Gravitational Wave Open Data

A quick introduction

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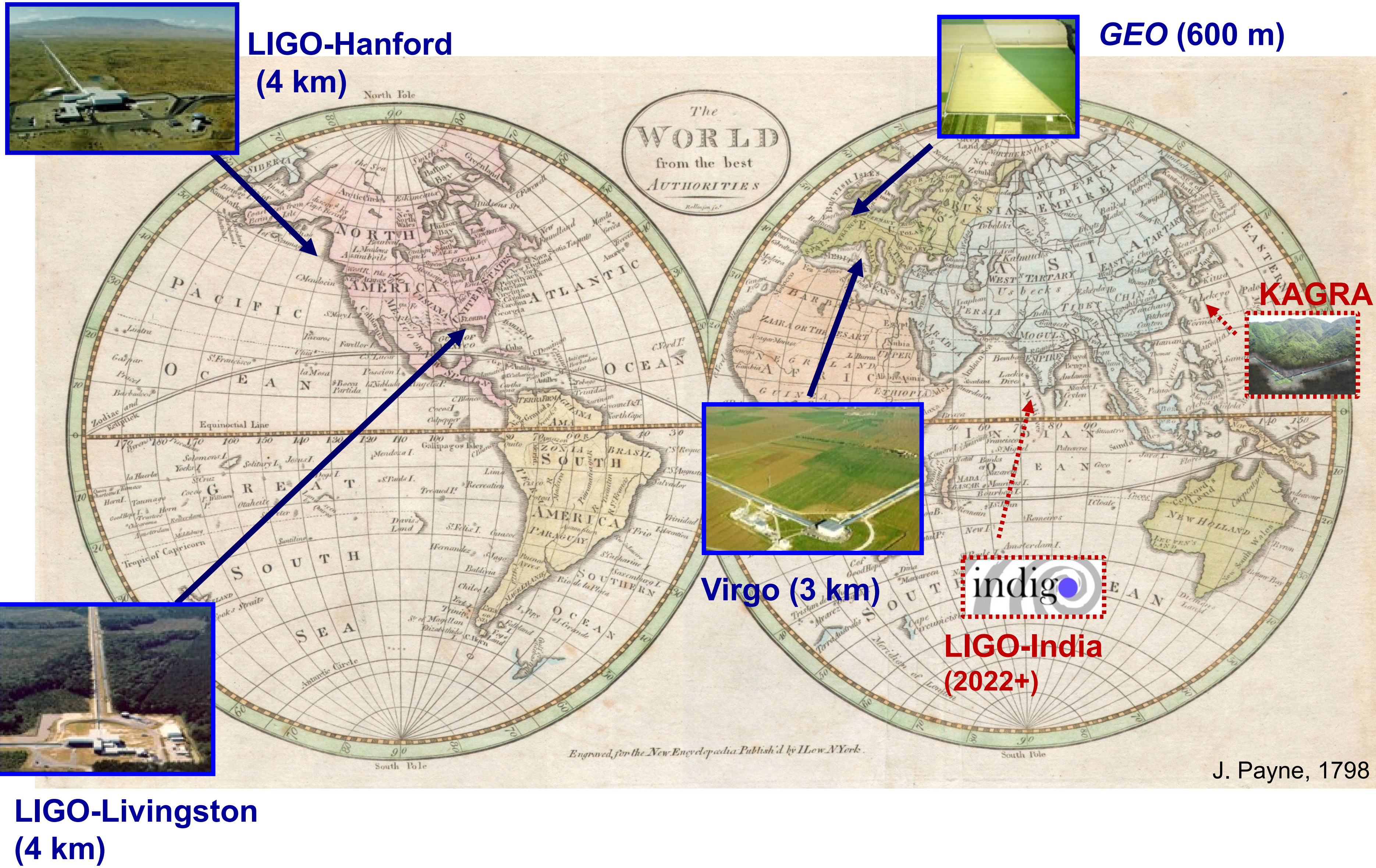
On behalf of the GWOSC team
& the LIGO and Virgo Collaboration

Multimessenger Data Analysis in the CTA era
Sexten, 24-28 June 2019

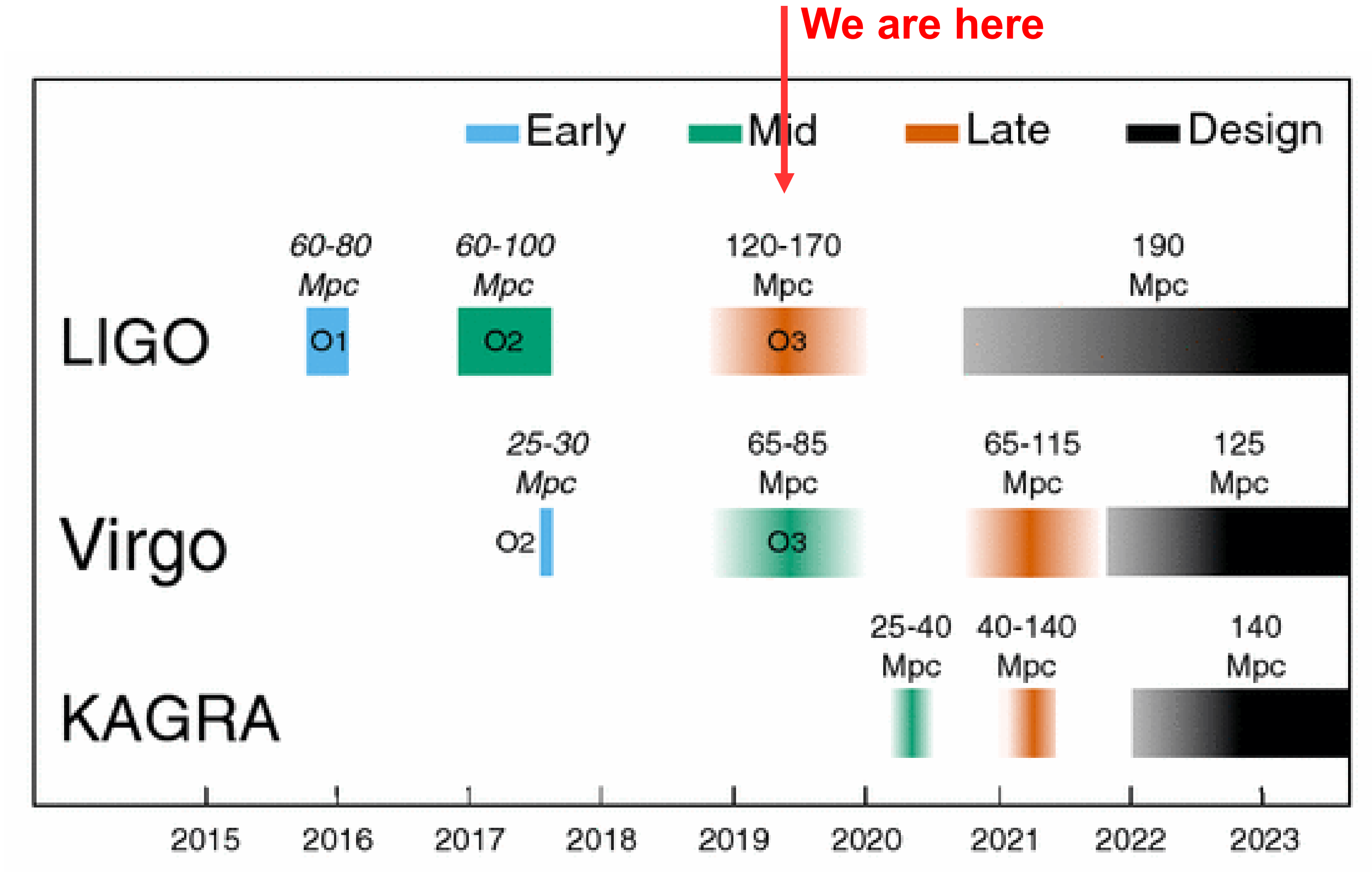
The era of advanced GW detectors



M. Razzano

Welcome to O3!

