angle from celestial equator along a celestial meridian
- **Right Ascension (0-24h)**
  - Measured in hh:mm:ss
  - Increasing eastwards

Location-independent, but...

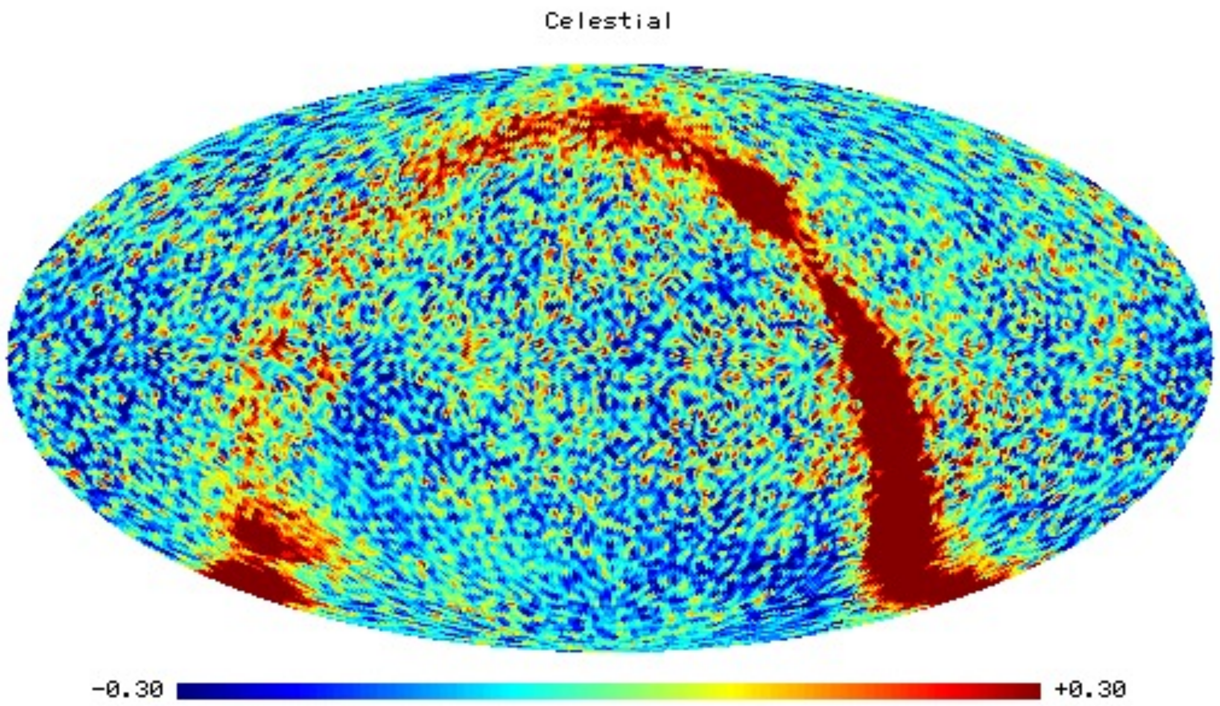
Astronomical Coordinates - Galactic

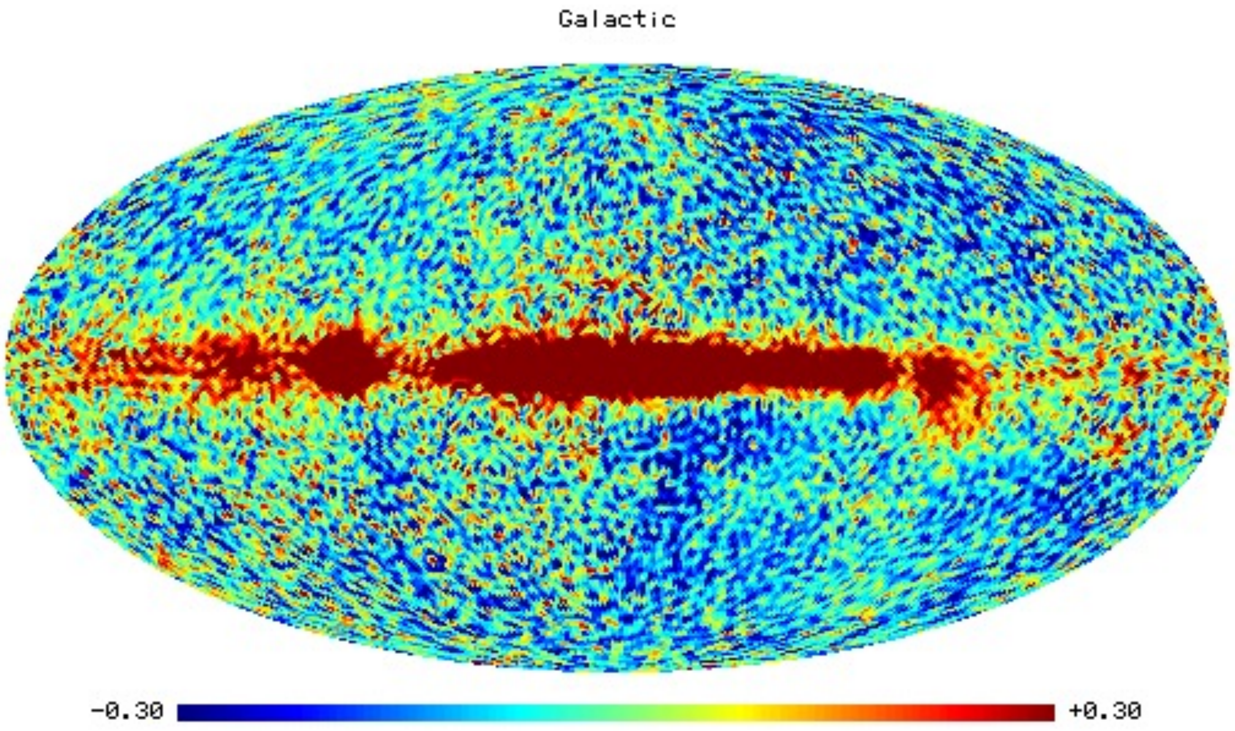


Credits: Swinburne University

- **Galactic latitude (B) : -90° - 90°**
- **Galactic longitude (L) – 0°-360°, from the GC**

Astronomical Coordinates - Galactic





Equatorial → **Galactic**

Credits: NASA/COBE

IAU designation AT 2017gfo) was located at $\alpha(\mathrm{J2000.0}) = 13^{\mathrm{h}}09^{\mathrm{m}}48\overset{\mathrm{s}}{.}085 \pm 0.018$, $\delta(\mathrm{J2000.0}) = -23°22'53\overset{''}{.}343 \pm 0.218$ at a projected distance of $10\overset{''}{.}6$ from the center of NGC 4993, an early-type galaxy in the ESO 508 group at a distance of $\simeq$40 Mpc (Tully–Fisher distance from Freedman et al. 2001), consistent with the gravitational-wave luminosity distance (LIGO Scientific Collaboration & Virgo Collaboration et al. 2017b).

Examples with Astropy: The transient counterpart of GW170817

[2]:
```
import numpy as np
from astropy import units as u
from astropy.coordinates import SkyCoord
```

Coordinate conversion. The case of the transient in NGC4993

Here we get the coordinates of the galaxy NGC4993, where the electromagnetic counterpart of GW170817 was found. How many degrees is above the Galactic plane?

We use Astropy to set coordinates and convert.

First we take coordinates of transient AT2017gfo from B. P. Abbott et al 2017 ApJL 848 L12 (

[3]:
```
#Define a position in the sky using SkyCoord object
#Equatorial coordinates are in the "icrs" frame

#One way is to define it using a string
c_at2017gfo = SkyCoord('13h09m48.085s', '-23d22m53.343s', frame='icrs')
```

[7]:
```
# You can access the coordinates as string
c_at2017gfo.ra
```

[7]: 197°27′01.275″

[6]:
```
# You can access the coordinates in degrees
print("RA is %.3f " % c_at2017gfo.ra.deg)
```

```
RA is 197.450
```

[10]:
```
#or convert to string
c_at2017gfo.to_string("dms")
```

[10]:
```
'197d27m01.275s -23d22m53.343s'
```

Examples with Astropy: The transient counterpart of GW170817

IAU designation AT 2017gfo) was located at $\alpha(\mathrm{J2000.0}) = 13^{h}09^{m}48\overset{s}{.}085 \pm 0.018$, $\delta(\mathrm{J2000.0}) = -23°22'53\overset{''}{.}343 \pm 0.218$ at a projected distance of $10\overset{''}{.}6$ from the center of NGC 4993, an early-type galaxy in the ESO 508 group at a distance of $\simeq$40 Mpc (Tully–Fisher distance from Freedman et al. 2001), consistent with the gravitational-wave luminosity distance (LIGO Scientific Collaboration & Virgo Collaboration et al. 2017b).

```
[12]: # or convert to string in hours and degrees
      c_at2017gfo.to_string("hmsdms")

[12]: '13h09m48.085s -23d22m53.343s'

[13]: #We can also convert to Galactic coordinates
      c_gal = c_at2017gfo.galactic
      c_gal

[13]: <SkyCoord (Galactic): (l, b) in deg
          (308.37941159, 39.29594894)>

[14]: #what is the Galactic Latitude?
      c_gal.b

[14]: 39°17′45.41617681″

[15]: #or in degrees
      print("B is degrees is %.3f" % c_gal.b.deg)

      B is degrees is 39.296
```

Coordinate conversion

IAU designation AT 2017gfo) was located at $\alpha(\mathrm{J2000.0}) = 13^{\mathrm{h}}09^{\mathrm{m}}48\overset{\mathrm{s}}{.}085 \pm 0.018$, $\delta(\mathrm{J2000.0}) = -23^{\circ}22'53\overset{''}{.}343 \pm 0.218$ at a projected distance of $10\overset{''}{.}6$ from the center of NGC 4993, an early-type galaxy in the ESO 508 group at a distance of $\simeq$40 Mpc (Tully–Fisher distance from Freedman et al. 2001), consistent with the gravitational-wave luminosity distance (LIGO Scientific Collaboration & Virgo Collaboration et al. 2017b).

Examples with Astropy: The transient counterpart of GW170817

What is the distance from NGC4993?

We need to find the coordinates of the galaxy and compute the separation

[18]:
```
#We can access from online archives directly from SIMBAD
c_ngc4993 = SkyCoord.from_name('NGC4993')
c_ngc4993.to_string("hmsdms")
```

[18]:
```
'13h09m47.69087616s -23d23m02.31404464s'
```

[21]:
```
#Compute the Angle separation. Not too different from the paper

angle_sep = c_at2017gfo.separation(c_ngc4993)
angle_sep
```

[21]: $0^{\circ}00'10.4845043''$

Examples with Astropy:
Can I observe that transient?

Let us assume that LIGO/VIRGO/KAGRA issued an alert for a certain region of the sky, and some observatories found a host galaxy for your transient. Can you with your telescope observe it? For instance, let's use NGC4993. Is the NGC4993 galaxy above the horizon from Blankenberge tonight? We assume coordinates are 51°18′N 03°07′E (from Wikipedia)

[79]:
```
#First, do the relevant imports
from astropy.coordinates import EarthLocation
```

[80]:
```
#convert coordinates to decimal (approx)
my_lat = 51.3
my_lon = 3.1

my_site = EarthLocation(lat=my_lat*u.deg, lon=my_lon*u.deg, height=3*u.m)
my_site
```

[80]: $(3990192.6, 216101.11, 4954482.7)\ \mathrm{m}$

[82]:
```
#Set the time
from astropy.time import Time
from astropy.coordinates import SkyCoord, EarthLocation, AltAz

utcoffset = +2*u.hour  # UTC+2
time = Time('2024-9-10 23:00:00') - utcoffset

ngc4993altaz = c_ngc4993.transform_to(AltAz(obstime=time,location=my_site))
ngc4993altaz
```

[82]:
```
<SkyCoord (AltAz: obstime=2024-09-10 21:00:00.000, location=(3990192.6301693534, 216101.10818430173, 4954482.745488351) m, pressure=0.0 hPa, temperature=0.0 deg_C, relative_humidity=0.0, obswl=1.0 micron): (az, alt) in deg
    (270.23880486, -30.93731665)>
```

H=-30°…no ☹

Examples with Astropy: Can I observe that transient?

Uhm...no :(BUT, can we see it on some part of the year?

