LSC LIGO Scientific Collaboration

VIRGO

# Gravitational Wave Open Science

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# GWOSC

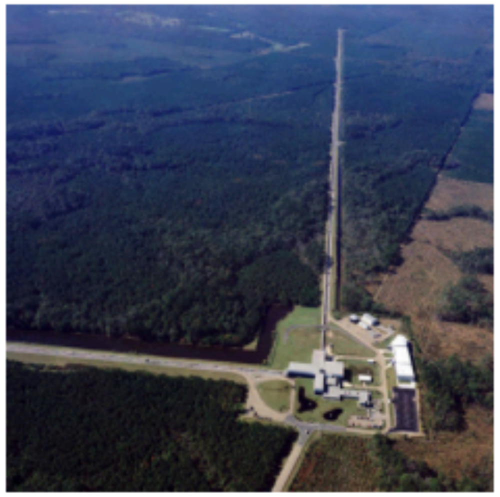
https://www.gw-openscience.org/

Gravitational Wave Open Science Center

Data ▾ Software ▾ Online Status ▾ About GWOSC ▾

**The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.**

LIGO Hanford Observatory, Washington
(Credits: C. Gray)



LIGO Livingston Observatory, Louisiana
(Credits: J. Giaime)

Virgo detector, Italy
(Credits: Virgo Collaboration)

**Get started!**

**LIGO/Virgo alerts began April 2, 2019**

**Download data**

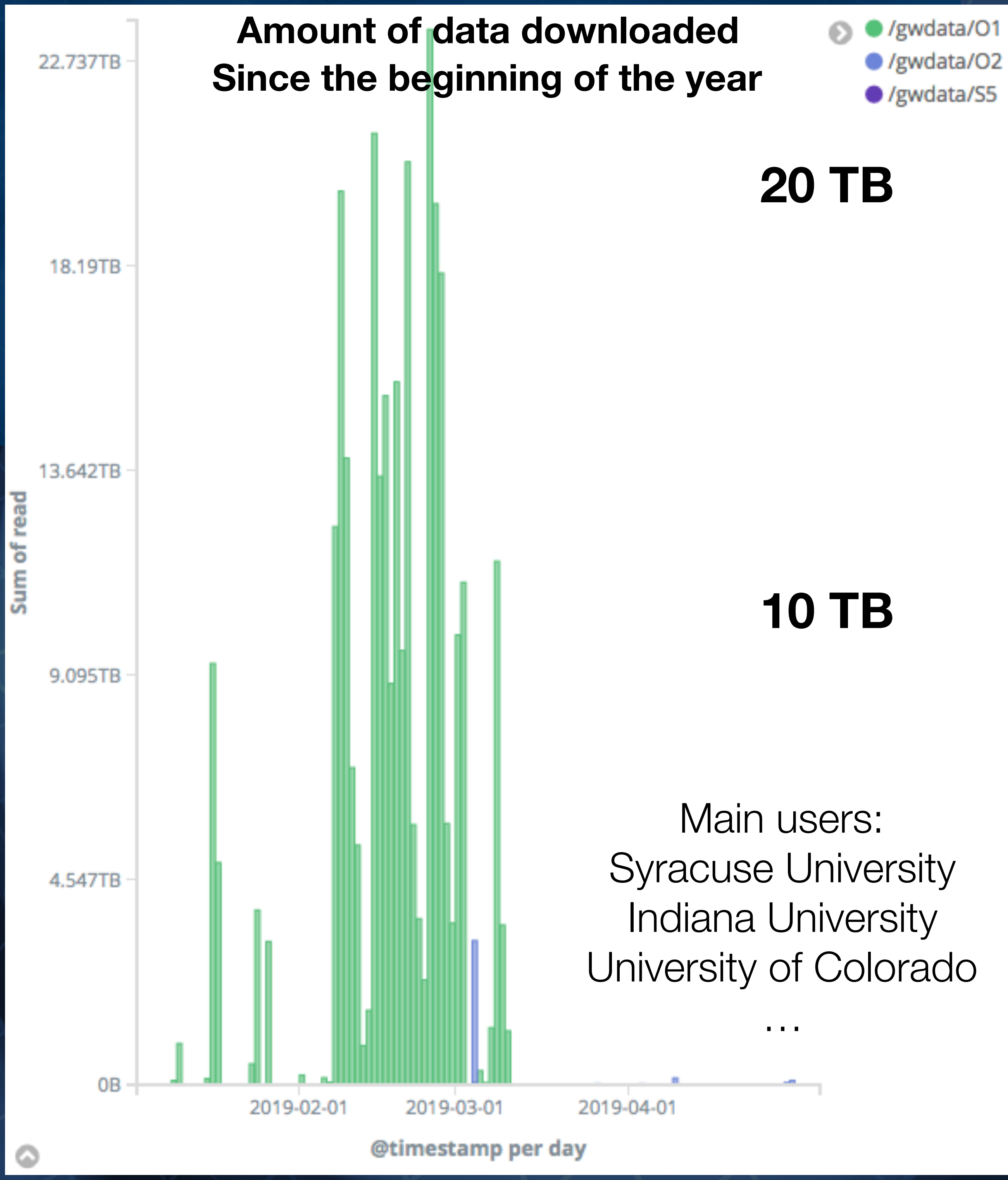
**Join the email list**

**Attend an open data workshop**

Importance of Open Science:
- Public owns the data
- Maximize discovery
- Multi-messenger astronomy
- Wider community