- Abbott et al. 2018 “Observing scenario” paper, LRR



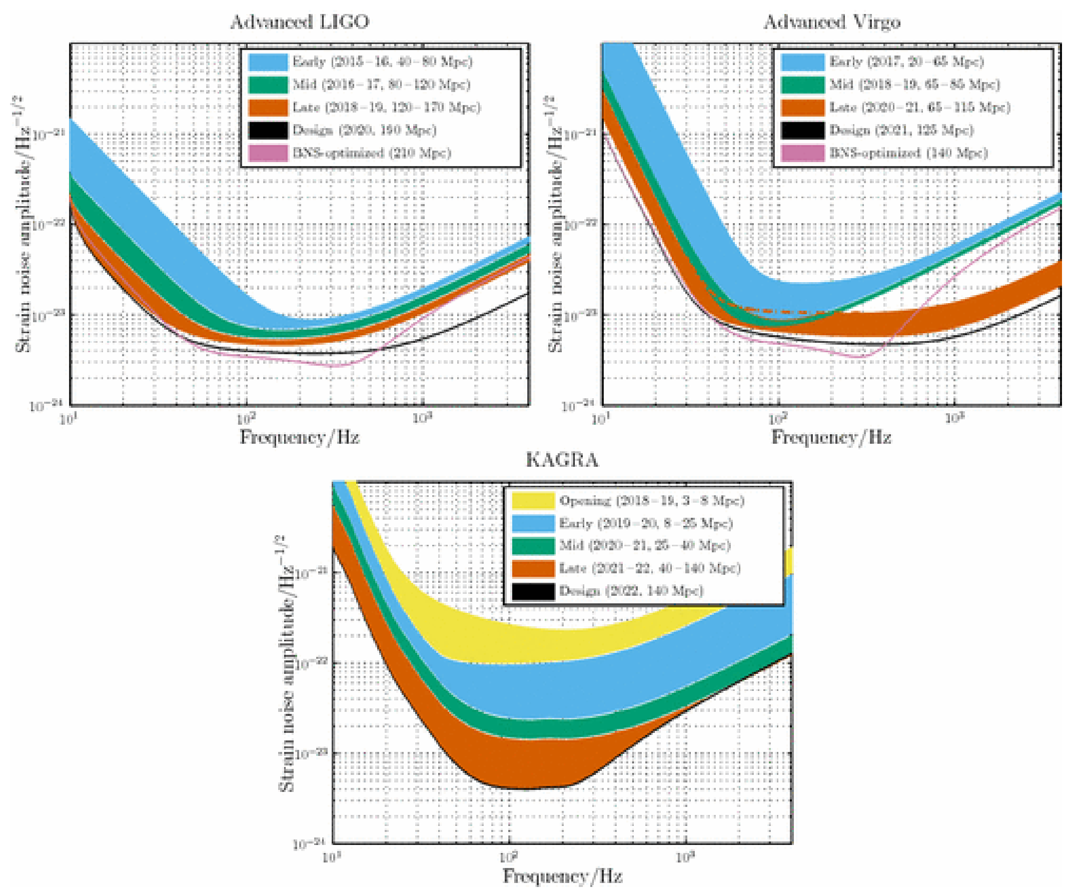
Why the Advanced detectors?

- Abbott et al. 2018 “Observing scenario” paper, LRR

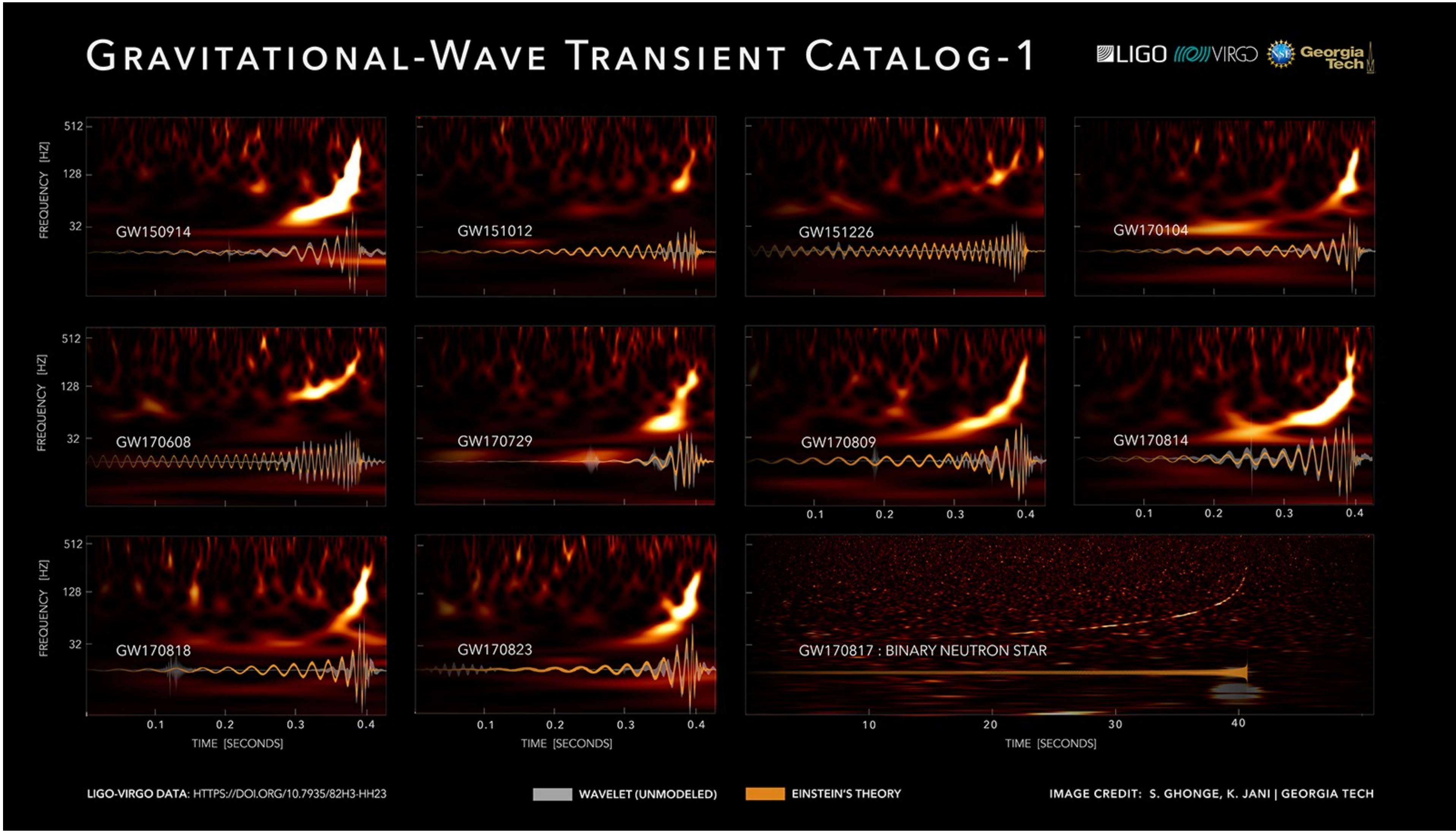
Significant upgrades to increase sensivitity by 10x
Wrt “previous generation” LIGO and Virgo (2010s’)

This means 10x distance reach
→ 10^3x larger volume
→ 10^3 number of events

Extremely tiny signals
Arm deformation ~10^{-18} m



The first GW catalog of transients



GWTC-1
Abbott et al 2019, arXiv:1811.12907

GW open data on the web

Hosted at the Gravitational Wave Open Science Center (GWOSC)

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

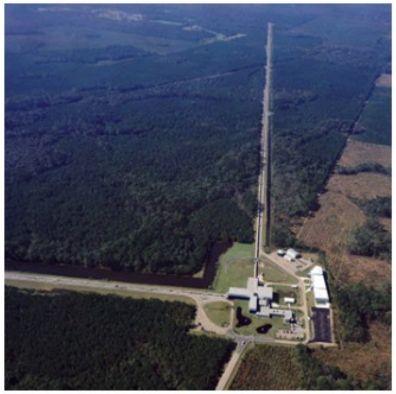
Gravitational Wave Open Science Center

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!