What about a southern location? E.g. the ESO Paranal? We can do a plot to compute it

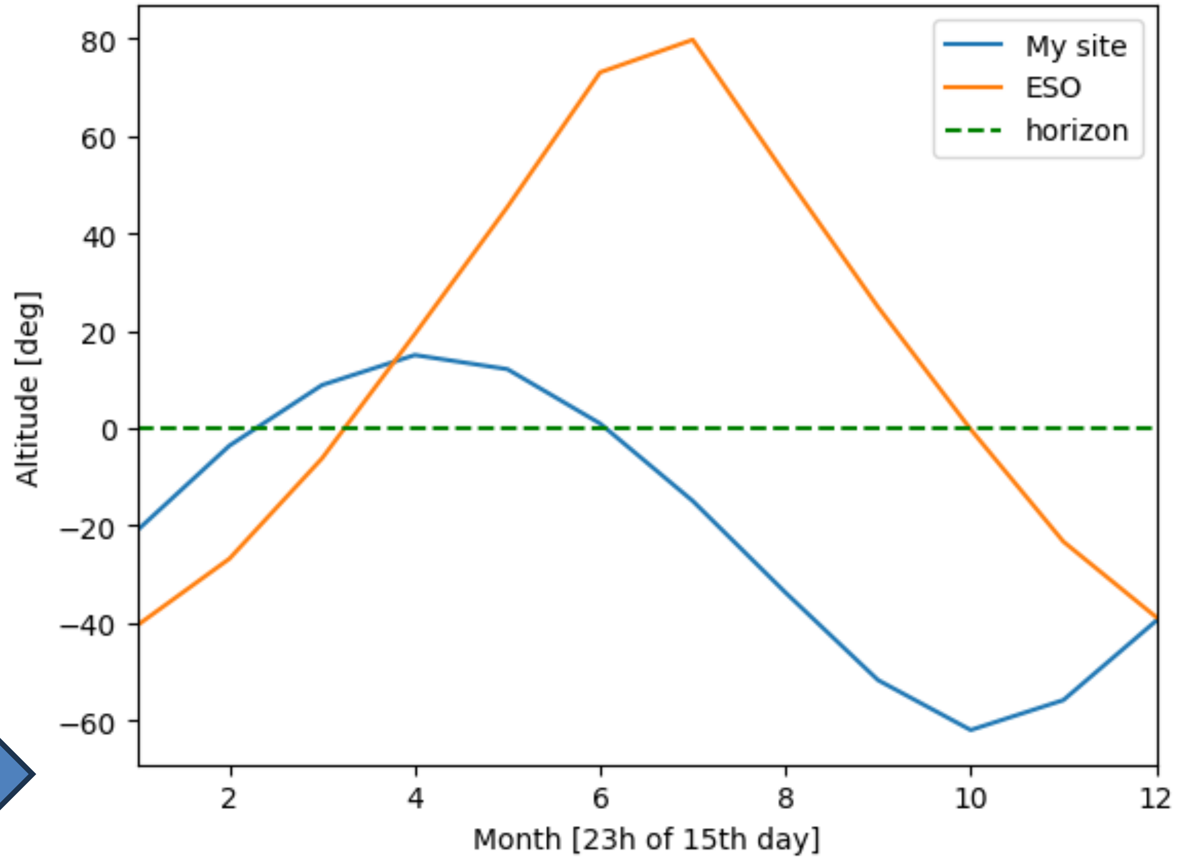
[59]:
```
#First, create an array of 12 months and altitudes
arr_months = np.arange(12)+1
arr_alt_mysite = np.zeros(12)
arr_alt_eso = np.zeros(12)
```

[60]:
```
#lets define a site for paranal
#via the astropy DB
loc_eso = EarthLocation.of_site('Paranal Observatory (ESO)')
loc_eso
```

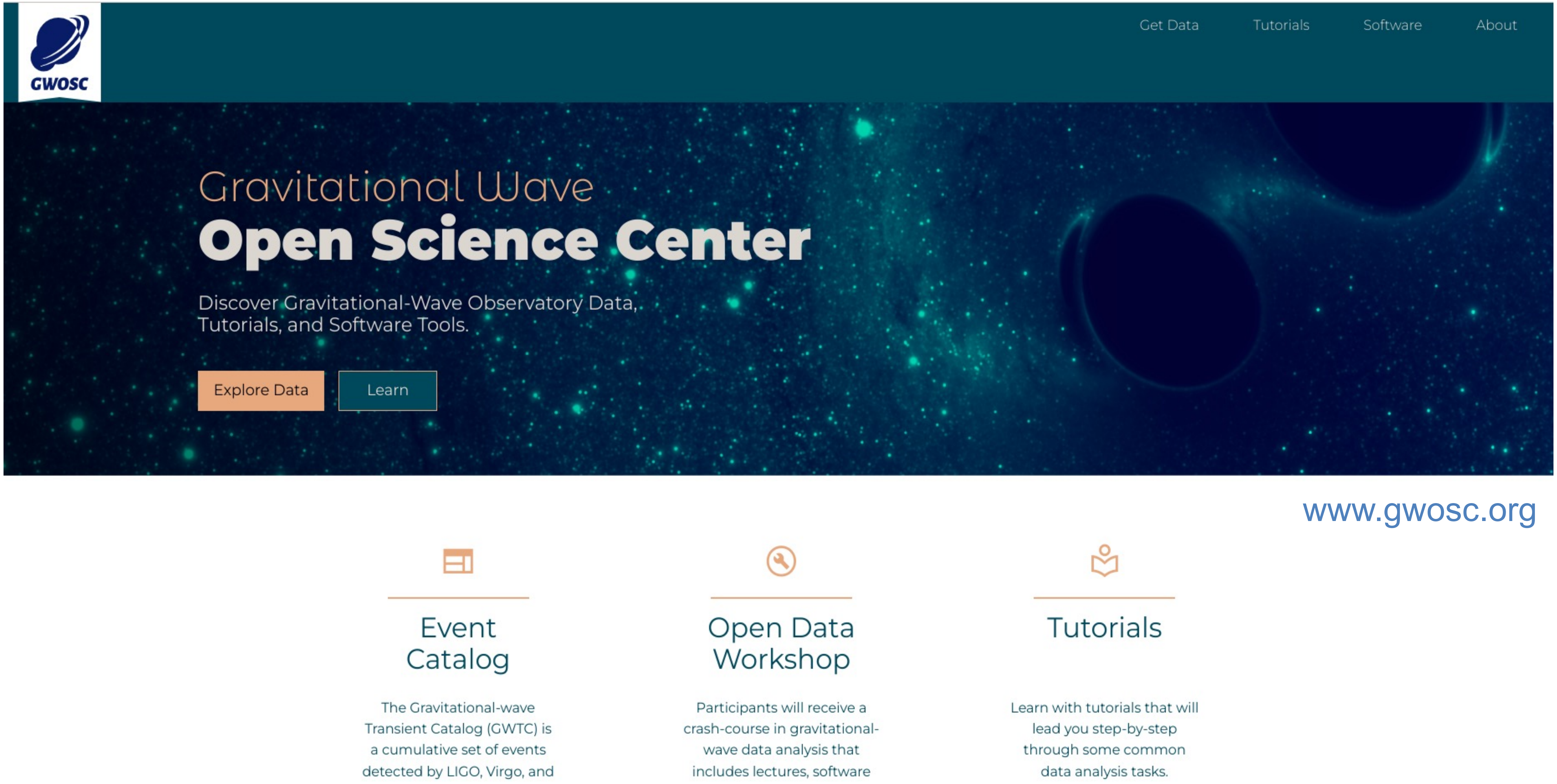
[60]: $(1946404.3, -5467644.3, -2642728.2)\ \mathrm{m}$

[65]:
```
for mi in arr_months:
    time = Time('2024-'+str(mi)+'-15 23:00:00') #UTC time
    #at out site
    arr_alt = c_ngc4993.transform_to(AltAz(obstime=time,location=my_site))
    arr_alt_mysite[mi-1] = arr_alt.alt.deg
    #at ESO
    arr_alt = c_ngc4993.transform_to(AltAz(obstime=time,location=loc_eso))
    arr_alt_eso[mi-1] = arr_alt.alt.deg
```

We can then build an array and plot



GW open data on the web



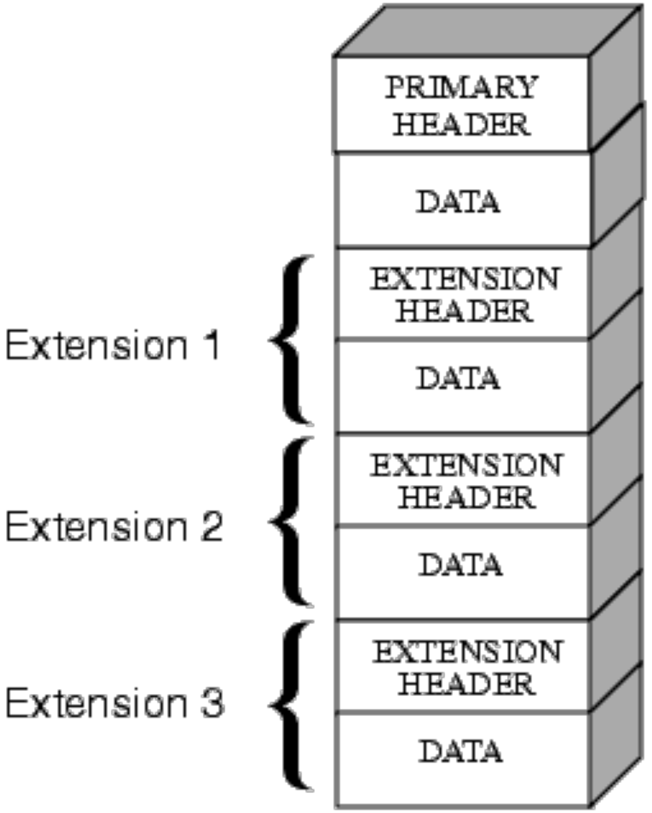
www.gwosc.org

GW Data format vs Astro data format

GWOSC provides data in some formats: ASCII, frame and h5

- Frame files: standard format in the GW community
  - Binary with header (metadata) + extension (time series)
  - Times in GPS

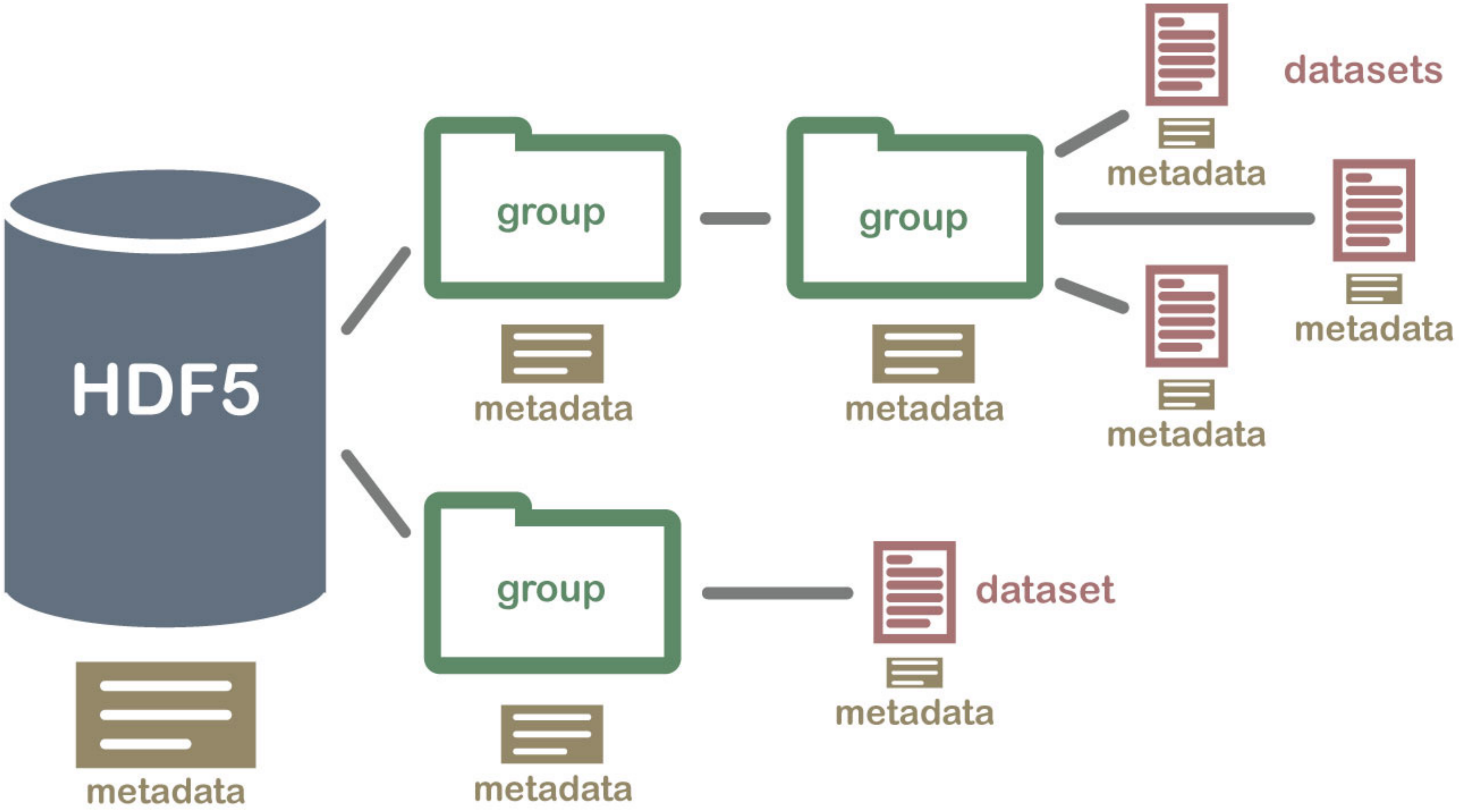
- Not too different from FITS format used in astronomy
  - Flexible Image Transport System (FITS)
  - Standard since 1981
  - Mainly images, but much more
  - Tables, spectra, catalogs



Credits: STScI

GW Data format: Hierarchical Data Format (HDF5)