# GWOSC Impact

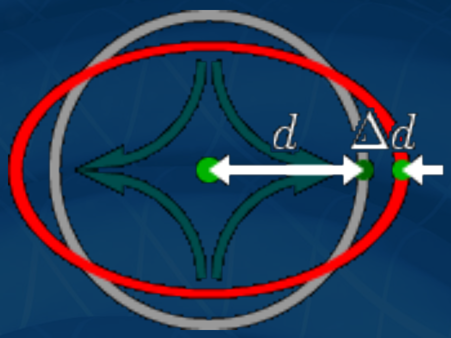
- Examples of projects using GWOSC data: https://www.gw-openscience.org/projects/
  - ✓ Scientific papers (about 60 at the moment)
  - ✓ Pioneer Academics student projects
  - ✓ iPhone App: Gravitational Wave Events
  - ✓ Online Course
  - ✓ Art installation



# LIGO/Virgo data

- LIGO/Virgo data: strain, data quality and hardware injections
- LIGO/Virgo data are arranged in files provided in different formats:
  - HDF5: easily readable in python, MATLAB, C/C++, and IDL
  - Frame format (.gwf)
  - Text file

**Reminder: strain**




$$h = \frac{\Delta d}{d} = \frac{change\ in\ relative\ position}{separation}$$

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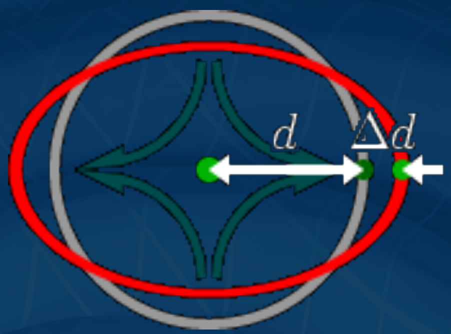
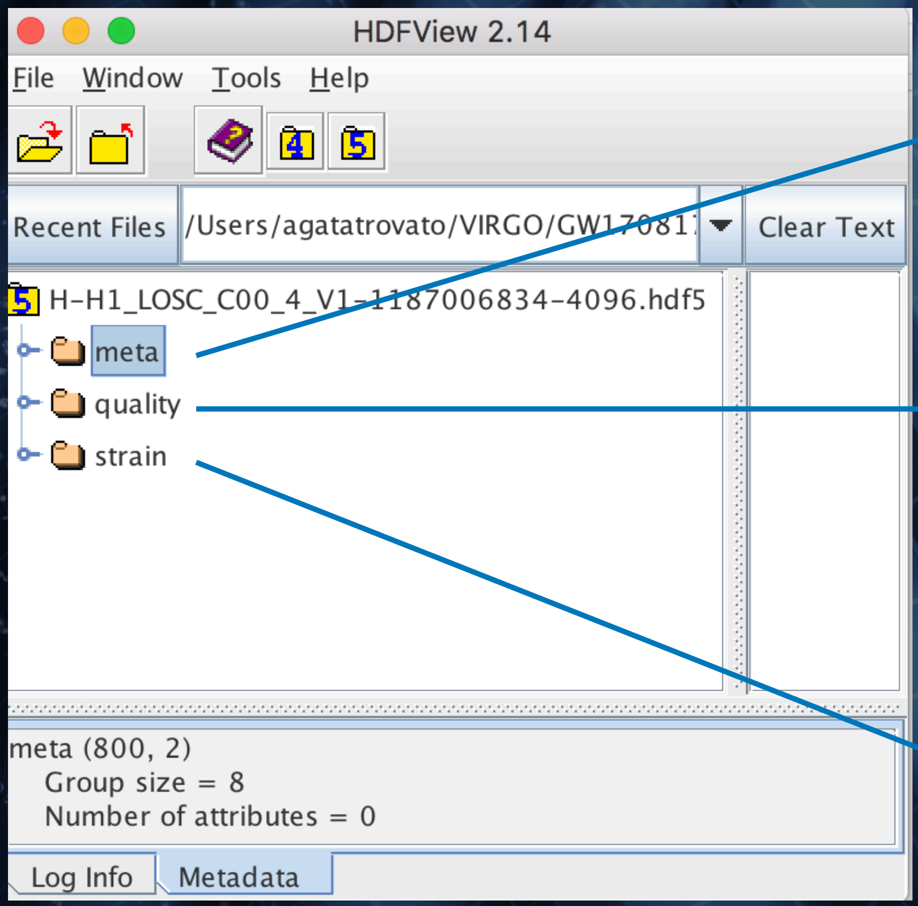



$$h = \frac{\Delta d}{d} = \frac{\textit{change in relative position}}{\textit{separation}}$$

You can use HDFView to quickly see what is inside the file




Meta-data for the file. This is basic information such as the GPS times covered, which instrument, etc.

Refers to data quality. The main item here is a 1 Hz time series describing the data quality for each second of data.

Strain data from the interferometer. In some sense, this is "the data", the main measurement performed by LIGO/Virgo.