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

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
  - First chunck of O3 will come in April 2021

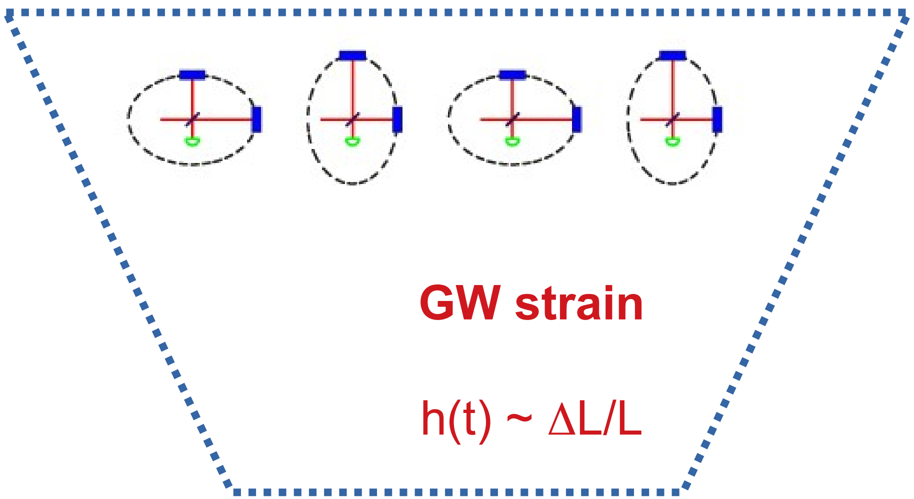
- Supporting documentation and tools
  - Help the external community in using data
  - Lots of tutorials
  - Materials from periodic Open Data Workshops (Last one this April in Paris)

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)
- Advanced Virgo
  - O2 (2016 – 2017)



Timelines

- Information on data availability over time

Gravitational Wave Open Science Center

Data ▾ Software ▾ Online Status ▾ About GWOSC ▾

Strain Data
Catalogs
Timelines

Timeline **Timeline** technology provides instant access to time-based metadata on scales from seconds to centuries. **Timeline** is developed by the Gravitational Wave Open Science Center, which is supported by the U.S. National Science Foundation.

Welcome to **Timeline**. This page provides information on when LIGO was collecting science mode data, as well as data quality classifications and injection times.

Timeline Queries

- Use the **All Timeline Query Form** to request any of the Timeline or Segment Lists
- Use the **Run Timeline Query Form** to request any of the Run Timeline or Segment Lists.
- Use the **Pre-Catalog Event Timeline Query Form** to request any of the Pre-Catalog Event Timeline or Segment Lists.
- Use the **Catalog Timeline Query Form** to request any of the Catalog Timeline or Segment Lists.
- Use the **Marginal CBC Trigger Timeline Query Form** to request any of the Marginal CBC Trigger Timeline or Segment Lists.

Timeline Quick Links

Some common example plots are linked below:

Science Mode Timelines

- Five detectors since 2005

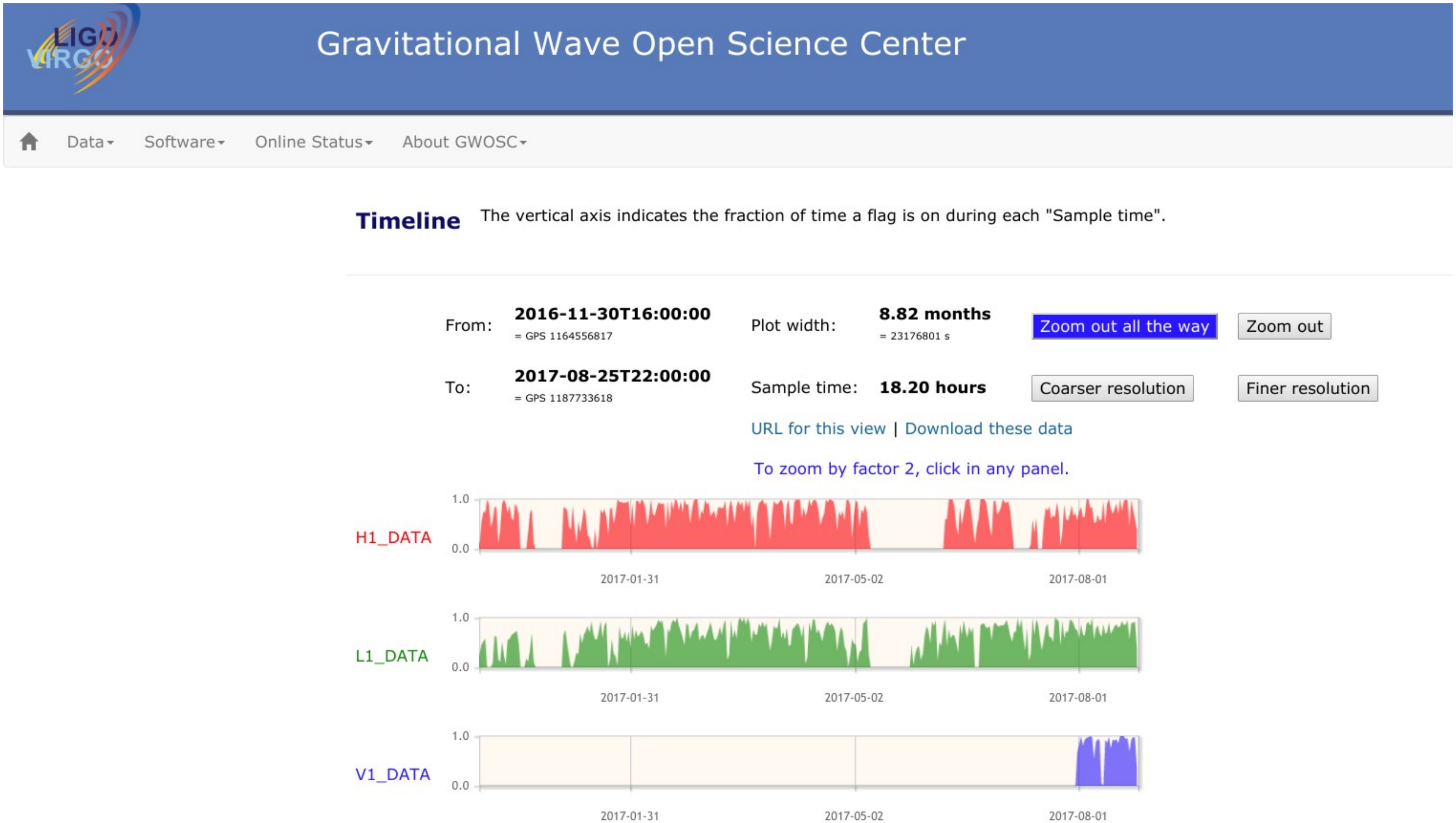
Timelines from the O2 run, 2016-2017

- Three detectors over the O2 run
- Passes O2 Burst checks for H1, L1, V1
- Passes O2 CBC checks for H1, L1, V1
- Times with no Continuous-Wave injections

Timelines from the O1 run, 2015-2016

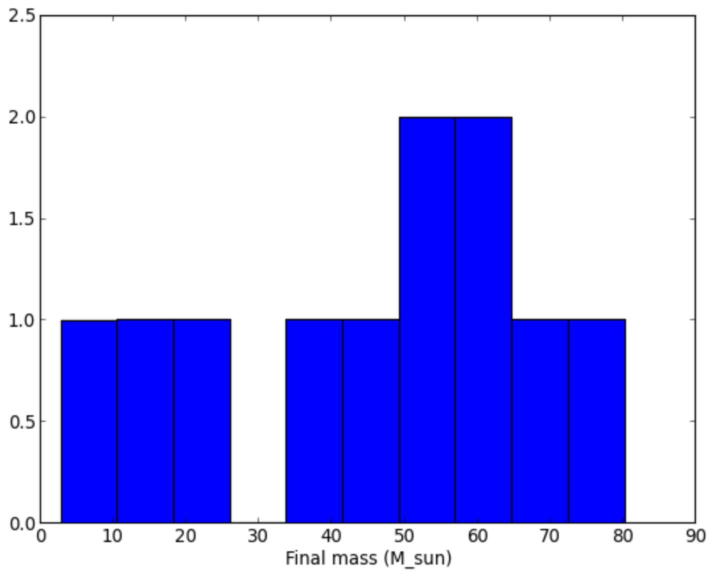
- Two detectors over the O1 run
- Passes O1 Burst checks for H1, L1
- Passes O1 CBC checks for H1, L1