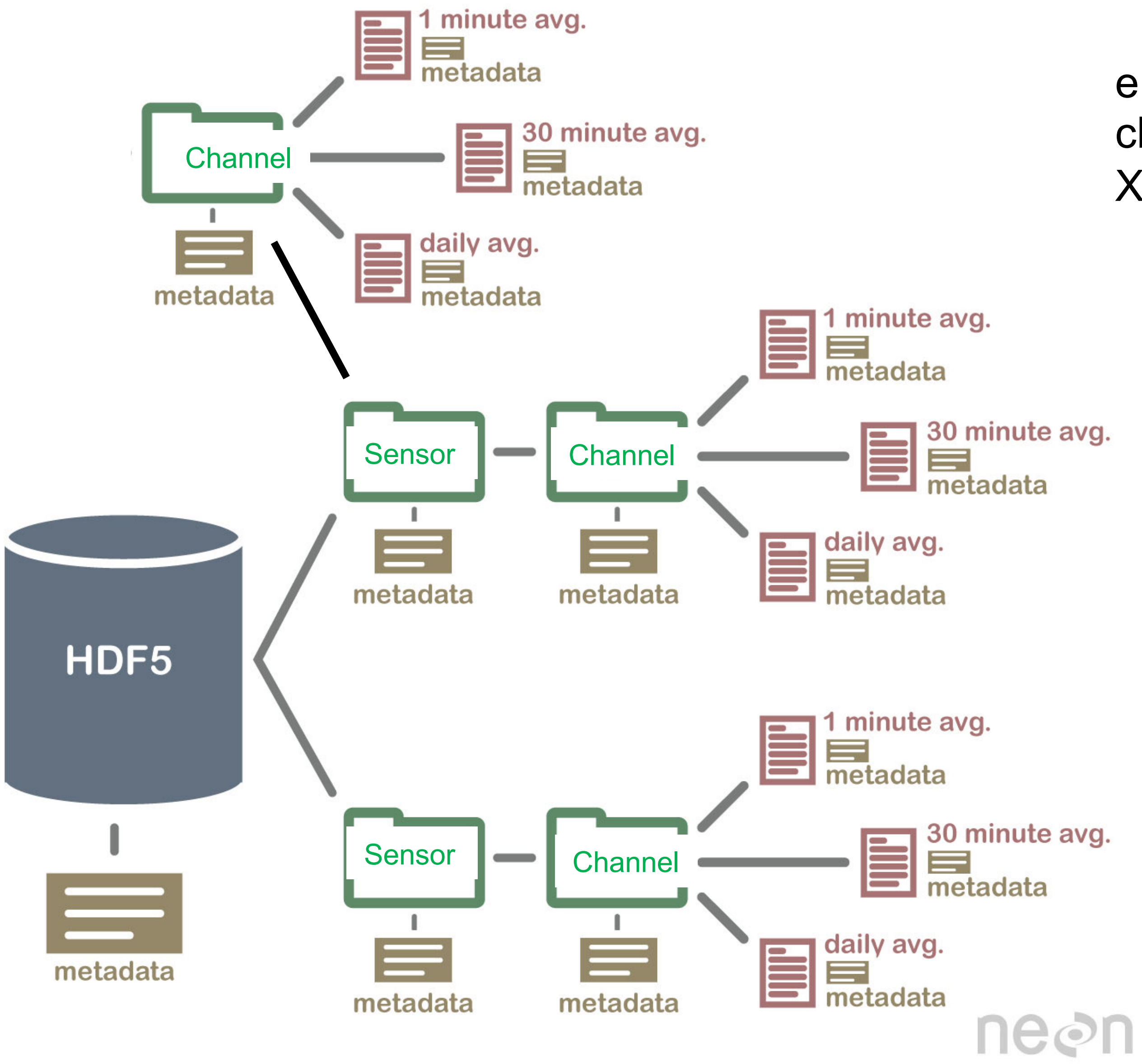
Sam structure: metadata + data. Also possibility of creating data groups



Credits: National Ecological Observatory Network

GW Data format: Hierarchical Data Format (HDF5)

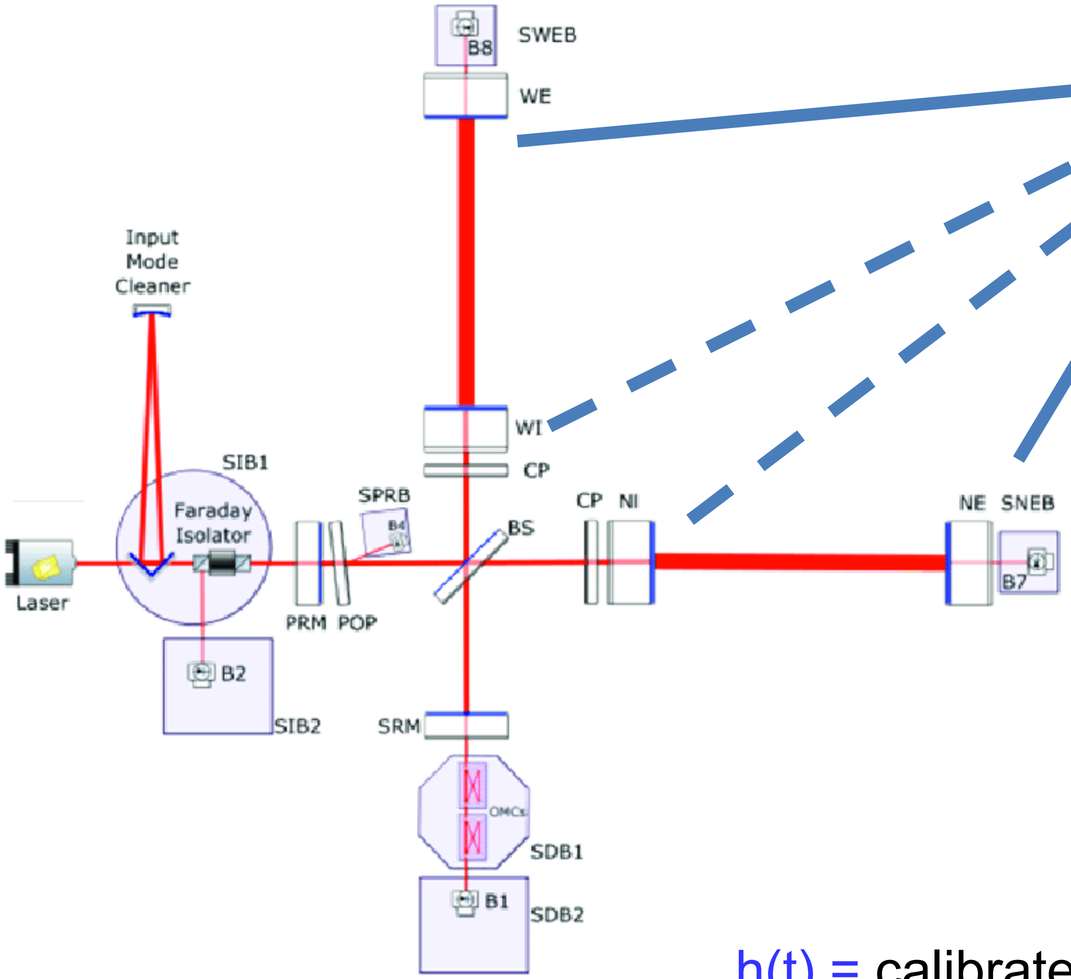
Sam structure: metadata + data. Also possibility of creating data groups



e.g. Sensors can have multiple channels (e.g. accelerometers, X,Y,Z)

Credits: National Ecological Observatory Network (adapted from)

GW Data format: data channels



Auxiliary channels = data e.g. from sensors subsystems and environment. Not sensitive to GW passage but to external noise → Useful for noise hunting and to monitor the status of the detector

h(t) = calibrated strain from output port (i.e. our "science channel")
Sampled at 16-20 kHz, but available subsampled data (e.g. 8 kHz)

Credits: Acernese et al 2018,CQG

Released data

GWOSC provides two main types of data

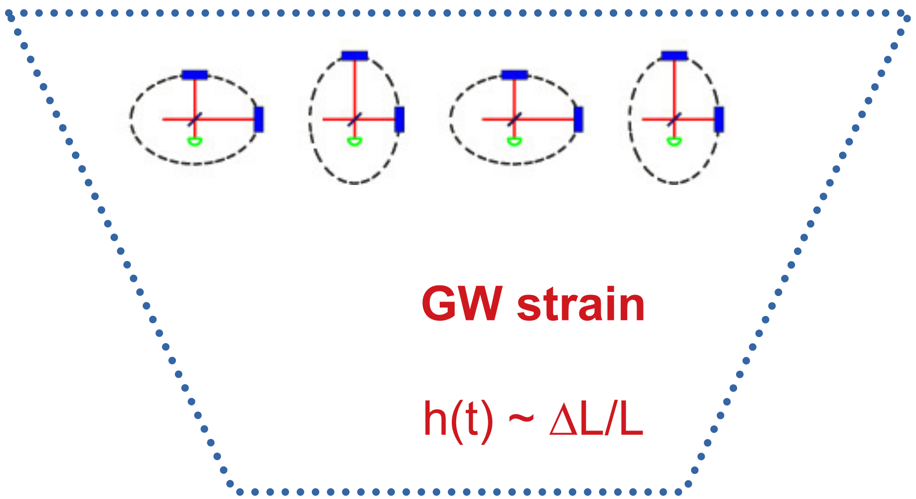
- GW related to events (e.g. Binary Black Holes, etc)
  - About 1-hour window centered on the event(s)
  - Released with the publication of the event(s)
  - GW Strain data, size ~Gb
- GW “bulk” data
  - Bulk datasets of each observing run (size ~Tb)
  - Releases after 18 months from the end of the run
  - Data blocks of 6 months, released every 6 months
  - Data up to O3 available
- Supporting documentation and tools
  - Help the external community in using data
  - Lots of tutorials
  - Materials from periodic Open Data Workshops

GW data products

- Releases include GW strain, data quality and injections
  - Timeseries
  - Various formats, including standard “frame” files (GWF) and HDF5

Available Releases

- LIGO
  - S5 (2005 - 2007)
  - S6 (2009 – 2010)
- Advanced LIGO
  - O1 (2015 – 2016)
  - O2 (2016 – 2017)
  - O3 (2019 - 2020)
- Advanced Virgo
  - O2 (2016 – 2017)
  - O3 (2019 - 2020)



Timelines

Timeline O3b

From: 2019-11-01T15:00:00 (GPS=1256655618)

To: 2020-03-27T17:00:00 (GPS=1269363618)

Duration: 12708000 s

Strain Data for H1 | Strain Data for L1 | Strain Data for V1

Timeline Stats

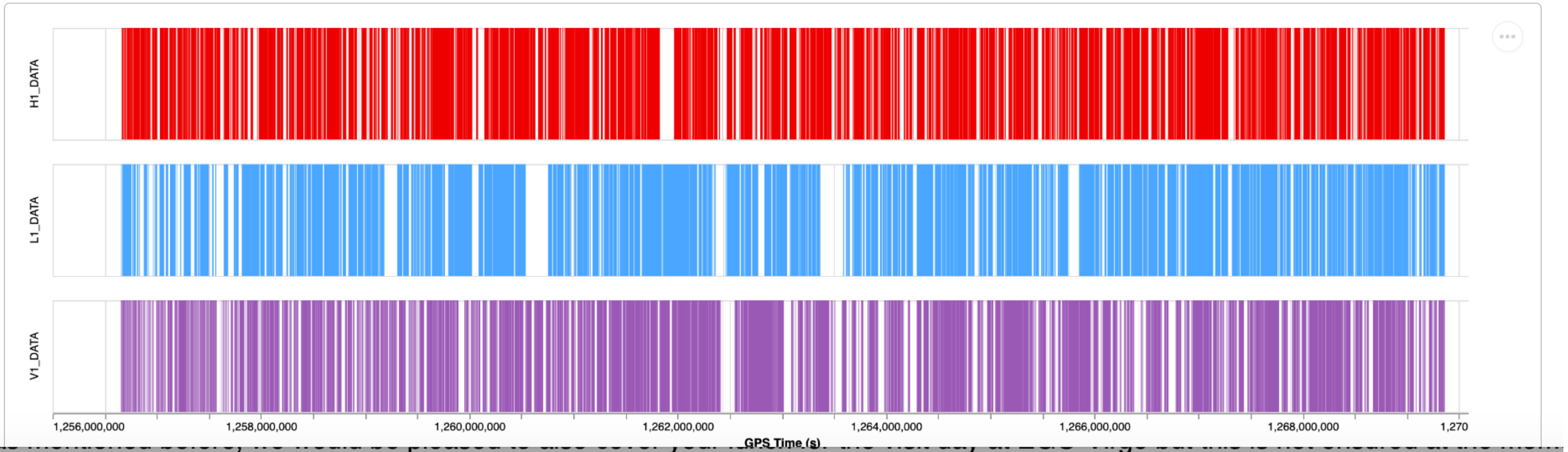
	Time Active	Duty Cycle	Segments
H1_DATA	9967195 s	78.43%	414
L1_DATA	9810816 s	77.20%	352
V1_DATA	9591207 s	75.47%	1192

Download Segments

JSON | ASCII

H1_DATA | L1_DATA | V1_DATA

☑ H1_DATA ☑ L1_DATA ☑ V1_DATA



Credits: GWOSC

Event List

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. For further information, see documentation for individual releases: GWTC-1, GWTC-2, GWTC-2.1, and GWTC-3.