# GWOSC releases

- Open data can be found at https://www.gw-openscience.org
- Two different types of data release:

***Gravitational wave data surrounding discoveries***

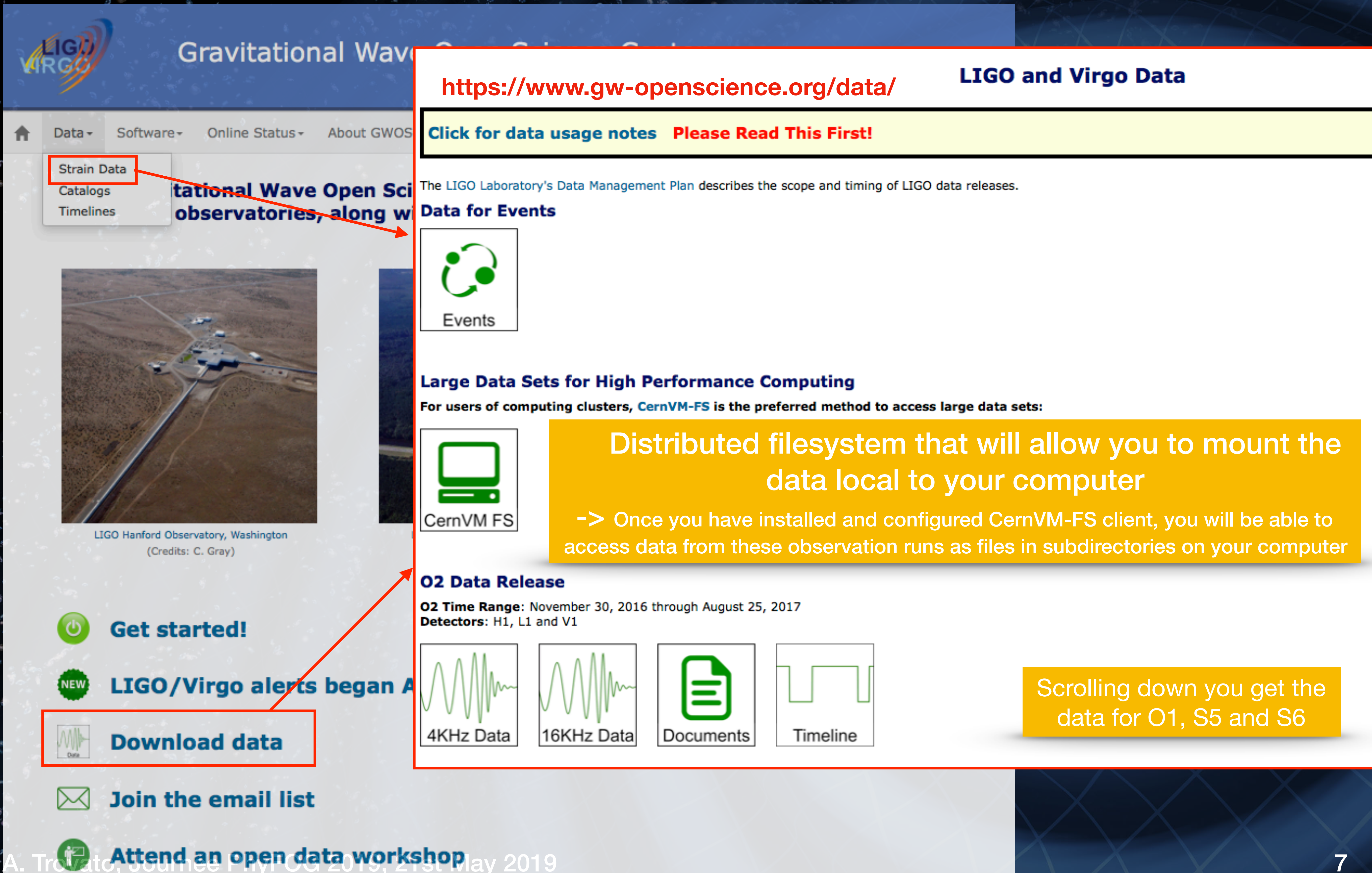
***Data taken during a whole observation run***

- Some releases:

**BBH = Binary Black Hole*
***BNS = Binary Neutron Star*

| Data | Date of release |
|---|---|
| GW150914: First Observed BBH* | Feb 2016 |
| GW170817: First Observed BNS** | Oct 2017 (about 60 days after the discovery) |
| First Observing run, **O1** (Sep 2015 - Jan 2016) | Jan 2018 |
| GWTC-1 Catalog (O1 + O2 detections) | Dec 2018 |
| Second Observing run, **O2** (Nov 2016 - Aug 2017) | Feb 2019 |

# GWOSC bulk data



# GWTC-1: Gravitational-Wave Transient Catalog of Compact Binary Mergers

- https://www.gw-openscience.org/catalog/
- 11 confident detection + 14 marginal triggers
- Strain data + documentation + auxiliary data products (Skymaps, Parameter Estimation Samples,…)