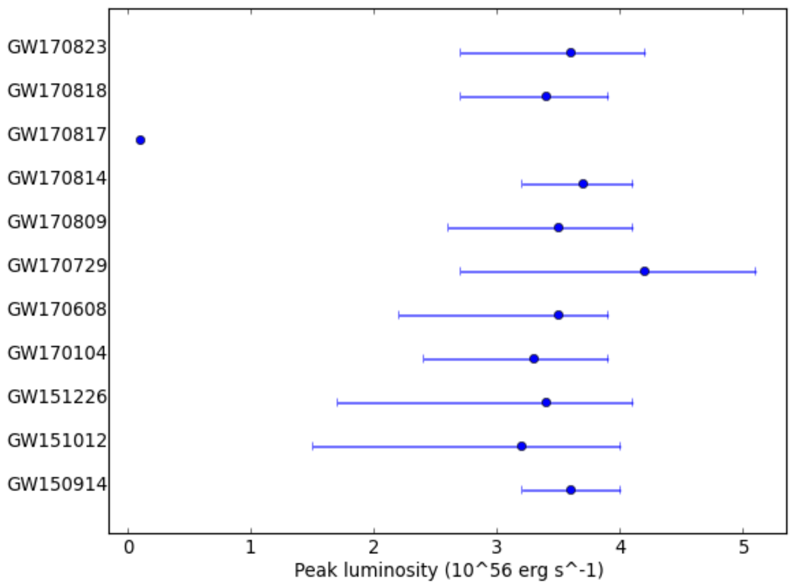
Timelines – example from O2



Strain data – Catalogs

- Previously, each event published separately, now included in catalogs
  - https://www.gw-openscience.org/catalog/
- GWTC-1
  - Released in Dec 2018 (arXiv:1811.12907)
  - 11 confident detections + 14 marginal triggers
  - Strain data + skymaps, etc...





Strain data – Catalogs

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)	Radiated energy (M_sun X c^2)	Peak luminosity (10^56 erg s^-1)	FAR cWB (yr^-1)	FAR gstLAL (yr^-1)	FAR PyCBC (yr^-1)	Source redshift	Sky localization (deg^2)	Network SNR cWB	Network SNR gstLAL	Network SNR PyCBC	UTCtime
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	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}$	< 1.63e-04	< 1.00e-07	< 1.53e-05	$0.09^{+0.03}_{-0.03}$	179	25.2	24.4	23.6	09:50:45.4
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	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7}$	NA	7.92e-03	0.17	$0.21^{+0.09}_{-0.09}$	1555	NA	10.0	9.5	09:54:43.4
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	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}$	0.02	< 1.00e-07	< 1.69e-05	$0.09^{+0.04}_{-0.04}$	1033	11.9	13.1	13.1	03:38:53.6
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	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9}$	2.91e-04	< 1.00e-07	< 1.37e-05	$0.19^{+0.07}_{-0.08}$	924	13.0	13.0	13.0	10:11:58.6
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	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3}$	1.44e-04	< 1.00e-07	< 3.09e-04	$0.07^{+0.02}_{-0.02}$	396	14.1	14.9	15.4	02:01:16.5
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	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}$	0.02	0.18	1.36	$0.48^{+0.19}_{-0.20}$	1033	10.2	10.8	9.8	18:56:29.3
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	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}$	NA	< 1.00e-07	1.45e-04	$0.20^{+0.05}_{-0.07}$	340	NA	12.4	12.2	08:28:21.8
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	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}$	< 2.08e-04	< 1.00e-07	< 1.25e-05	$0.12^{+0.03}_{-0.04}$	87	17.2	15.9	16.3	10:30:43.5
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$0.00^{+0.02}_{-0.01}$	$1.186^{+0.001}_{-0.001}$	≤ 0.89	≤ 2.8	40^{+10}_{-10}	1187008882.4	≥ 0.04	≥ 0.1	NA	< 1.00e-07	< 1.25e-05	$0.01^{+0.00}_{-0.00}$	16	NA	33.0	30.9	12:41:04.4
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	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}$	NA	4.20e-05	NA	$0.20^{+0.07}_{-0.07}$	39	NA	11.3	NA	02:25:09.1
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	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9}$	2.14e-03	< 1.00e-07	< 3.29e-05	$0.34^{+0.13}_{-0.14}$	1651	10.8	11.5	11.1	13:13:58.5

Strain data – Single events

GWTC-1-confident

GW170814

Effective inspiral spin,	$\mathbf{0.07}^{+0.12}_{-0.11}$
Luminosity distance, *Mpc*	$\mathbf{580}^{+160}_{-210}$
Final spin,	$\mathbf{0.72}^{+0.07}_{-0.05}$
Primary mass, *M_sun*	$\mathbf{30.7}^{+5.7}_{-3.0}$
FAR gstLAL, *yr^-1*	**< 1.00e-07**
FAR PyCBC, *yr^-1*	**< 1.25e-05**
Secondary mass, *M_sun*	$\mathbf{25.3}^{+2.9}_{-4.1}$
chirp mass, *M_sun*	$\mathbf{24.2}^{+1.4}_{-1.1}$
Radiated energy, *M_sun X c^2*	$\mathbf{2.7}^{+0.4}_{-0.3}$
Network SNR gstLAL,	**15.9**
Source redshift,	$\mathbf{0.12}^{+0.03}_{-0.04}$
FAR cWB, *yr^-1*	**< 2.08e-04**
UTCtime,	**10:30:43.5**
Peak luminosity, *10^56 erg s^-1*	$\mathbf{3.7}^{+0.4}_{-0.5}$
Sky localization, *deg^2*	**87**
Final mass, *M_sun*	$\mathbf{53.4}^{+3.2}_{-2.4}$
GPS time (s),	**1186741861.5**
Network SNR PyCBC,	**16.3**
Network SNR cWB,	**17.2**

Download Data Files:

V1 4096sec 4KHz	V-V1_GWOSC_4KHZ_R1-1186739814-4096.hdf5 V-V1_GWOSC_4KHZ_R1-1186739814-4096.gwf V-V1_GWOSC_4KHZ_R1-1186739814-4096.txt.gz
V1 4096sec 16KHz	V-V1_GWOSC_16KHZ_R1-1186739814-4096.hdf5 V-V1_GWOSC_16KHZ_R1-1186739814-4096.gwf V-V1_GWOSC_16KHZ_R1-1186739814-4096.txt.gz
V1 32sec 4KHz	V-V1_GWOSC_4KHZ_R1-1186741846-32.hdf5 V-V1_GWOSC_4KHZ_R1-1186741846-32.gwf V-V1_GWOSC_4KHZ_R1-1186741846-32.txt.gz
V1 32sec 16KHz	V-V1_GWOSC_16KHZ_R1-1186741846-32.hdf5 V-V1_GWOSC_16KHZ_R1-1186741846-32.gwf V-V1_GWOSC_16KHZ_R1-1186741846-32.txt.gz
H1 4096sec 4KHz	H-H1_GWOSC_4KHZ_R1-1186739814-4096.hdf5 H-H1_GWOSC_4KHZ_R1-1186739814-4096.gwf H-H1_GWOSC_4KHZ_R1-1186739814-4096.txt.gz
H1 4096sec 16KHz	H-H1_GWOSC_16KHZ_R1-1186739814-4096.hdf5 H-H1_GWOSC_16KHZ_R1-1186739814-4096.gwf H-H1_GWOSC_16KHZ_R1-1186739814-4096.txt.gz
H1 32sec 4KHz	H-H1_GWOSC_4KHZ_R1-1186741846-32.hdf5 H-H1_GWOSC_4KHZ_R1-1186741846-32.gwf H-H1_GWOSC_4KHZ_R1-1186741846-32.txt.gz
H1 32sec 16KHz	H-H1_GWOSC_16KHZ_R1-1186741846-32.hdf5 H-H1_GWOSC_16KHZ_R1-1186741846-32.gwf H-H1_GWOSC_16KHZ_R1-1186741846-32.txt.gz

each file:

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

Bulk data

Available in 2 ways

Large Data Sets for High Performance Computing

For users of computing clusters, CernVM-FS is the preferred method to access large data sets:

CernVM FS

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

O2 Data Release

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

4KHz Data | 16KHz Data | Documents | Timeline

O1 Data Release

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

Search archive

Detector status

GWOSC Calendar ▾ Today Yesterday Observing Run 1 Summary Observing Run 2 Summary

Gravitational-Wave Observatory Status

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

Information is available for dates after November 30, 2016. The Advanced LIGO and Advanced Virgo detectors are currently in the third observing run, known as O3, which began April 1, 2019. Summaries of previous observing runs are available in the menu above. For overviews of LIGO and Virgo observing runs, see the O3 schedule or arXiv:1304.0670.