Note, this catalog is only updated periodically, and may not contain recently published events. For the most recent events, you can browse all available events.

Previous versions of this catalog are archived in zenodo.

- Toggle columns on/off with Display button at right.
- Click an event name for all versions and more information.
- Values in the table below are from the **Default SEARCH** and **Default PE** cases found in the individual event's page.
- See Event Portal Usage Notes for more details.

List contains 93 events.

✥ Focus

Display all | Display ▾

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

Credits: GWOSC

Strain data – Single events

each file:

- Metadata
- GW strain
- Data quality (1 Hz rate)

GW150914

(1) O1_O2-Preliminary | (2) O1_O2-Preliminary | (3) GWTC-1-confident

Documentation

Release: GWTC-1-confident

Event UID: GW150914-v3

Names: GW150914

GPS: 1126259462.4

UTC Time: 2015-09-14 09:50:44

Timeline: Query for segments

DOI: https://doi.org/10.7935/82H3-HH23

https://doi.org/10.7935/82H3-HH23

Event from GWTC-1. For documentation, see:
https://arxiv.org/abs/1811.12907
https://doi.org/10.7935/82H3-HH23

GWTC-2.1 PE for GW150914 (update)

Waveform Family: C01:Mixed

Date added: May 13, 2022

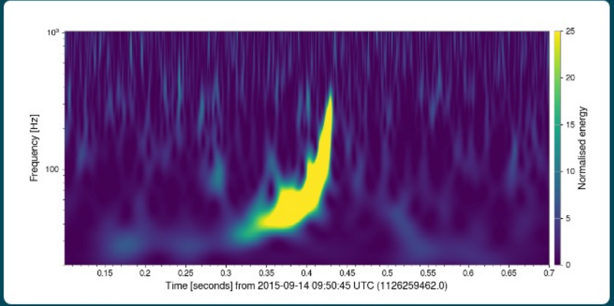
show / hide parameters

Source File

Posterior Samples Zenodo Entry

Skymap for GW150914

H1 strain



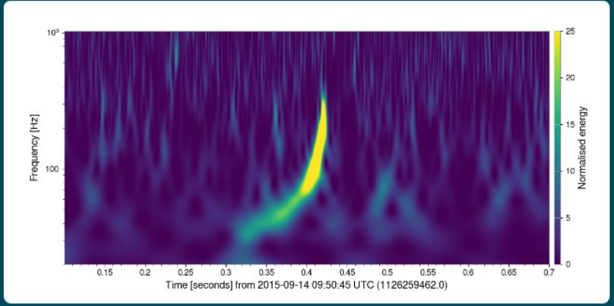
32sec · 16KHz: GWF HDF TXT

32sec · 4KHz: GWF HDF TXT

4096sec · 16KHz: GWF HDF TXT

4096sec · 4KHz: GWF HDF TXT

L1 strain



32sec · 16KHz: GWF HDF TXT

Credits: GWOSC

Bulk data

Large Data Sets

CVMFS Docs

For users of computing clusters or if accessing large amounts of data, CernVM-FS is the preferred method to access public data.

CernVM FS
i.e. mount a
network disk on your PC

O3 Auxiliary Data Release

Documents

Time Range: April 1, 2019 through March 27, 2020

Detectors: 86 channels from H1 and L1

O3GK Data Release

4 kHz Data | 16 kHz Data | Documents | Timeline | MICH/PRCL Data

O3GK Time Range: April 7, 2020 through April 21, 2020

Detectors: G1 and K1

O3b Data Release

4 kHz Data | 16 kHz Data | Documents | Timeline

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

Detectors: H1, L1 and V1

O3a Data Release

4 kHz Data | 16 kHz Data | Documents | Timeline

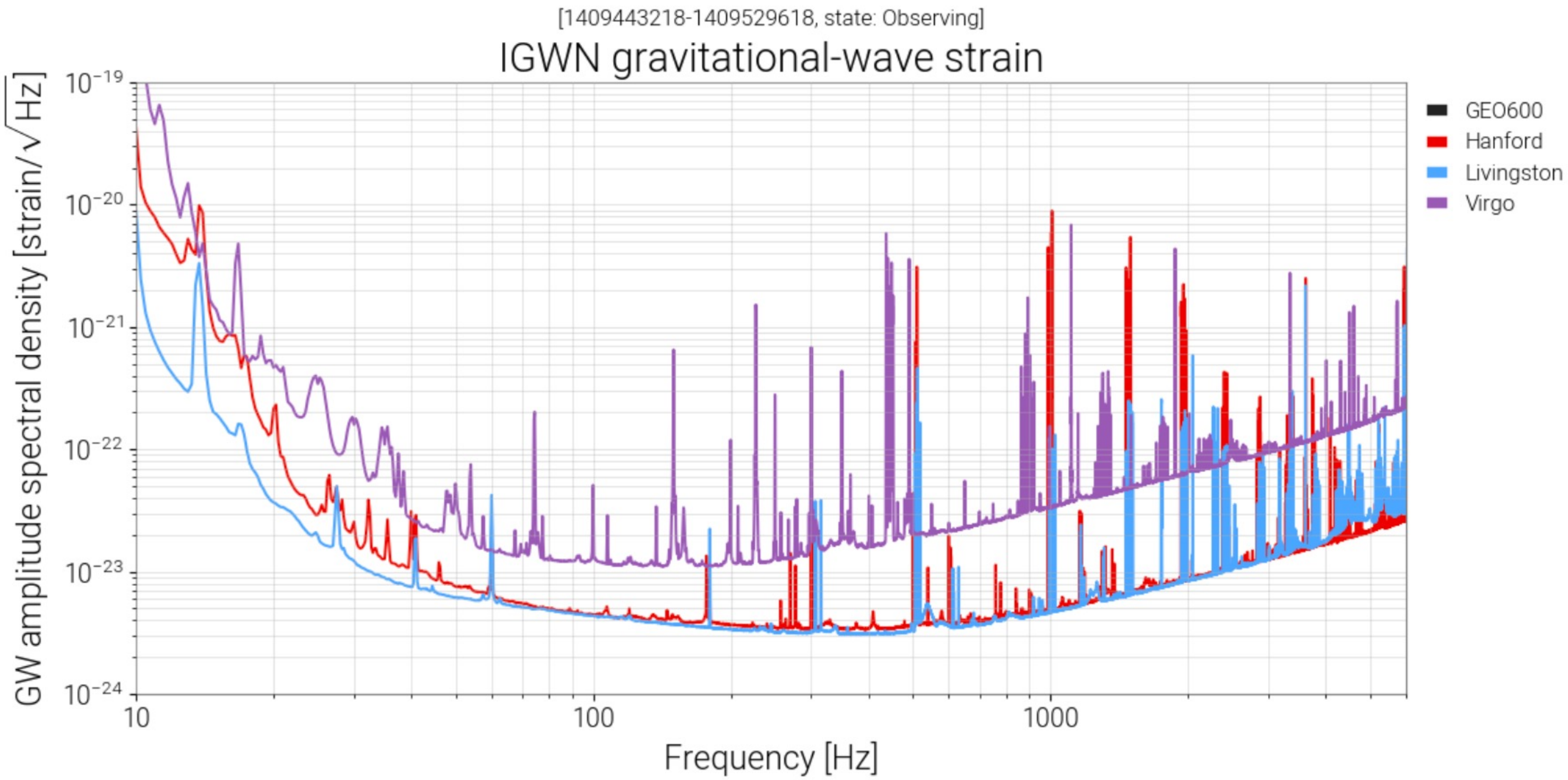
O3a Time Range: April 1, 2019 through October 1, 2019

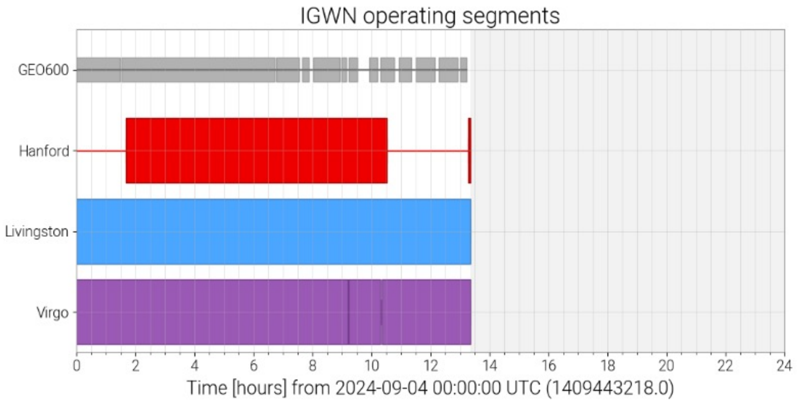
Detectors: H1, L1 and V1

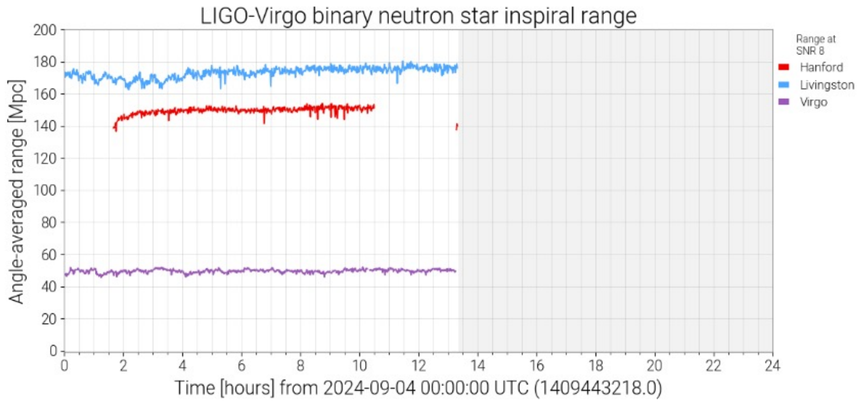
Credits: GWOSC

[Today's Summary Page](https://gwosc.org/detector_status/today)