JSON Parameter Table

Show/hide columns

SORT: **PRIMARY MASS (M_SUN) ↑**

| Event | Primary mass (M_sun) | Secondary mass (M_sun) | Effective inspiral spin | chirp mass (M_sun) | Final spin | Final mass (M_sun) | Luminosity distance (Mpc) | GPS time (s) |
|---|---|---|---|---|---|---|---|---|
| GW150914 | $35.6^{+4.8}_{-3.0}$ | $30.6^{+3.0}_{-4.4}$ | $-0.01^{+0.12}_{-0.13}$ | $28.6^{+1.6}_{-1.5}$ | $0.69^{+0.05}_{-0.04}$ | $63.1^{+3.3}_{-3.0}$ | $430^{+150}_{-170}$ | 1126259462.4 |
| GW151012 | $23.3^{+14.0}_{-5.5}$ | $13.6^{+4.1}_{-4.8}$ | $0.04^{+0.28}_{-0.19}$ | $15.2^{+2.0}_{-1.1}$ | $0.67^{+0.13}_{-0.11}$ | $35.7^{+9.9}_{-3.8}$ | $1060^{+540}_{-480}$ | 1128678900.4 |
| GW151226 | $13.7^{+8.8}_{-3.2}$ | $7.7^{+2.2}_{-2.6}$ | $0.18^{+0.20}_{-0.12}$ | $8.9^{+0.3}_{-0.3}$ | $0.74^{+0.07}_{-0.05}$ | $20.5^{+6.4}_{-1.5}$ | $440^{+180}_{-190}$ | 1135136350.6 |
| GW170104 | $31.0^{+7.2}_{-5.6}$ | $20.1^{+4.9}_{-4.5}$ | $-0.04^{+0.17}_{-0.20}$ | $21.5^{+2.1}_{-1.7}$ | $0.66^{+0.08}_{-0.10}$ | $49.1^{+5.2}_{-3.9}$ | $960^{+430}_{-410}$ | 1167559936.6 |
| GW170608 | $10.9^{+5.3}_{-1.7}$ | $7.6^{+1.3}_{-2.1}$ | $0.03^{+0.19}_{-0.07}$ | $7.9^{+0.2}_{-0.2}$ | $0.69^{+0.04}_{-0.04}$ | $17.8^{+3.2}_{-0.7}$ | $320^{+120}_{-110}$ | 1180922494.5 |
| GW170729 | $50.6^{+16.6}_{-10.2}$ | $34.3^{+9.1}_{-10.1}$ | $0.36^{+0.21}_{-0.25}$ | $35.7^{+6.5}_{-4.7}$ | $0.81^{+0.07}_{-0.13}$ | $80.3^{+14.6}_{-10.2}$ | $2750^{+1350}_{-1320}$ | 1185389807.3 |
| GW170809 | $35.2^{+8.3}_{-6.0}$ | $23.8^{+5.2}_{-5.1}$ | $0.07^{+0.16}_{-0.16}$ | $25.0^{+2.1}_{-1.6}$ | $0.70^{+0.08}_{-0.09}$ | $56.4^{+5.2}_{-3.7}$ | $990^{+320}_{-380}$ | 1186302519.8 |
| GW170814 | $30.7^{+5.7}_{-3.0}$ | $25.3^{+2.9}_{-4.1}$ | $0.07^{+0.12}_{-0.11}$ | $24.2^{+1.4}_{-1.1}$ | $0.72^{+0.07}_{-0.05}$ | $53.4^{+3.2}_{-2.4}$ | $580^{+160}_{-210}$ | 1186741861.5 |
| GW170817 | $1.46^{+0.12}_{-0.10}$ | $1.27^{+0.09}_{-0.09}$ | $0.00^{+0.02}_{-0.01}$ | $1.186^{+0.001}_{-0.001}$ | $\leq 0.89$ | $\leq 2.8$ | $40^{+10}_{-10}$ | 1187008882.4 |
| GW170818 | $35.5^{+7.5}_{-4.7}$ | $26.8^{+4.3}_{-5.2}$ | $-0.09^{+0.18}_{-0.21}$ | $26.7^{+2.1}_{-1.7}$ | $0.67^{+0.07}_{-0.08}$ | $59.8^{+4.8}_{-3.8}$ | $1020^{+430}_{-360}$ | 1187058327.1 |
| GW170823 | $39.6^{+10.0}_{-6.6}$ | $29.4^{+6.3}_{-7.1}$ | $0.08^{+0.20}_{-0.22}$ | $29.3^{+4.2}_{-3.2}$ | $0.71^{+0.08}_{-0.10}$ | $65.6^{+9.4}_{-6.6}$ | $1850^{+840}_{-840}$ | 1187529256.5 |

# Software for GW data

- Software for working with Gravitational Wave Data available to the public: https://www.gw-openscience.org/software/
- Part of the software developed by LIGO/Virgo and open-source

**GWpy**

a python package for gravitational-wave astrophysics.

**PyCBC**

Free and open software to study gravitational waves.

**Bilby**

Bilby: a user-friendly Bayesian inference library.

### 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.

### LALSuite

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

### 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.

# GWOSC Tutorials

- GWOSC tutorials:
  - ✓ https://www.gw-openscience.org/tutorials/

**Second Open Data Workshop: Paris, April 8 -10 2019**
(Materials will be made available on GWOSC soon)

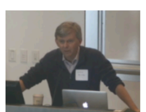
### Tutorials

Each tutorial will lead you step-by-step through some common data analysis tasks. While GWOSC data can be analyzed using libraries in many software languages (C, C++, Matlab, etc.), most of th
tutorials use Python. See also the software page for more examples.

See the tutorial setup page for help installing software to run these tutorials.

Tutorials shown here are not used to produce published results. For gravitational-wave software analysis packages that are used to produce LSC and Virgo Collaboration publications, see software page.

**Gravitational Wave Open Data Workshop Web Course (2018)**

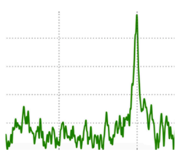


Self-paced web course on GWOSC data analysis

**Course Material**

**First Open Data Workshop (March 2018):**
slides + videos of the presentations + Jupiter notebook for hands-on sessions

**Binary Black Hole Events**



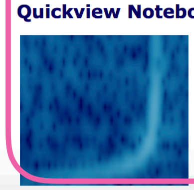
Use matched filtering to find signals hidden in noise.