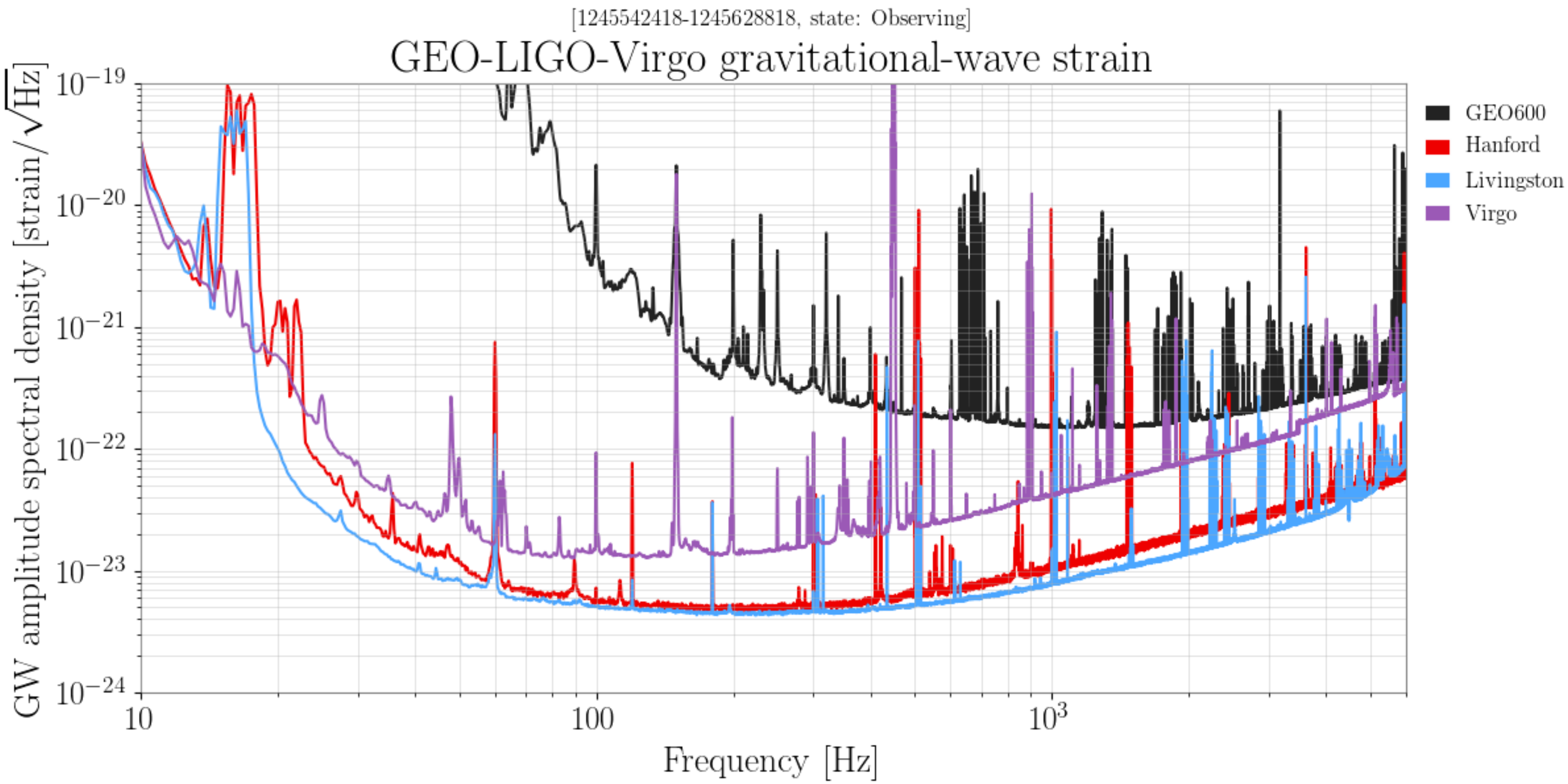
- Today's Summary Page
- Virgo Status Page
- Current Status (GWISTAT)
- LIGO/Virgo Alerts (GraceDB)

LIGO Hanford

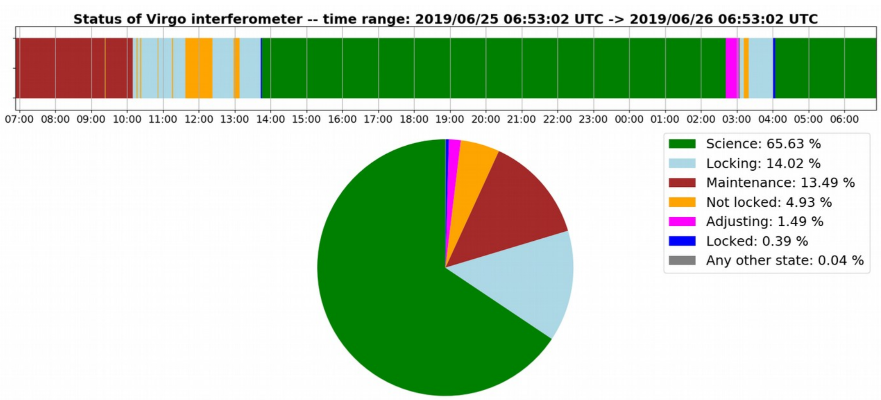
LIGO Livingston

Virgo

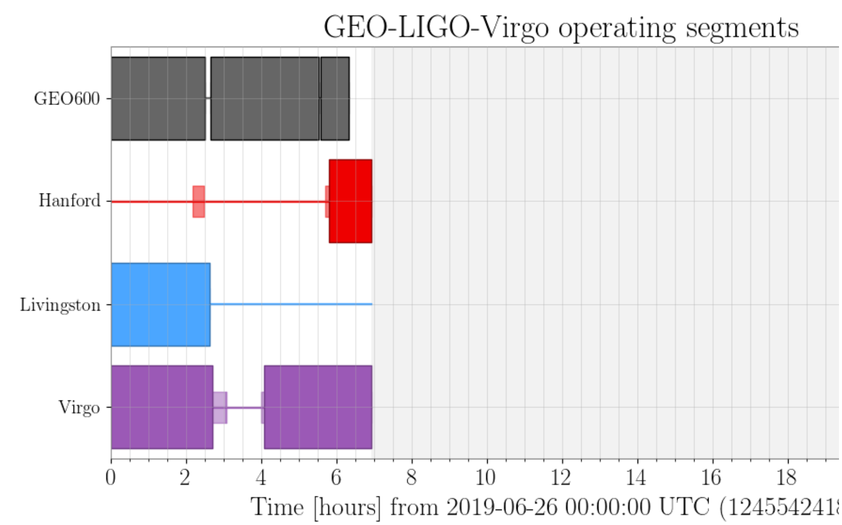
GEO600



[1245542418-1245628818, state: Observing]
GEO-LIGO-Virgo gravitational-wave strain
GW amplitude spectral density [strain/√Hz]
Frequency [Hz]
GEO600
Hanford
Livingston
Virgo



Status of Virgo interferometer -- time range: 2019/06/25 06:53:02 UTC -> 2019/06/26 06:53:02 UTC
Science: 65.63 %
Locking: 14.02 %
Maintenance: 13.49 %
Not locked: 4.93 %
Adjusting: 1.49 %
Locked: 0.39 %
Any other state: 0.04 %



GEO-LIGO-Virgo operating segments
GEO600
Hanford
Livingston
Virgo
Time [hours] from 2019-06-26 00:00:00 UTC (124554241

GWOSC-based projects

Projects with GWOSC data

Some examples of projects using GWOSC data are shown on this page.

Listing a project here does not imply endorsement by LIGO Laboratory, the LIGO Scientific Collaboration or the Virgo Collaboration.

If you have completed a project with GWOSC data, please let us know!

Scientific Publications

Below are the fifty most recent publications citing GWOSC, as listed by INSPIRE HEP.
For a complete list, please query INSPIRE HEP.