https://gwosc.org/detector_status/today



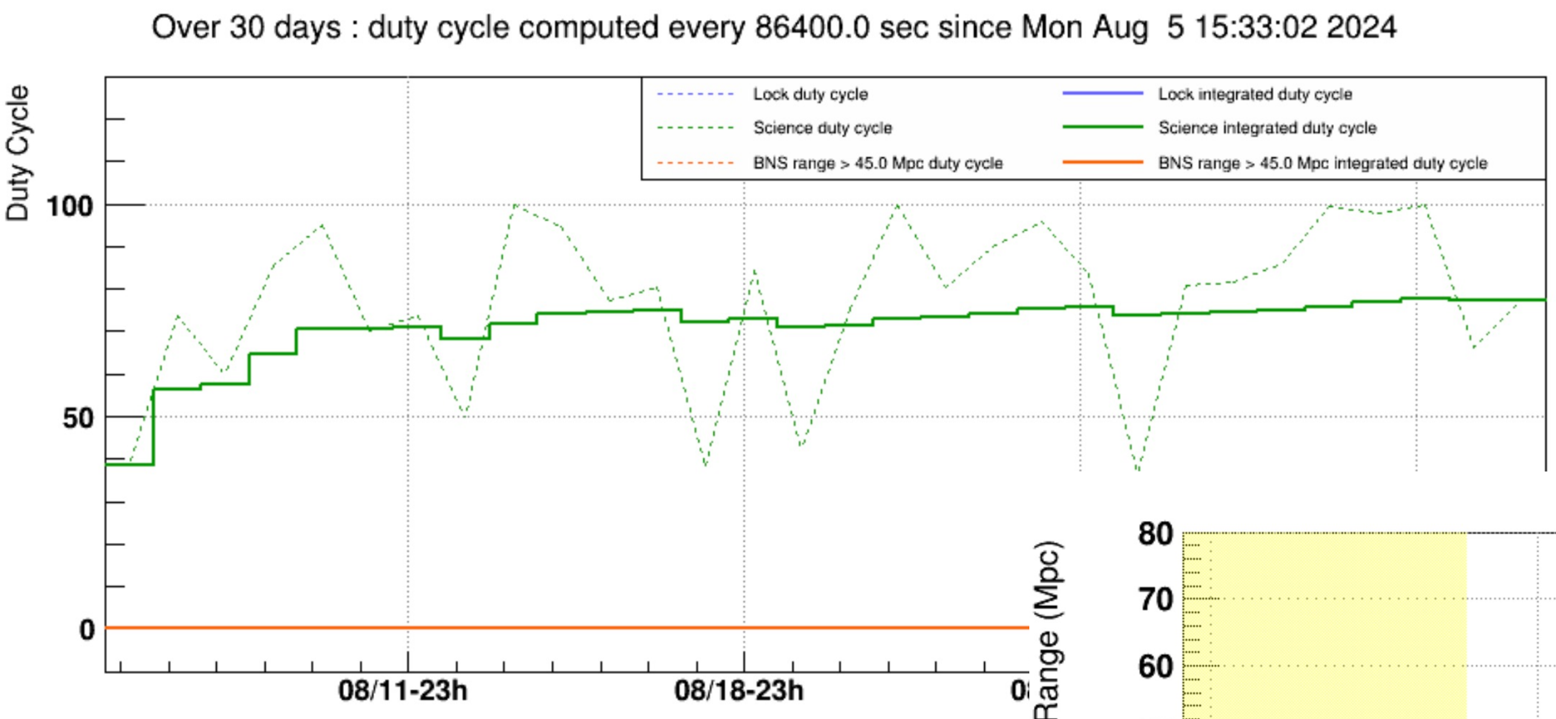


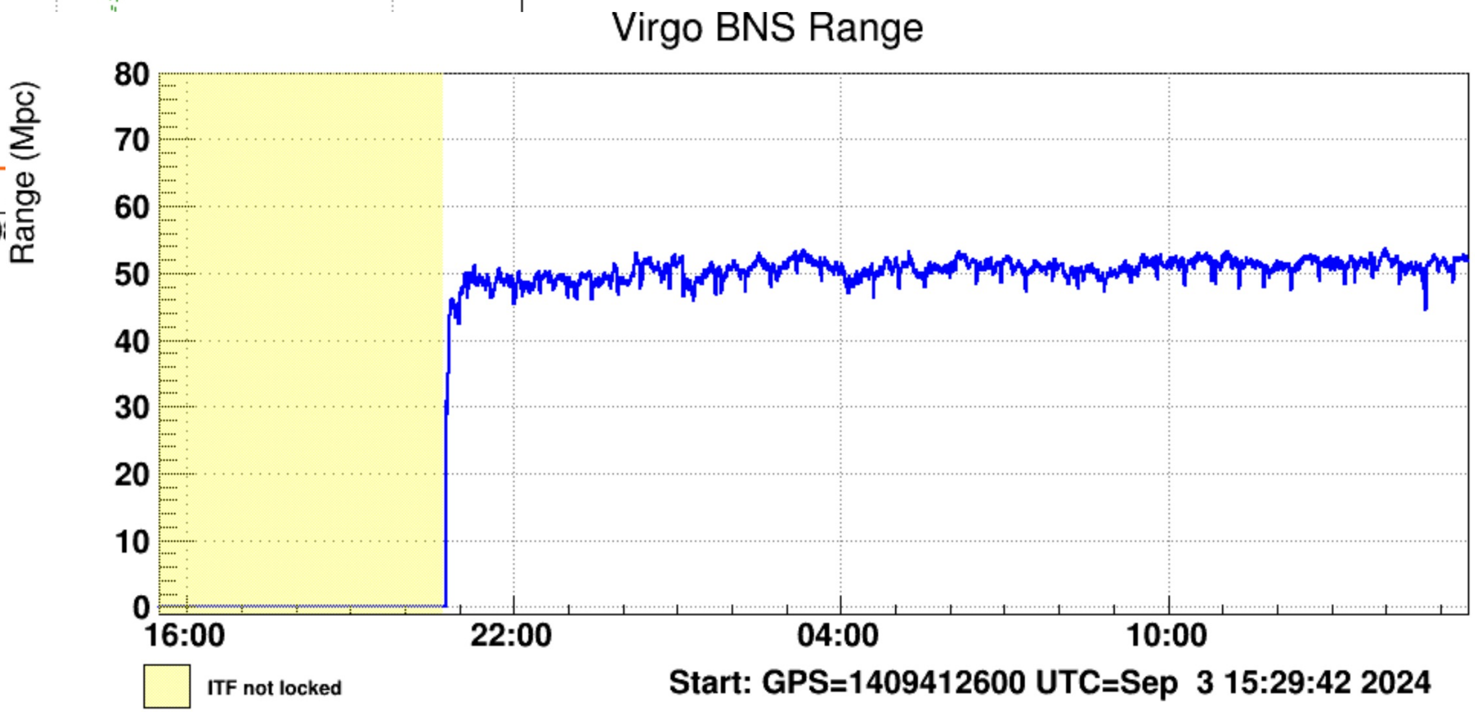


Credits: GWOSC

Virgo status

http://www.virgo-gw.eu/status.html





Credits: EGO/Virgo

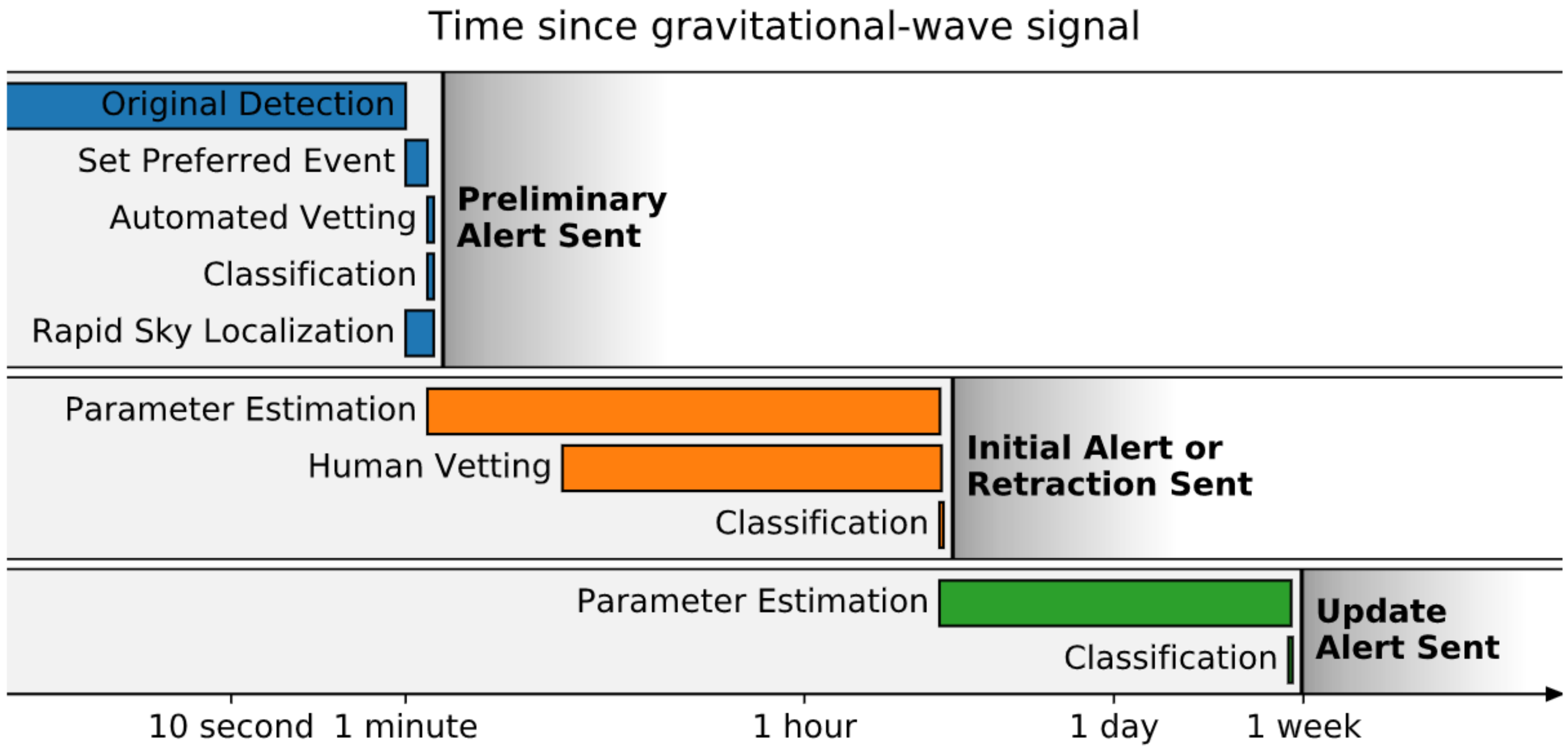
Multimessenger opportunitie

Open Public Alerts (OPA)

- LIGO/Virgo release alerts in low latency for transient candidates
  - No human vetting for Preliminary alert
  - Alerts distributed via Gamma-ray Coordinated Network (GCN)
  - Available at the Gravitational Wave Event Database (GraceDB) website
  - (https://graced.ligo.org)
- OPA User Guide & Mailing list
  - Available at https://emfollow.docs.ligo.org/userguide/quickstart.html
  - Mailing list at https://wiki.gw-astronomy.org/OpenLVEM

Credits: GWOSC

Multimessenger opportunities in O3



From OPA User Guide

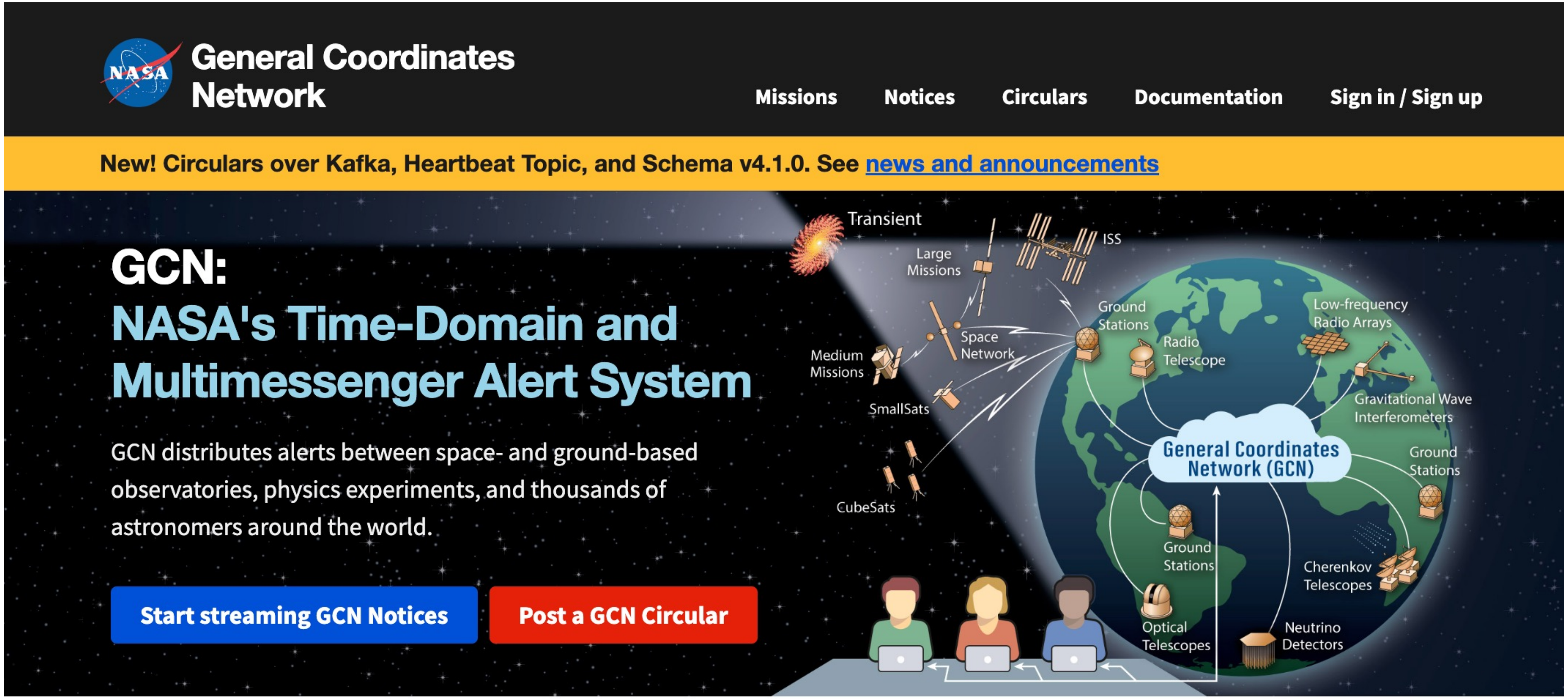
Last GraceDB triggers

UID	Labels	FAR (Hz)	Created
S240904ce	LOW_SIGNIF_LOCKED PASTRO_READY EM_READY EMBRIGHT_READY DQOK SKYMAP_READY LOW_SIGNIF_PRELIM_SENT	6.948e-06	2024-09-04 14:49:02 UTC
S240904bv	DQOK LOW_SIGNIF_PRELIM_SENT SKYMAP_READY LOW_SIGNIF_LOCKED EM_READY	4.902e-06	2024-09-04 13:37:23 UTC
S240904bl	DQOK LOW_SIGNIF_LOCKED EMBRIGHT_READY SKYMAP_READY EM_READY PASTRO_READY LOW_SIGNIF_PRELIM_SENT	6.029e-06	2024-09-04 09:09:48 UTC
S240904bk	SKYMAP_READY DQOK LOW_SIGNIF_LOCKED PASTRO_READY EM_READY EMBRIGHT_READY LOW_SIGNIF_PRELIM_SENT	1.880e-05	2024-09-04 09:08:34 UTC
S240904o	EMBRIGHT_READY LOW_SIGNIF_PRELIM_SENT LOW_SIGNIF_LOCKED PASTRO_READY SKYMAP_READY EM_READY DQOK	1.585e-05	2024-09-04 02:57:14 UTC
S240903cz	LOW_SIGNIF_PRELIM_SENT EMBRIGHT_READY SKYMAP_READY DQOK LOW_SIGNIF_LOCKED PASTRO_READY EM_COINC EM_READY	4.681e-06	2024-09-03 23:04:50 UTC
S240903cm	DQOK PASTRO_READY SKYMAP_READY LOW_SIGNIF_LOCKED EMBRIGHT_READY EM_READY LOW_SIGNIF_PRELIM_SENT	8.653e-06	2024-09-03 21:40:42 UTC
S240903aq	PASTRO_READY LOW_SIGNIF_LOCKED EMBRIGHT_READY SKYMAP_READY LOW_SIGNIF_PRELIM_SENT DQOK EM_READY	1.351e-05	2024-09-03 06:09:05 UTC

https://gracedb.ligo.org/latest

And you can check out the GCN page

https://gcn.nasa.gov (new site!)