**Run:** Azure | mybinder (Beta)

**View:** GW150914| LVT151012| GW151226| GW170104

**Download:** file with data | Jupyter notebook | Python script

**Quickview Notebook**



Make summary plots for any short segment of GWOSC data.

**Run:** Azure | mybinder (Beta)

**Download:** IPython 4

**Introduction to LIGO Data Files**

[**Run:** workspace]

- Step 0) Software Setup
- Step 1) Download LIGO Data
- Step 2) What's in a LIGO Data File?
- Step 3) Working with Data Quality
- Step 4) Using the example API (readligo)

**Working with Data**

[**Run:** workspace]

- LOSC Example API
- Working with Segment Lists
- FFTs, PSDs, and Spectrograms:
  - Lots of Plots tutorial
  - Browse the plot gallery
- LSC software stack and frame reading software
- See the structure of an HDF5 file
- Plot GW150914 data [**Now superseded by the BBH Event tutorial**]
  - HTML | zip file with data

**Searching for astrophysical sources**

- Find an Inspiral
- Find an Inspiral Hardware Injection
- Find a Burst Injection: Slides | Script

**Automated Downloads**

- Discover and download LIGO data
- Automatically discover and download LIGO data
- Automatically download and process ALL the data

**LIGO and Virgo Collaboration Members**

- Get data on the LIGO Data Grid: Quickstart | Tutorial

Short tutorials about the basics of data analysis applied to some detected events

More specific tutorials on the data structure and how to read them

# GW Open Data Workshop #2

https://indico.in2p3.fr/e/gw-odw2

**Gravitational wave**

**Open Data Workshop #2**

**Paris, April 8-10 2019**

AstroParticule & Cosmologie
Paris Diderot University

*Three-day workshop to learn how to access and analyze LIGO and Virgo data*

http://www.gw-openscience.org

EGO European Gravitational Observatory · cnrs IN2P3 Les deux infinis · Asterics Astronomy ESFRI & Research Infrastructure Cluster · PNHE Programme national hautes énergies · GPhys

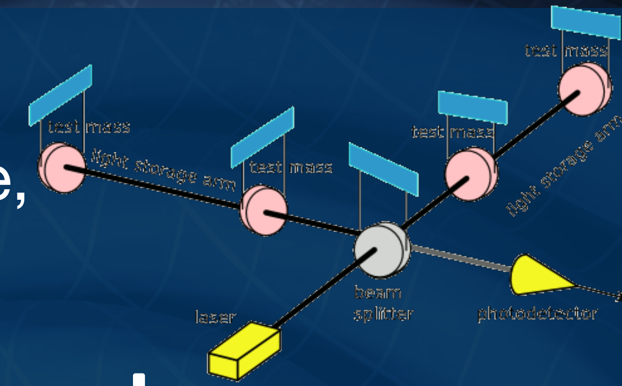
# GW-ODW2: Attendance

- ~65 people attended a 2.5-day workshop at APC, Paris
- 54 participants from 11 countries in Europe (FR, DE, SP, GR, TR, PL, CH, IT, SE), US and CN
- Majority of PhD students/postdocs, but also several senior researchers and few participants outside the academic world

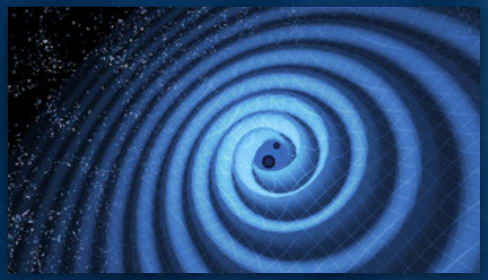
https://indico.in2p3.fr/e/gw-odw2

# GW-ODW2: Learning objectives

- <u>Basics about gravitational-wave detectors</u>
  - ✓ Measurement principle, detector response to gravitational wave, calibration and systematic, major noise sources




- <u>Open data access, visualization and basic pre-processing</u>
  - ✓ Access, visualization, filtering and whitening



- <u>Compact binary mergers</u>
  - ✓ Gravitational waveform models, Matched filtering techniques, analysis background and transient noise rejection, Bayesian estimation of compact binary parameters, source sky localization