1) Custom Execution Environments with Containers in Pegasus-enabled Scientific Workflows
Karan Vahi, Mats Rynge, George Papadimitriou, *et al.*
arxiv:1905.08204 | INSPIRE

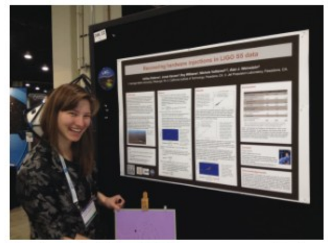
2) Searching for Dark Photon Dark Matter in LIGO O1 Data
Huai-Ke Guo, Keith Riles, Feng-Wei Yang, *et al.*
arxiv:1905.04316 | INSPIRE

3) All-sky search for short gravitational-wave bursts in the second Advanced LIGO and Advanced Virgo run
B.P. Abbott, R. Abbott, T.D. Abbott, *et al.*
arxiv:1905.03457 | INSPIRE

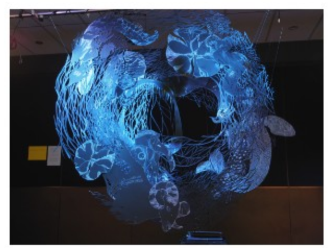
4) Testing the no-hair theorem with GW150914
Maximiliano Isi, Matthew Giesler, Will M. Farr, *et al.*
arxiv:1905.00869 | INSPIRE

5) Gravitational-Wave Asteroseismology with Fundamental Modes from Compact Binary Inspirals
Geraint Pratten, Patricia Schmidt, Tanja Hinderer
arxiv:1905.00817 | INSPIRE

6) Multi-messenger Extended Emission from the Compact Remnant in GW170817
Maurice H.P. M. van Putten, Massimo Della Valle, Amir Levinson

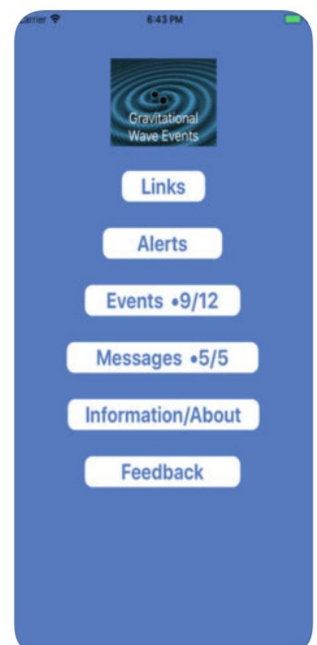


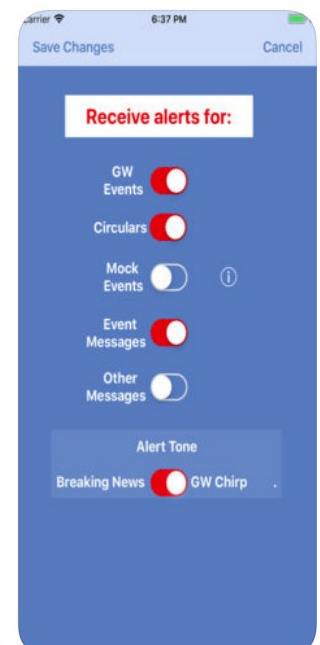
Student Ashley Disbrow presents her work at the 2014 American Astronomical Society meeting in Washington, DC.



Student Emma Wadley created the installation titled Void (2016), shown above. Her artist stat includes this description: "I have used black paper to represent fear through the colour associated with death, shadows and the deepe

Gravitational Wave Events
Iphone only





LIGO-Virgo alerts

Gravitational Wave Open Science Center

Data Software Online Status About GWOSC

LIGO/Virgo Public Alerts

Announcement

From GCN Circular 24045:

Our third observing run ("O3") began as scheduled on 2019 April 1 at 15:00 UTC. At that time the LIGO Hanford, LIGO Livingston, and Virgo Observatories transitioned from engineering and commissioning to observing. All three detectors are operating at good sensitivity and stability. We are analyzing data in low latency and processing candidate transient events automatically.

As of April 2 20:00 UTC, we have configured our low-latency analysis pipeline to send public alerts for significant gravitational-wave transient candidates that are detected in coincidence across two or more gravitational-wave detectors.

Automated Preliminary GCN Notices will be sent immediately without any human intervention. Shortly afterward, they will be vetted by an LSC/Virgo rapid response team and either confirmed with an Initial GCN Notice and Circular, or withdrawn with a Retraction.

Retraction notices may be issued more frequently over the next few weeks as our understanding of the instrumental background improves.

For further information about vetting procedures, analysis methodology, and the contents of LIGO/Virgo public alerts, refer to the LIGO/Virgo Public Alerts User Guide: https://emfollow.docs.ligo.org/userguide/

This marks the beginning of the era of public alerts for the field of gravitational-wave astronomy.

Resources

- LIGO/Virgo Alerts User Guide
- Gravitational Wave Candidate Event Database (GraceDB)
- GCN: The Gamma-ray Coordinates Network
- GW Events iPhone app
- Press release on start of O3

LIGO-Virgo alerts

GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | LATEST | DOCUMENTATION | LOGIN

Latest — as of 26 June 2019 07:01:58 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-	2019-05-10 03:00:03

Hands-on: GW emission

Recap on the GW strain
In the far zone (i.e. far from the source), we can connect the GWs generated from the source, with the mass distribution of the source

In particular, under condition of slow motion and weak field, when we have a non-vanishing quadrupole momentum of the mass distribution, we have GW emission

$$h_{ij}^{TT}(t,z) \simeq \frac{2G}{c^4 r} \ddot{I}_{ij}^{TT}(t-r/c)$$

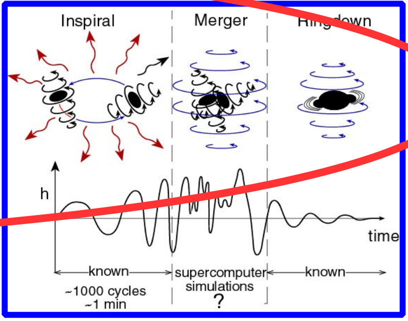
$G/c^4 \sim 10^{49}\ s^2 g^{-2} cm^{-1}$

1/r dependence

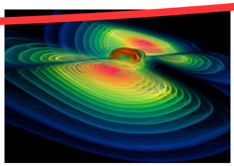
Expected sources detectable by LIGO/Virgo

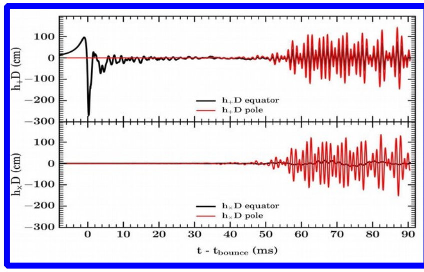
Transients

- **Coalescence of compact binary systems (NSs and/or BHs)**
  - Known waveforms (template banks)
  - $E_{gw} \sim 10^{-2}\ Mc^2$



- **Core-collapse of massive stars**
  - Uncertain waveforms
  - $E_{gw} \sim 10^{-8} – 10^{-4}\ Mc^2$

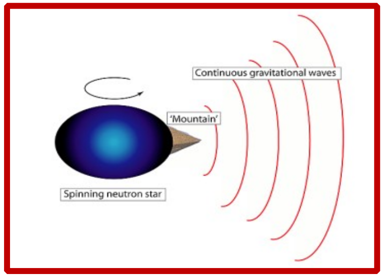




Ott, C. 2009

Non transients

- **Rotating neutron stars**
  - Quadrupole emission from star's asymmetry
  - Continuous and Periodic
- **Stochastic background**
  - Superposition of many signals (mergers, cosmological, etc)
  - Low frequency