The General Coordinates Network (GCN) is a public collaboration platform run by NASA for the astronomy research community to share alerts and rapid communications about high-energy, multimessenger, and transient phenomena. For more information, see What is GCN? or check out our slide deck.

GCN Notices

GCN Notices (can be filtered)

LIGO/Virgo/KAGRA

Gravitational-wave transients detected by the LIGO, Virgo, and KAGRA network.

GW

IceCube

High-energy astrophysical neutrino event candidates detected by IceCube, aggregated by AMON.

NU

HAWC

High-energy gamma rays detected by HAWC, aggregated by AMON.

GAMMA

IceCube–HAWC Coincidences

Coincidences between IceCube neutrino and HAWC gamma-ray events, aggregated by AMON.

GAMMA NU

IceCube Cascades

High-energy cascades detected by IceCube, aggregated by AMON.

NU

MAXI

X-ray transients detected by the MAXI instrument on the ISS.

X-RAY

Fermi GRBs

GRBs detected by the GBM and LAT instruments on Fermi.

GAMMA

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/LVC NOTICE
NOTICE_DATE:      Wed 04 Sep 24 14:49:35 UT
NOTICE_TYPE:      LVC Preliminary
TRIGGER_NUM:      S240904ce
TRIGGER_DATE:     20557 TJD;   248 DOY;   2024/09/04 (yyyy/mm/dd)
TRIGGER_TIME:     53326.491210 SOD {14:48:46.491210} UT
SEQUENCE_NUM:     1
GROUP_TYPE:       1 = CBC
SEARCH_TYPE:      1 = AllSky
PIPELINE_TYPE:    15 = pycbc
FAR:              6.949e-06 [Hz]  (one per 1.7 days)  (one per 0.00 years)
PROB_NS:          0.91 [range is 0.0-1.0]
PROB_REMNANT:     0.00 [range is 0.0-1.0]
PROB_BNS:         0.00 [range is 0.0-1.0]
PROB_NSBH:        0.01 [range is 0.0-1.0]
PROB_BBH:         0.00 [range is 0.0-1.0]
PROB_MassGap:     0.23 [range is 0.0-1.0]
PROB_TERRES:      0.99 [range is 0.0-1.0]
TRIGGER_ID:       0x10
MISC:             0x1898C07
SKYMAP_FITS_URL:  https://gracedb.ligo.org/api/superevents/S240904ce/files/bayestar.multiorder.fits,0
EVENTPAGE_URL:    https://gracedb.ligo.org/superevents/S240904ce/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.
```

https://gcn.nasa.gov

GCN Circulars

GCN Circulars

GCN Circulars are rapid astronomical bulletins submitted by and distributed to community members worldwide. They are used … discoveries, observations, quantitative near-term predictions, requests for follow-up observations, or future observing plans related … energy, multi-messenger, and variable or transient astrophysical events. See the documentation for help with subscribing to or subm… Circulars.

Search | Filter by date | New

Search for Circulars by submitter, subject, or body text (e.g. 'Fermi GRB').
To navigate to a specific circular, enter the associated Circular ID (e.g. 'gcn123', 'Circular 123', or '123').

37382. GRB 240828A: SVOM/GRM observation
37381. LIGO/Virgo/KAGRA S240825ar: Upper limits from Swift/BAT-GUANO
37380. LIGO/Virgo/KAGRA S240807h: Upper limits from Swift/BAT-GUANO
37379. Fermi Gamma-ray Burst Monitor trigger 240831A is not a GRB
37378. LIGO/Virgo/KAGRA S240902bq: Updated Sky localization
37377. GRB 240828A: GECAM detection
37376. GRB 240831B: Fermi GBM Final Localization
37375. Fermi Gamma-ray Burst Monitor trigger 746882332/240901471 is not a GRB
37374. LIGO/Virgo/KAGRA S240902bq: Identification of a GW compact binary merger candidate
37373. GRB 240825A: Magnitude Correction in SVOM/C-GFT Optical Observations
37372. GRB 240825A: MeerLICHT afterglow detection
37371. Fermi trigger No 746923430: Global MASTER-Net observations report
37370. GRB 240828A: SAO RAS AS-500(2) optical observations
37369. GRB 240821A: VLT spectroscopic observations
37368. Fermi trigger No 746882332: Global MASTER-Net observations report
37367. GRB 240825A: TSHAO Optical Upper Limit
37366. GRB 240829B: GRBAlpha detection
37365. GRB240828B: REM optical/NIR upper limits
37364. Fermi trigger No 746816563: Global MASTER-Net observations report

GCN Circular 37380

Subject LIGO/Virgo/KAGRA S240807h: Upper limits from Swift/BAT-GUANO
Date 2024-09-04T02:16:08Z (14 hours ago)
From Samuele Ronchini at PSU <sjs8171@psu.edu>
Via Web form

Samuele Ronchini (PSU), Aaron Tohuvavohu (U Toronto), Tyler Parsotan (NASA GSFC), Jamie A. Kennea (PSU), James DeLaunay (PSU), Gayathri Raman (PSU) report:

Swift/BAT was observing 63% of the GW localization probability (bayestar.multiorder.fits) at merger time. A fraction 35% of the GW localization posterior is contained inside the BAT coded FoV.

The LVK notice, distributed in near real-time, triggered the Swift Mission Operations Center operated Gamma-ray Urgent Archiver for Novel Opportunities (GUANO; Tohuvavohu et al. 2020, ApJ, 900, 1).

Upon trigger by this notice, GUANO sent a command to the Swift Burst Alert Telescope (BAT) to save 200 seconds of BAT event-mode data from [-50,+150] seconds around the time of the burst. All the requested event mode data was delivered to the ground.

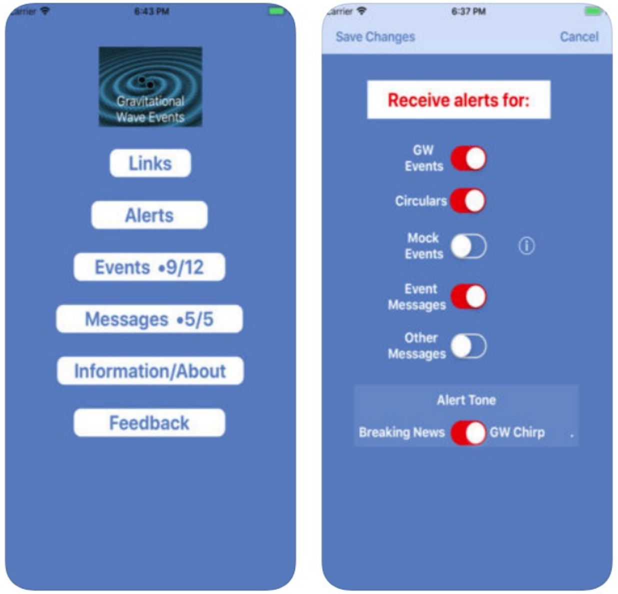
GCN Circular 37378

Subject LIGO/Virgo/KAGRA S240902bq: Updated Sky localization
Date 2024-09-03T09:17:58Z (a day ago)
From Christopher P L Berry at LVK Collaboration <christopher.berry@ligo.org>
Via Web form

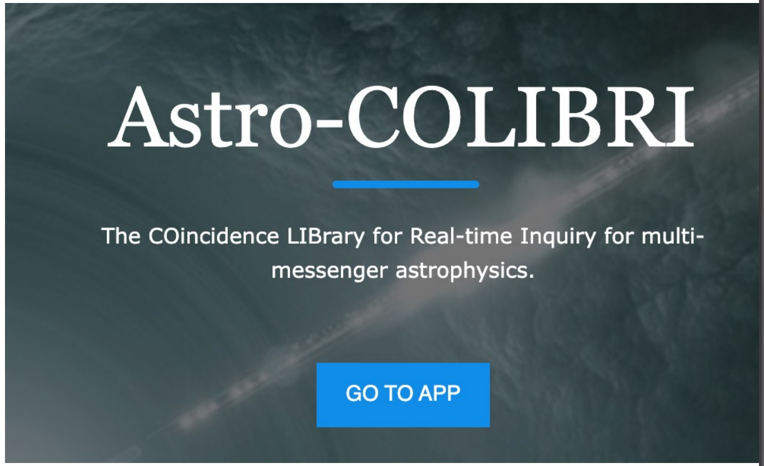
```
The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration report:

We have conducted further analysis of the LIGO Hanford Observatory (H1), LIGO Livingston Observatory
(L1), and Virgo Observatory (V1) data around the time of the compact binary merger (CBC) candidate
S240902bq (GCN Circular 37374). Parameter estimation has been performed using Bilby [1] and a new sky
map, Bilby.multiorder.fits,0, distributed via GCN Notice, is available for retrieval from the GraceDB
event page:

https://gracedb.ligo.org/superevents/S240902bq

For the Bilby.multiorder.fits,0 sky map, the 90% credible region is well fit by an ellipse with an area
of 779 deg2 described by the following DS9 region (right ascension, declination, semi-major axis, semi-
minor axis, position angle of the semi-minor axis):
   icrs; ellipse(05h33m, +42d39m, 56.48d, 4.58d, 117.03d)
Marginalized over the whole sky, the a posteriori luminosity distance estimate is 2420 +/- 828 Mpc (a
posteriori mean +/- standard deviation).

For further information about analysis methodology and the contents of this alert, refer to the
LIGO/Virgo/KAGRA Public Alerts User Guide https://emfollow.docs.ligo.org/.

 [1] Ashton et al. ApJS 241, 27 (2019) doi:10.3847/1538-4365/ab06fc and Morisaki et al. (2023)
arXiv:2307.13380
```

https://gcn.nasa.gov

Finally…everything on your phone



Gravitational Wave Events (Apple Store)



Astro-COLIBRI Web/Android/iOS

M. Razzano

The gwpy Package

- Gwpy is a public, Python-based package to access and manipulate GW data
- Easy to install via PIP or conda

https://gwpy.github.io/

Getting data from GWOSC

- Use the gwosc library (install with pip or conda)
- You can get a list of all the events available

```
[1]: #explore the events in the dataset
     from gwosc.datasets import find_datasets
     events = find_datasets(type="event")
     print(events)
```

```
['151008-v1', '151012.2-v1', '151116-v1', '161202-v1', '161217-v1', '170208-v1', '170219-v1', '170405-v1', '170412-v1', '170423-v1', '17061
-v1', '170630-v1', '170705-v1', '170720-v1', '190924_232654-v1', '191118_212859-v1', '191223_014159-v1', '191225_215715-v1', '200114_020818-
v1', '200121_031748-v1', '200201_203549-v1', '200214_224526-v1', '200214_224526-v2', '200219_201407-v1', '200311_103121-v1', 'GRB051103-v1',
'GW150914-v1', 'GW150914-v2', 'GW150914-v3', 'GW151012-v1', 'GW151012-v2', 'GW151012-v3', 'GW151226-v1', 'GW151226-v2', 'GW170104-v1', 'GW17
0104-v2', 'GW170608-v1', 'GW170608-v2', 'GW170608-v3', 'GW170729-v1', 'GW170809-v1', 'GW170814-v1', 'GW170814-v2', 'GW170814-v3', 'GW170817-
v1', 'GW170817-v2', 'GW170817-v3', 'GW170818-v1', 'GW170823-v1', 'GW190403_051519-v1', 'GW190408_181802-v1', 'GW190408_181802-v2', 'GW19041
-v1', 'GW190412-v2', 'GW190412-v3', 'GW190412_053044-v4', 'GW190413_052954-v1', 'GW190413_052954-v2', 'GW190413_134308-v1', 'GW190413_13430
-v2', 'GW190421_213856-v1', 'GW190421_213856-v2', 'GW190424_180648-v1', 'GW190424_180648-v2', 'GW190425-v1', 'GW190425-v2', 'GW190425_08180
-v3', 'GW190426_152155-v1', 'GW190426_152155-v2', 'GW190426_190642-v1', 'GW190503_185404-v1', 'GW190503_185404-v2', 'GW190512_180714-v1', '
W190512_180714-v2', 'GW190513_205428-v1', 'GW190513_205428-v2', 'GW190514_065416-v1', 'GW190514_065416-v2', 'GW190517_055101-v1', 'GW190517_
055101-v2', 'GW190519_153544-v1', 'GW190519_153544-v2', 'GW190521-v1', 'GW190521-v2', 'GW190521-v3', 'GW190521_030229-v4', 'GW190521_074359-
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190620_030421-v1', 'GW190620_030421-v2', 'GW190630_185205-v1', 'GW190630_185205-v2', 'GW190701_203306-v1', 'GW190701_203306-v2', 'GW190706_
22641-v1', 'GW190706_222641-v2', 'GW190707_093326-v1', 'GW190707_093326-v2', 'GW190708_232457-v1', 'GW190708_232457-v2', 'GW190719_215514-v
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0717-v1', 'GW191113_071753-v1', 'GW191126_115259-v1', 'GW191127_050227-v1', 'GW191129_134029-v1', 'GW191204_110529-v1', 'GW191204_171526-v
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62426-v2', 'GW200112_155838-v1', 'GW200115-v1', 'GW200115_042309-v2', 'GW200128_022011-v1', 'GW200129_065458-v1', 'GW200202_154313-v1', 'GW2
00208_130117-v1', 'GW200208_222617-v1', 'GW200209_085452-v1', 'GW200210_092254-v1', 'GW200216_220804-v1', 'GW200219_094415-v1', 'GW200220_06
1928-v1', 'GW200220_124850-v1', 'GW200224_222234-v1', 'GW200225_060421-v1', 'GW200302_015811-v1', 'GW200306_093714-v1', 'GW200308_173609-v
1', 'GW200311_115853-v1', 'GW200316_215756-v1', 'GW200322_091133-v1', 'GW230529_181500-v1', 'blind_injection-v1']
```

Getting data from GWOSC – get single event

- Once you have found the event you want to analize, you can retrieve its (GPS) time.
- Or, you can just look for data around a certain GPS time
- Remember…GPS time is used