- <u>Workflows</u>
  - ✓ Searches and parameter estimation

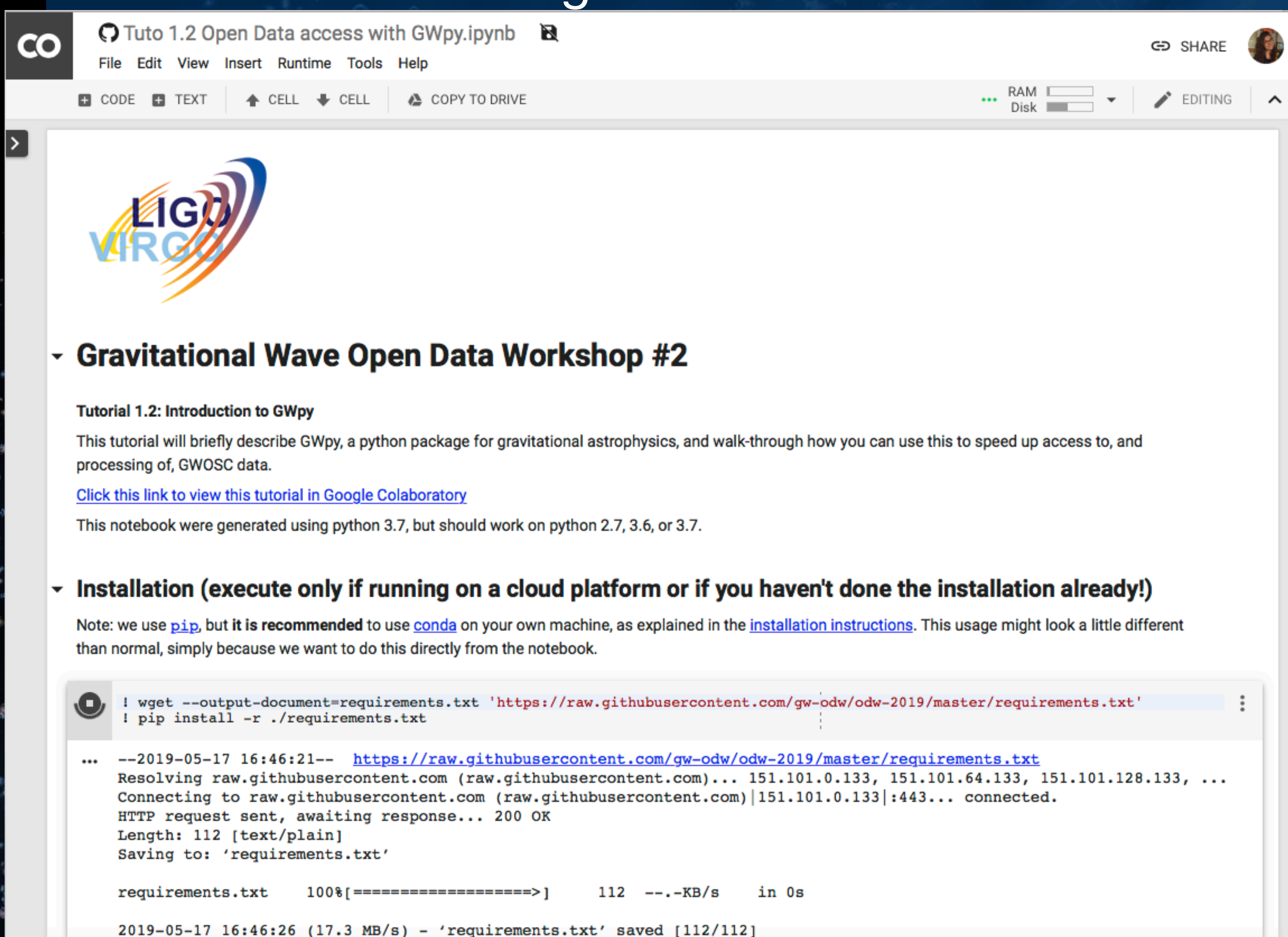
# GW-ODW2: Program

| Mon | Tue | Wed |
|---|---|---|
| Lectures 1<br><br>Basics, h(t) and data quality, open data and access | Lectures 2<br><br>Compact binaries<br>Waveform and searches<br>Param estimation<br>Sky loc & multimessenger | Challenge!<br><br>Apply your knowledges<br><br>Cool prizes! |
| Hands-on session<br><br>(gwpy, pycbc) | Hands-on session<br><br>(pycbc, bilby, gwsky & Aladin) | |
| Informal Q & A | | |


Lecturers : Jo van den Brand, Alan Weinstein, Agata Trovato, Duncan McLeod, Ed Porter, Ian Harry, Vivien Raymond, Sarah Antier

# GW-ODW2: Legacy

- Slides available (https://indico.in2p3.fr/e/gw-odw2)
- Lecture videos (in progress)
- Jupyter notebooks, challenge data set available online (https://github.com/gw-odw/odw-2019)
  - ✓ Run on the Google Colab cloud


Tuto 1.2 Open Data access with GWpy.ipynb

File Edit View Insert Runtime Tools Help

CODE TEXT CELL CELL COPY TO DRIVE RAM Disk EDITING SHARE

## Gravitational Wave Open Data Workshop #2

**Tutorial 1.2: Introduction to GWpy**

This tutorial will briefly describe GWpy, a python package for gravitational astrophysics, and walk-through how you can use this to speed up access to, and processing of, GWOSC data.

Click this link to view this tutorial in Google Colaboratory

This notebook were generated using python 3.7, but should work on python 2.7, 3.6, or 3.7.