Introdution to the hands-on

Even for **very** strong GW sources, and for **very** sensitive detector,

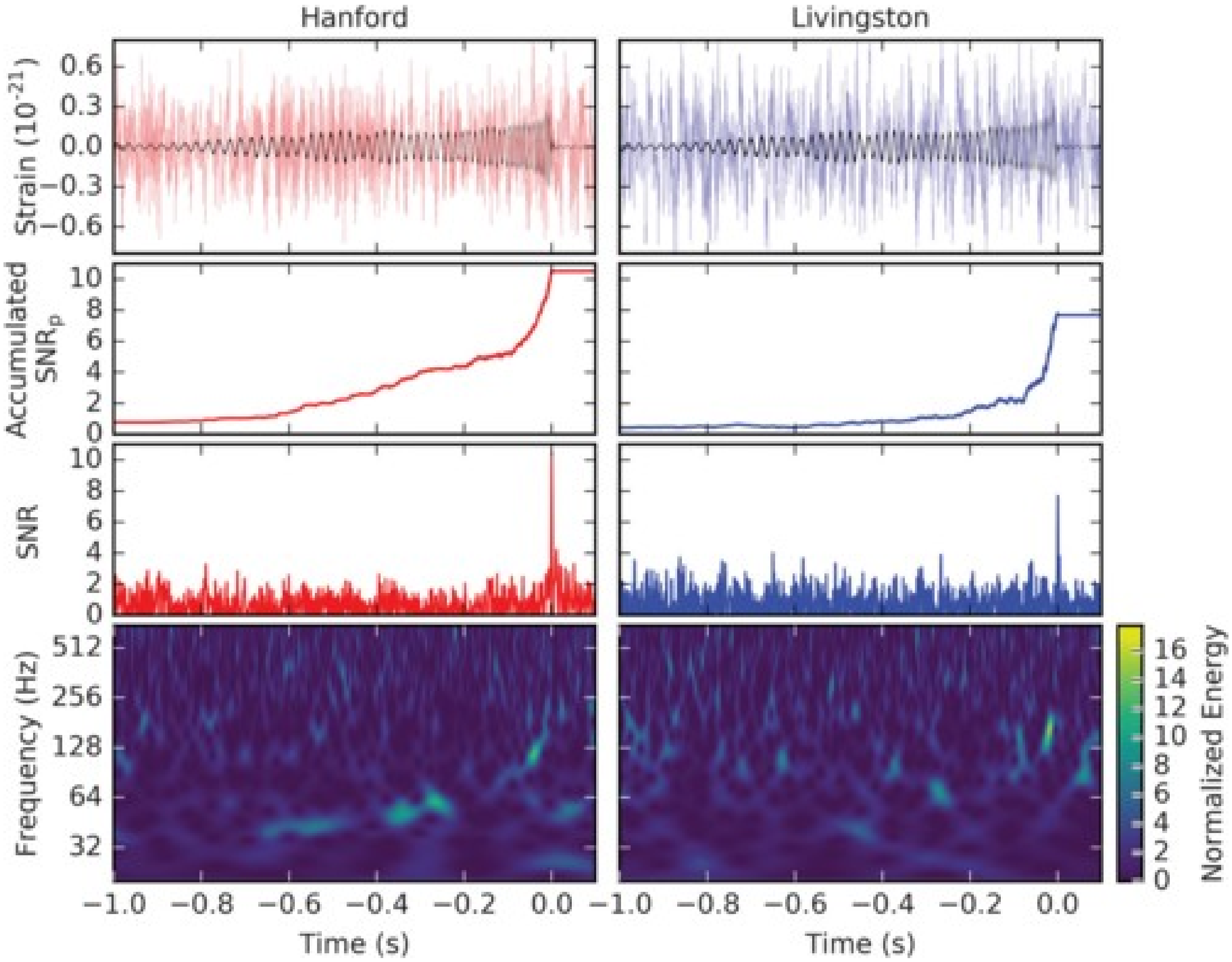
→ the signal is very very weak ($dL/L \sim 10^{-21}$)

GW data analysis aims at

- extracting the signal from a large noise (i.e. detection)
- estimating source parameters (i.e. characterization)

*

Signals buried in noise



GW151226

*

Random processes

Sequence of random variables
Instrumental noise is an example of random process timeseries x(t)

If we know the probability density function p(x), we can evaluate the expectation value:

$$\langle x \rangle := \int x \, p_x(x) dx \ .$$

If the statistical properties of the signal do not change, we say it is *stationary*, and

$$\langle x \rangle = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t) dt \ .$$

Statistical ensemble average
=
Long time average

*

Power Spectrum

We can evaluate the average of $x^2(t)$

$$\langle x^2 \rangle = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x^2(t)\,dt\ .$$

Windowed signal

$$x_T(t) = \begin{cases} x(t) & -T/2 < t < T/2 \\ 0 & \text{otherwise.} \end{cases}$$

$$\langle x^2 \rangle = \lim_{T\to\infty} \frac{1}{T} \int_{-\infty}^{\infty} x_T^2(t)\,dt$$

Parseval's Theorem

$$= \lim_{T\to\infty} \frac{1}{T} \int_{-\infty}^{\infty} |\tilde{x}_T^2(f)|^2\,df$$

x(t) is real → symmetry:

$$\tilde{x}_T(-f) = \tilde{x}_T^*(f)$$

$$= \lim_{T\to\infty} \frac{2}{T} \int_{0}^{\infty} |\tilde{x}_T^2(f)|^2\,df$$

$$= \int_{0}^{\infty} \boxed{S_x(f)}\,df\ ,$$

Power Spectral Density (PSD)

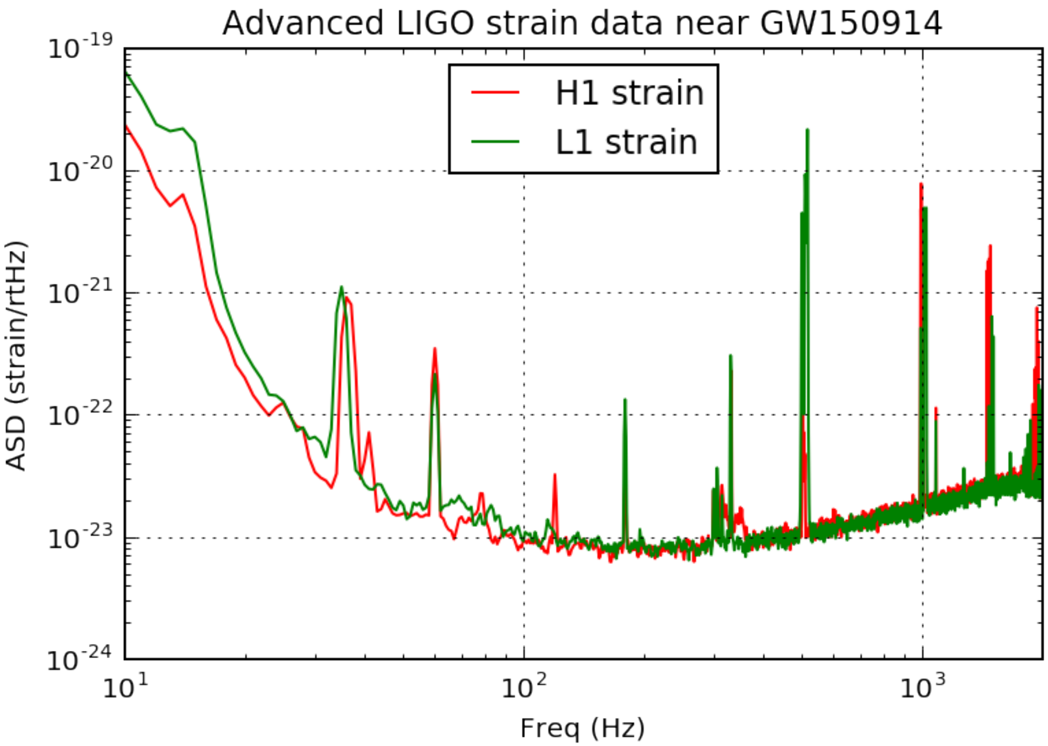
*

Power Spectrum

The definition of S(f) becomes:

$$S_x(f) := \lim_{T\to\infty} \frac{2}{T} \left| \int_{-T/2}^{T/2} x(t) e^{-2\pi i f t} dt \right|^2$$

The amplitude spectral density (ASD) is the sqrt of PSD



*

The gwpy Package

Gwpy is a public, Python-based package to access and manipulate GW data
It can be accessed from the Virtual Machine

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The gwpy Package

Strain data
h(t)
4KHz

Read the strain data and segments

```
from gwpy.timeseries import TimeSeries
from gwpy.segments import DataQualityFlag

# Define the interval
dt_win=256
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-3600,ev_t0_max+3600)
print("Done")
```

```
Get data for GW150914 (H1) GPS: 1126259206.40 - 1126259718.40
```

```
/opt/anaconda/envs/gw-env-py27/lib/python2.7/site-packages/gwpy/types/series.py:921: UserWarning: TimeSeries.crop g
iven end larger than current end, crop will end when the Series actually ends.
  % type(self).__name__)
```