```
[2]: #Let's see the data relative to the first detection
#you will receive a list of files, that you could download in your data dir for future use,
#or just use the fetch command (see below) to use the files in real time
ev_name = "GW150914"

#interferometer to use
ev_ifo = "H1"

from gwosc.datasets import event_gps
from gwosc.locate import get_event_urls

ev_gps = event_gps(ev_name)
event_urls = get_event_urls(ev_name)

print("%s,%.1f,%s" % (ev_name,ev_gps,event_urls))
```

```
GW150914,1126259462.4,['http://gwosc.org/eventapi/json/GWTC-1-confident/GW150914/v3/H-H1_GWOSC_4KHZ_R1-1126259447-32.hdf5', 'http://gwosc.or
g/eventapi/json/GWTC-1-confident/GW150914/v3/H-H1_GWOSC_4KHZ_R1-1126257415-4096.hdf5', 'http://gwosc.org/eventapi/json/GWTC-1-confident/GW15
0914/v3/L-L1_GWOSC_4KHZ_R1-1126259447-32.hdf5', 'http://gwosc.org/eventapi/json/GWTC-1-confident/GW150914/v3/L-L1_GWOSC_4KHZ_R1-1126257415-4
096.hdf5']
```

Getting data from GWOSC – get single event

- **Now we can fetch the data**
- **Don't forget to import gwpy!**

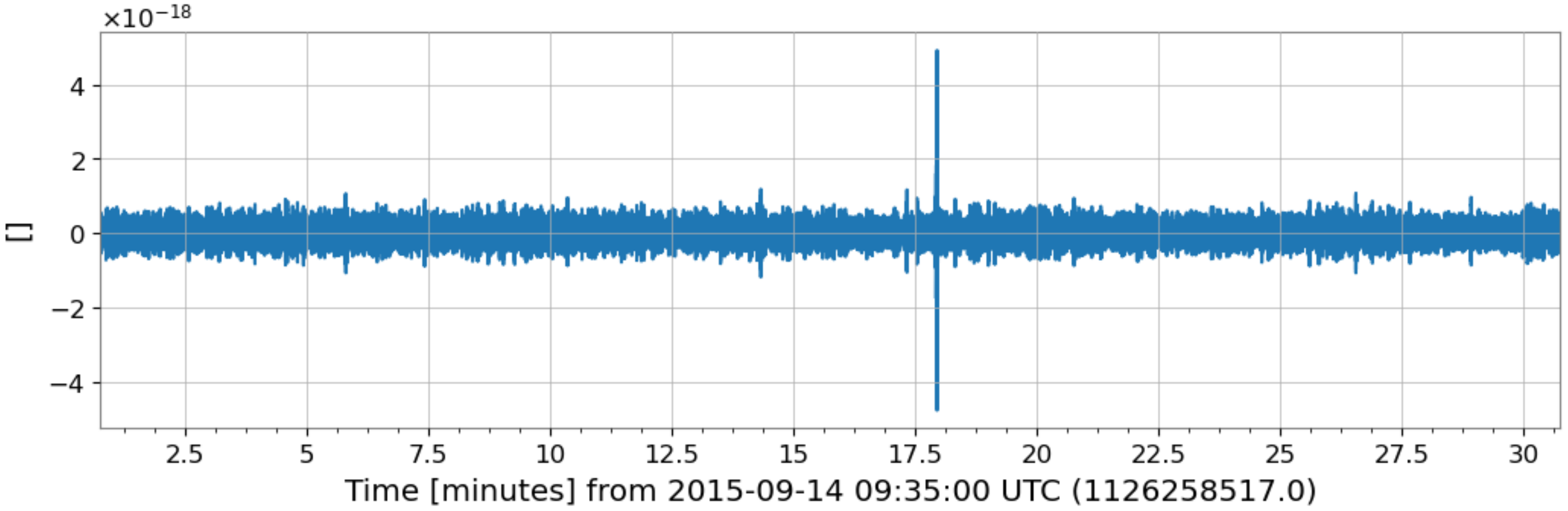
```
[6]: import gwpy
from gwpy.timeseries import TimeSeries
from gwpy.segments import DataQualityFlag

# Select a time interval of 30 mins around the event. This is because on GWOSC there is 1 hour data window released around
dt_win=3600*0.25
ev_t0_min = ev_gps-dt_win
ev_t0_max = ev_gps+dt_win

print("Get data for %s (%s) GPS: %.2f - %.2f" % (ev_name,ev_ifo,ev_t0_min,ev_t0_max))

#fetch the data. Use cache=True to keep the data in the cache memory (to speed things up)
data = TimeSeries.fetch_open_data(ev_ifo,ev_t0_min,ev_t0_max,cache=True)

#get the segments in a larger time window (just to have a bigger time span to look over)
segments = DataQualityFlag.fetch_open_data(ev_ifo+"_DATA",ev_t0_min-dt_win,ev_t0_max+dt_win)
print("Done")
```

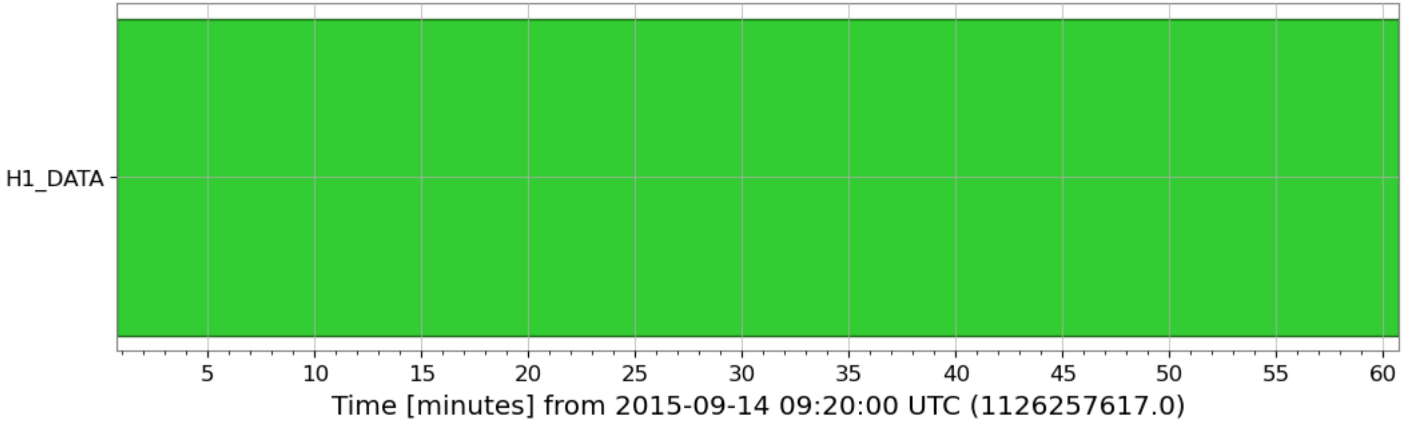
```
Get data for GW150914 (H1) GPS: 1126258562.40 - 1126260362.40
Done
```

Do some plotting with gwpy

- **It is quite easy**
- **Data is the h(t), data segments give you the quality of the data (green is ok!)**

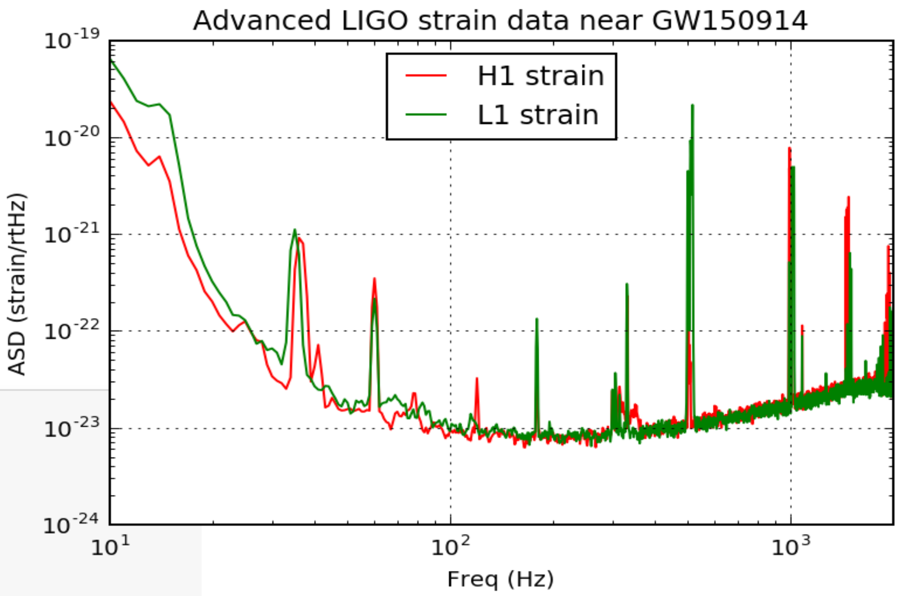
```
from gwpy.plot import Plot

%matplotlib inline

#Plot raw data....
plot_data=data.plot()
plot_data.show()

#..and segments. Green is data ok, red is data bad...
plot = segments.plot()
```



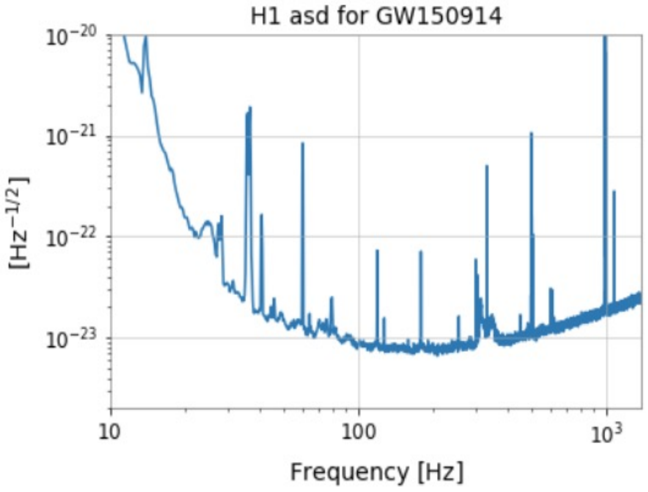


In this example, we take LIGO Hanford (H1) data

Building the ASD



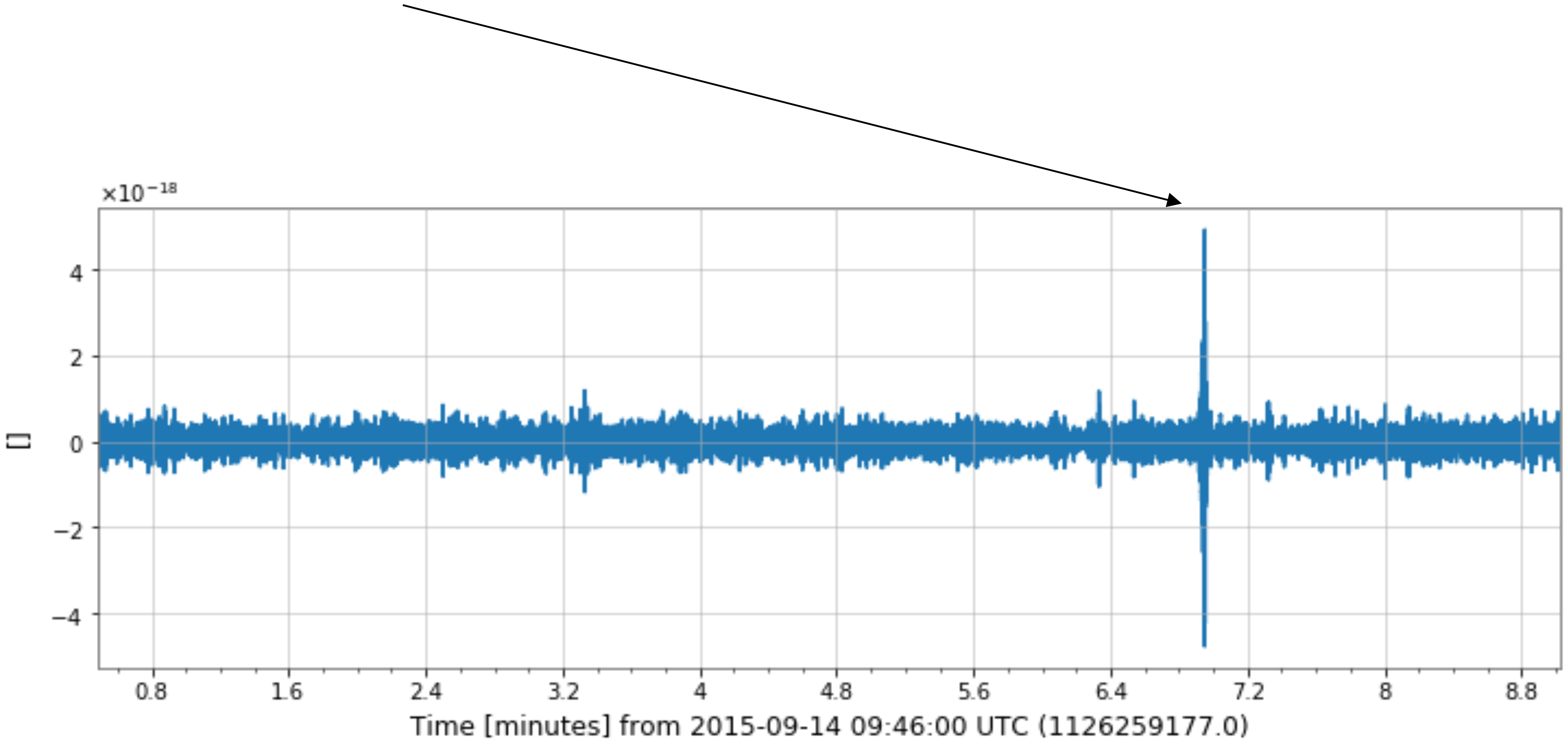
In [11]:
```
#Now we can plot the ASD as well, using the Welch method with a overlapping window of 4 seconds