## Installation (execute only if running on a cloud platform or if you haven't done the installation already!)

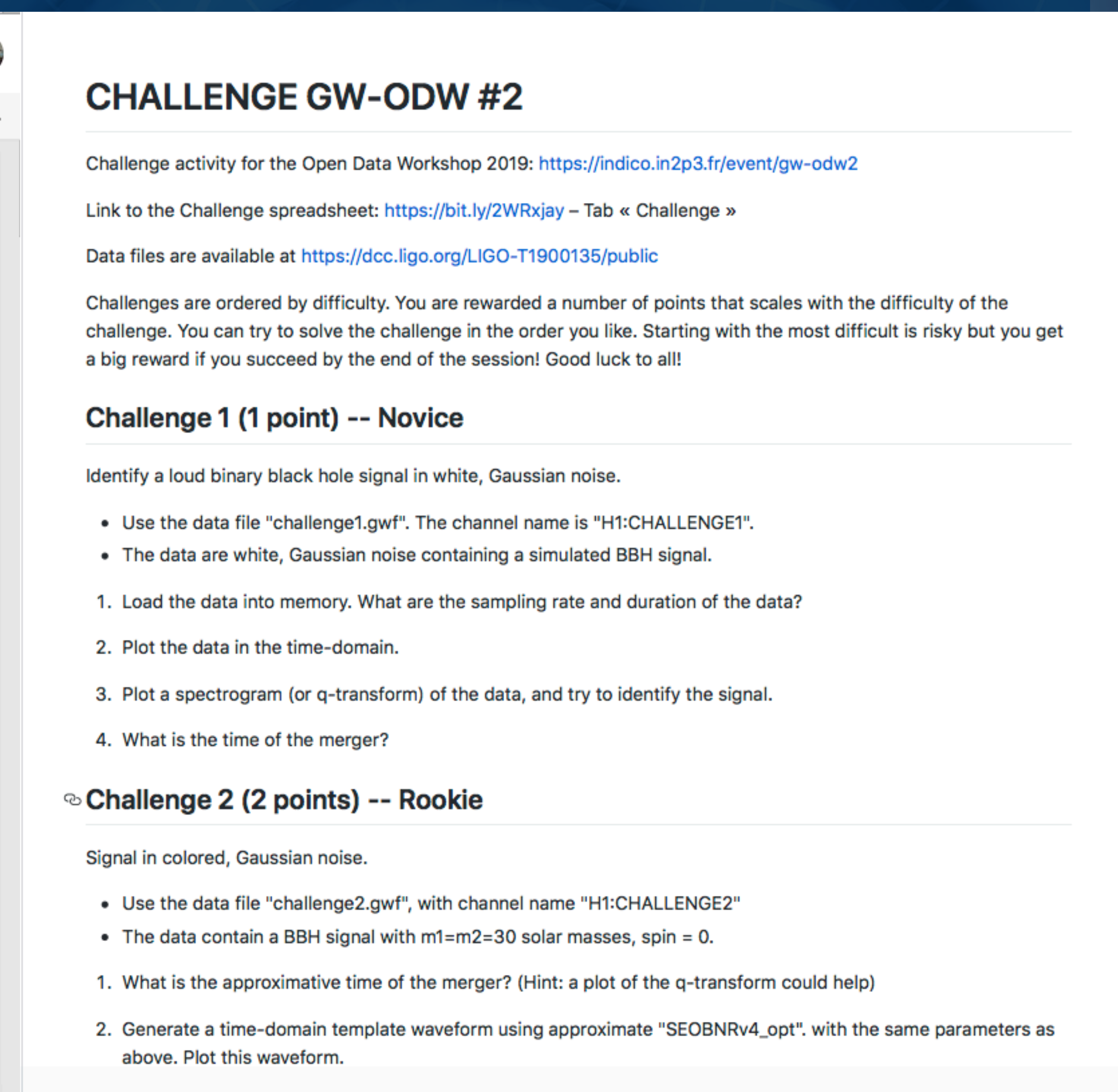
Note: we use pip, but **it is recommended** to use conda on your own machine, as explained in the installation instructions. This usage might look a little different than normal, simply because we want to do this directly from the notebook.

```
! wget --output-document=requirements.txt 'https://raw.githubusercontent.com/gw-odw/odw-2019/master/requirements.txt'
! pip install -r ./requirements.txt
```

```
--2019-05-17 16:46:21--  https://raw.githubusercontent.com/gw-odw/odw-2019/master/requirements.txt
Resolving raw.githubusercontent.com (raw.githubusercontent.com)... 151.101.0.133, 151.101.64.133, 151.101.128.133, ...
Connecting to raw.githubusercontent.com (raw.githubusercontent.com)|151.101.0.133|:443... connected.
HTTP request sent, awaiting response... 200 OK
Length: 112 [text/plain]
Saving to: 'requirements.txt'

requirements.txt    100%[===================>]     112  --.-KB/s    in 0s

2019-05-17 16:46:26 (17.3 MB/s) - 'requirements.txt' saved [112/112]
```


## CHALLENGE GW-ODW #2

Challenge activity for the Open Data Workshop 2019: https://indico.in2p3.fr/event/gw-odw2

Link to the Challenge spreadsheet: https://bit.ly/2WRxjay – Tab « Challenge »

Data files are available at https://dcc.ligo.org/LIGO-T1900135/public

Challenges are ordered by difficulty. You are rewarded a number of points that scales with the difficulty of the challenge. You can try to solve the challenge in the order you like. Starting with the most difficult is risky but you get a big reward if you succeed by the end of the session! Good luck to all!

### Challenge 1 (1 point) -- Novice

Identify a loud binary black hole signal in white, Gaussian noise.

- Use the data file "challenge1.gwf". The channel name is "H1:CHALLENGE1".
- The data are white, Gaussian noise containing a simulated BBH signal.

1. Load the data into memory. What are the sampling rate and duration of the data?
2. Plot the data in the time-domain.
3. Plot a spectrogram (or q-transform) of the data, and try to identify the signal.
4. What is the time of the merger?