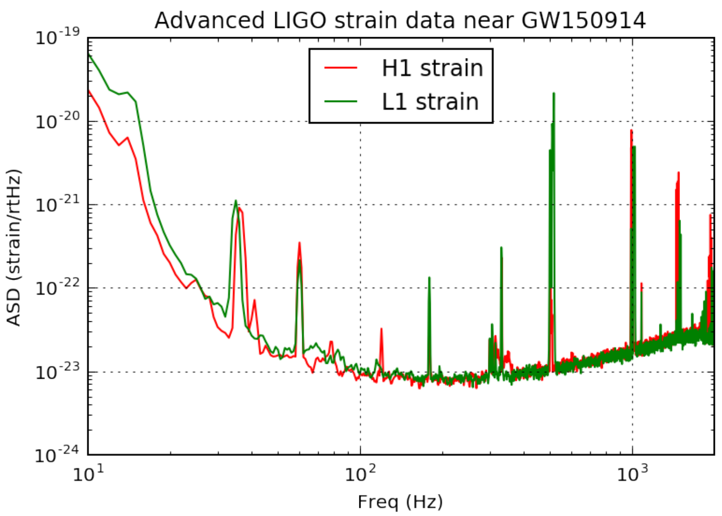
```
Done
```

Data Quality Segments

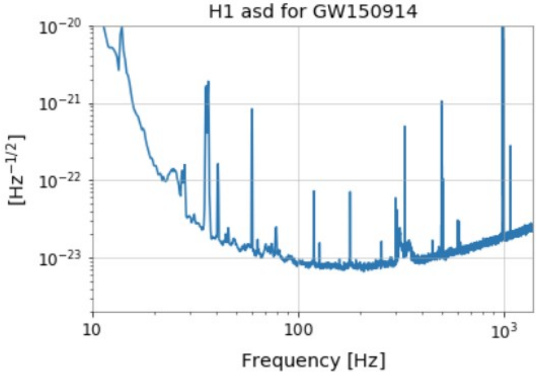
1 Hz

*

Building the ASD

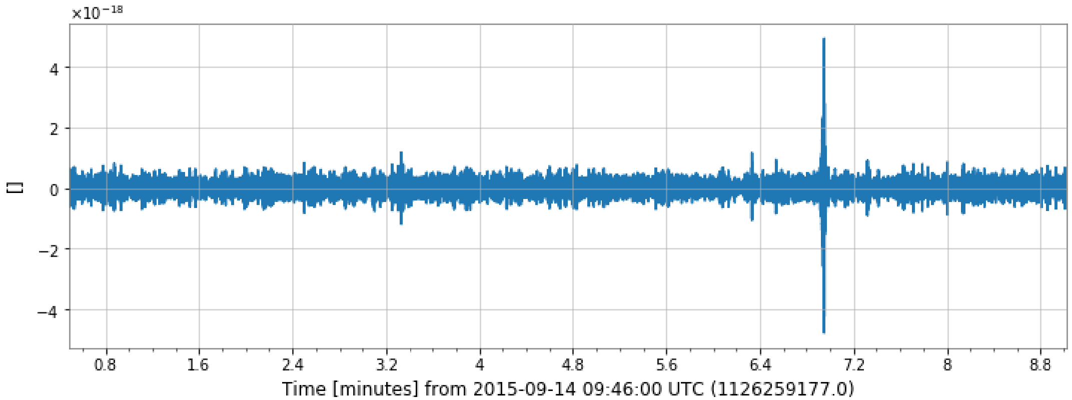


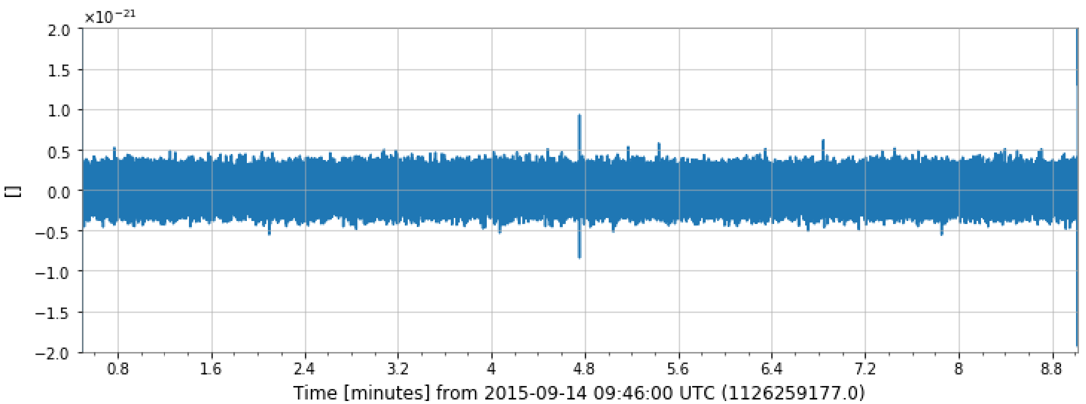

```
In [11]: #Now we can plot the ASD as well, using the Welch method with a overlapping window of 4 seconds

         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”)





We can zoom more...

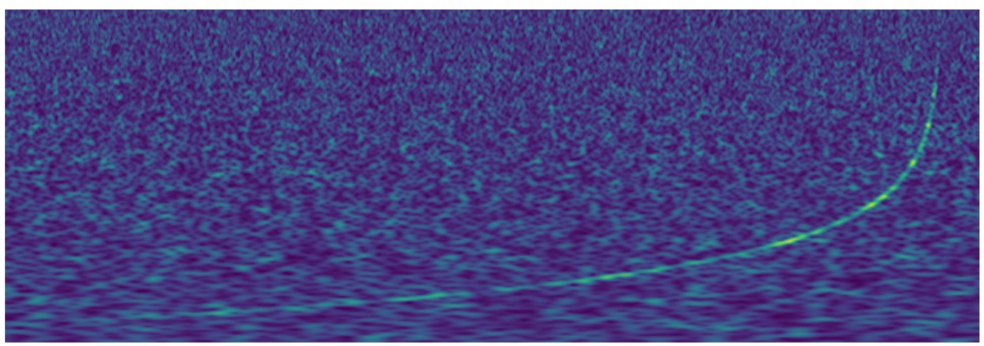
pyCBC

www.pycbc.org
Software suite for signal detection
(template matching)

PyCBC DOCUMENTATION TUTORIALS PUBLICATIONS CONTACT GITHUB

PyCBC

Free and open software to study gravitational waves.



PyCBC is a software package used to explore astrophysical sources of gravitational waves. It contains algorithms that can detect coalescing compact binaries and measure the astrophysical parameters of detected sources. PyCBC was used in the first direct

*

Matched filter

Recap fro Giovanni's talk: The likelihood ratio is

$$\Lambda(\mathcal{H}_1|s) = \frac{\mathrm{e}^{-(s-h,s-h)/2}}{\mathrm{e}^{-(s,s)/2}} = \mathrm{e}^{(s,h)}\mathrm{e}^{-(h,h)/2}$$

(s,h) Only dependence from data

Likelihood depends monotonically on (s,h), therefore we call it optimal statistic

$$(s,h) = 4\,\mathrm{Re}\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)}\,df$$

Also called this **matched filter**
(a noise-weighted correlation of anticipated signal with data)

If likelihood depends on parameters, we can find the set that maximize it
(parameter estimation)

*

Structure of the hands-on

The exercise will be divided in some parts

- Get the GW data, read and manipulate it
- Explore data in the time domain
- Explore data in the frequency domain and build the ASD
- Find the signal using the matched filter
- Next step would be the parameter estimation, but we won’t have too much time

Structure of the hands-on

A sketch of the exercise can be found at:

https://github.com/maxrazzano/gw-sexten2019

No git on the VM, so you should Download a ZIP of the repository (push the "Clone or download" button)

1) Then download and unzip the file
2) Go to the gw-sexten2019 directory
3) Source the setup script: source setup_gw_handson.sh
4) Launch the jupyter notebook and open the file in the notebooks directory
5) Follow the instructions, and then practice on another event (e.g. GW151226), using data from GWOSC

Enjoy!