asd = data.asd(fftlength=4, method="median")
plot = asd.plot()

ax = plot.gca()
ax.set_xlim(10, 1400)
ax.set_ylim(2e-24, 1e-20)
ax.set_title(ev_ifo+ " asd for "+ev_name)
plot.refresh()
```



•Filtering the signal

- With gwpy it is possible to bandpass the signal, to remove the dominant noise frequencies (e.g. the lower ones), or remove specific lines (e.g. “notching”)

- **Is this the signal?**

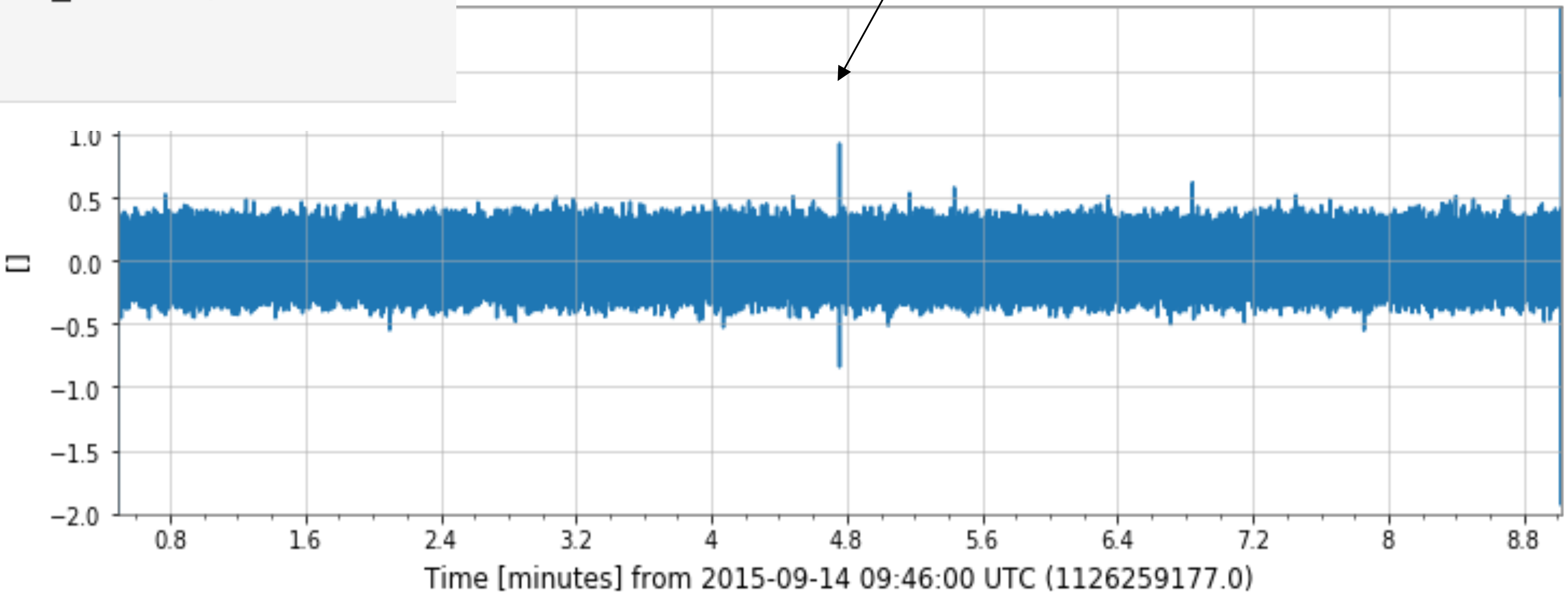


•Filtering the signal

- With gwpy it is possible to bandpass the signal, to remove the dominant noise frequencies (e.g. the lower ones), or remove specific lines (e.g. “notching”)

```
#then a medium frequency filter. Something is visible?
data_filtered=data.bandpass(50,250)

plot = data_filtered.plot()
ax = plot.gca()

#zoom around the event. Can we see something now?
ax.set_xlim(ev_gps-dt_win*0.1,ev_gps+dt_win*0.1)
ax.set_ylim(-2e-21,2e-21)
plot.refresh()
```

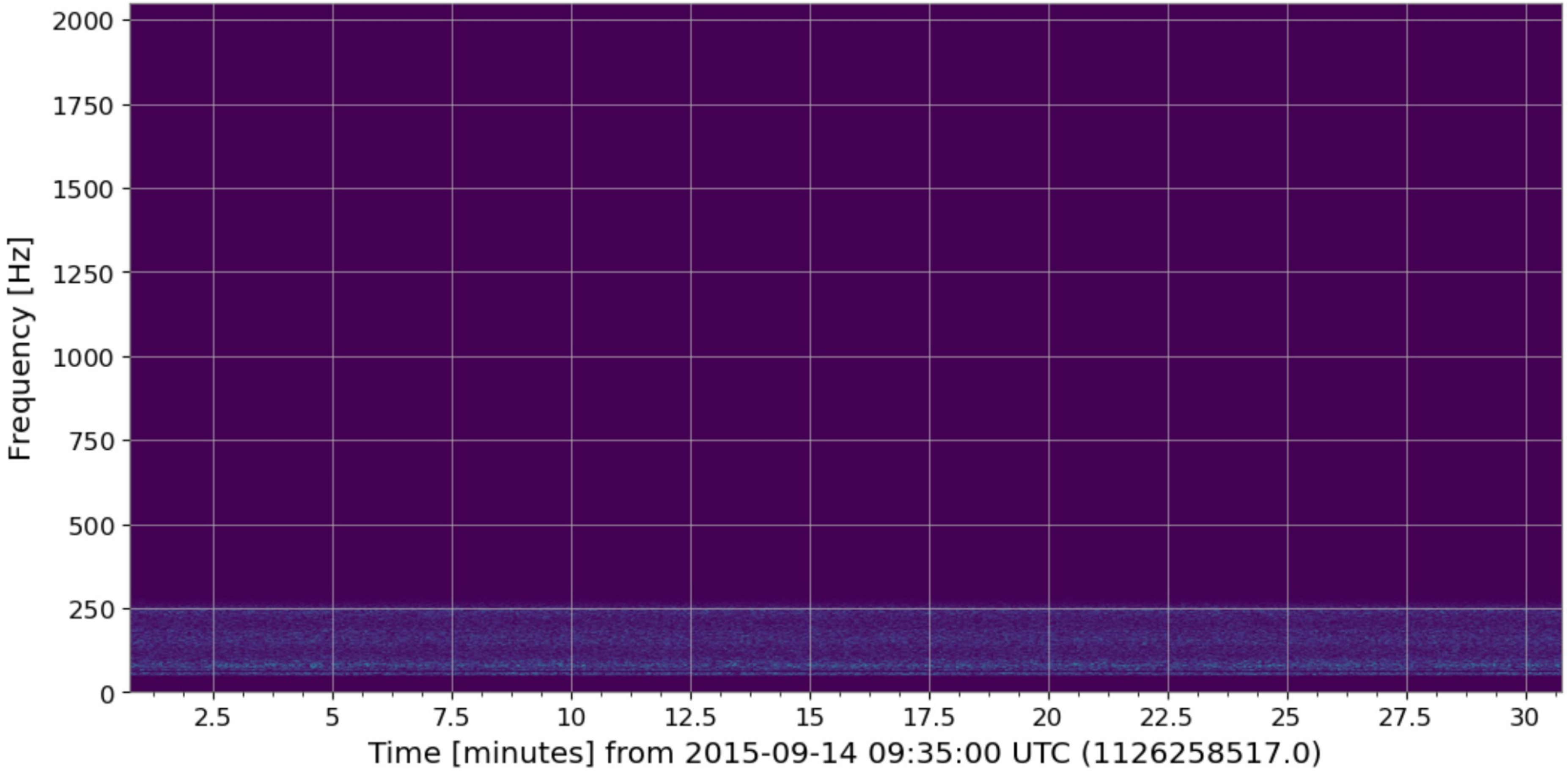
- **Here it is**



Spectrograms

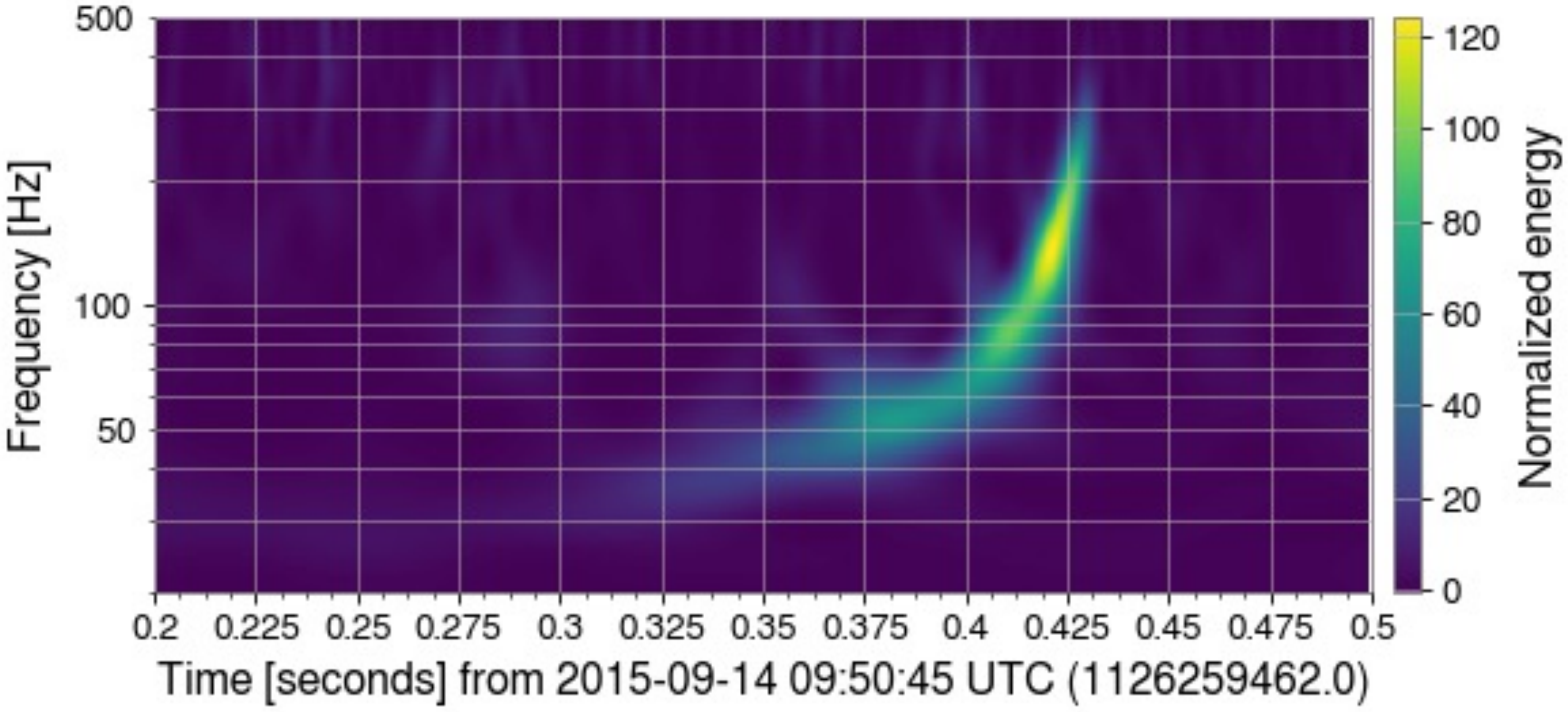
Spectrograms can be easily computed with gwpy

```
#now, the spectrograms
specgram = data_filtered.spectrogram2(fftlength=4, overlap=2, window='hann') ** (1/2.)
plot = specgram.plot()
```



Q transform

Similar to Wavelets (Morlet wavelet).
Filters centered t fk = $(2^{1/n})^k df_{min}$
Quality factor Q = f_k/df_k



What next?

- There is not just gwpy…
- There are not just Compact Binary Coalescences…
- Stay tuned!