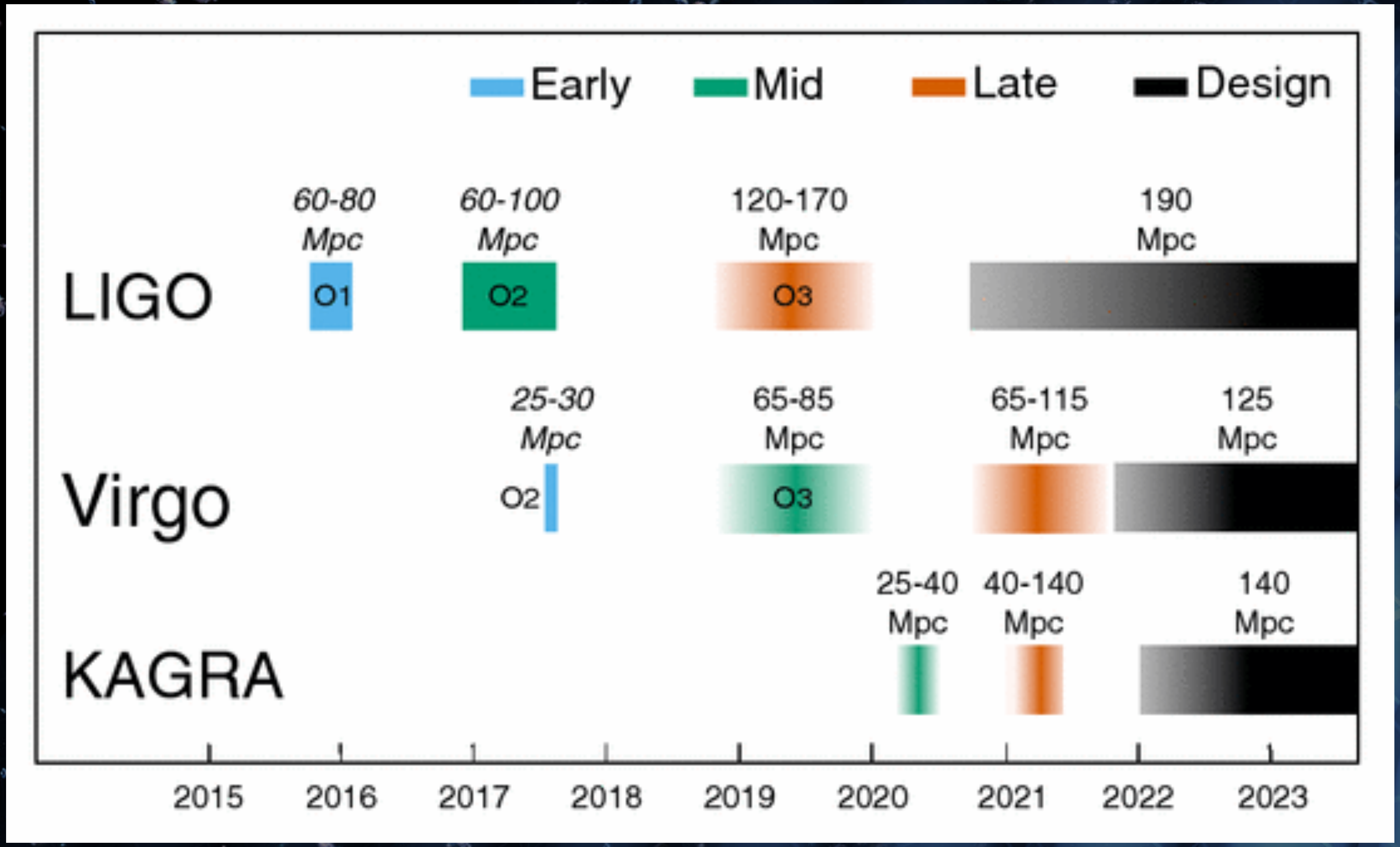
### Challenge 2 (2 points) -- Rookie

Signal in colored, Gaussian noise.

- Use the data file "challenge2.gwf", with channel name "H1:CHALLENGE2"
- The data contain a BBH signal with m1=m2=30 solar masses, spin = 0.

1. What is the approximative time of the merger? (Hint: a plot of the q-transform could help)
2. Generate a time-domain template waveform using approximate "SEOBNRv4_opt". with the same parameters as above. Plot this waveform.
3. Calculate a PSD of the data, and plot this on a log-log scale. Use axes ranging from 20 Hz up to the Nyquist

# O3




Current Observing run (O3) started April 2019

- ✓ 2 Binary neutron stars
- ✓ 10 Binary black holes
- ✓ 1 Neutron-star black-hole binary (if confirmed)

✓ Bulk data releases will occur every 6 months, in blocks of 6 months of data, with a latency of 18 months from the end of acquisition of each observing block. (Data Management Plan=>https://dcc.ligo.org/LIGO-M1000066/public)

> Apr 2019-Sept 2020, Release: Apr 2021 (first 6-month block)

# Conclusion

- Importance of Open Science vastly recognised by the scientific community
- GWOSC considered a good example model
- Open Data Workshop was a success
  - ✓ Good feedbacks from participants:
    - 20 feedbacks
    - 70% very positive experience + 30% positive experience
    - Suggestions:
      - Make it longer
      - Hands-on session on the 2nd day was too busy
      - “Present only one of the two modules (either gwpy or pycbc)”
      - 30% presentation ; 70% hands on
      - “Not enough time for skymaps”
      - Add more background in physics
- Stay tuned for the new releases


Thank you!
Questions?