Astrophysique des Hautes Energies dans l'Observatoire Virtuel

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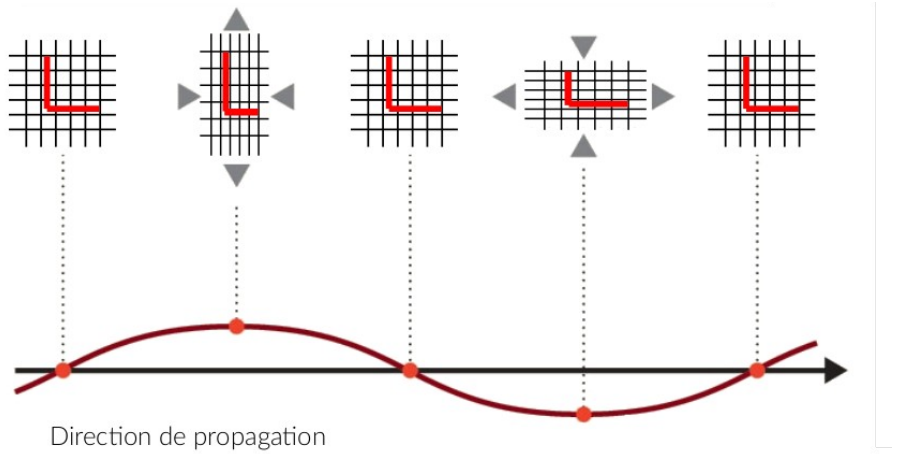


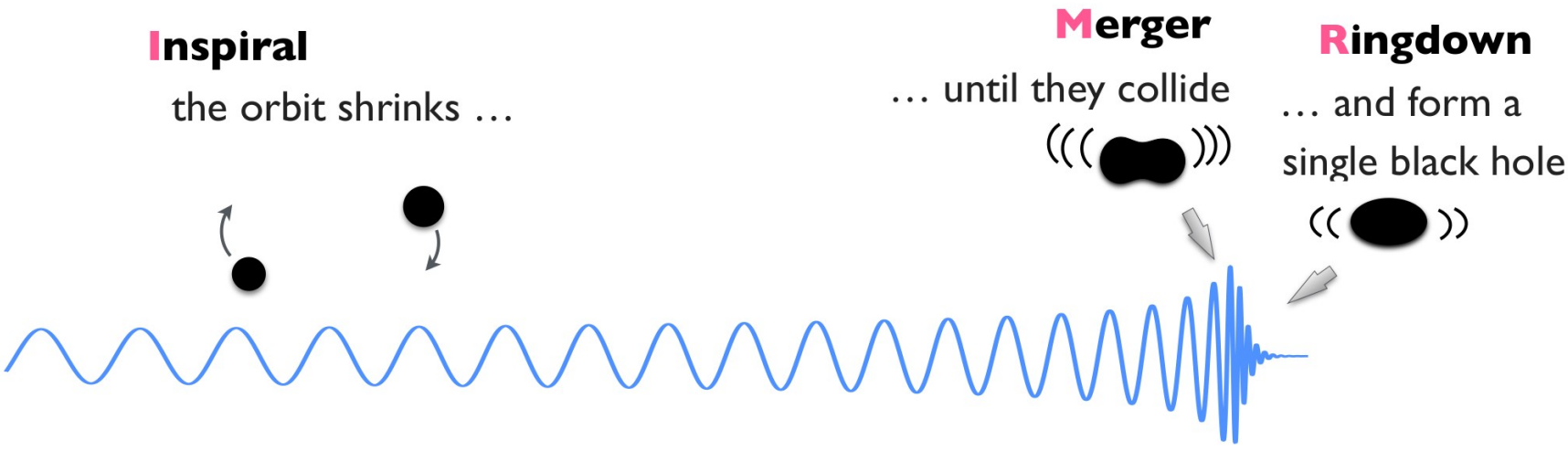
Gravitational wave strain
(space-time deformation)

$$h(t) = \frac{\delta \ell}{L}$$

Time series – 16 kHz sampling (“audio” band)

Continuous observation for ~1 yr typ.
With many on/off interruptions

Compact Binary Coalescence



2015 2016 2017 2018 2019 2020 2021

LIGO

O1
4 months
~50 days
coincident

1.5 TB (16 kHz)

O2
6 months
~ 100 days
coincident

Virgo

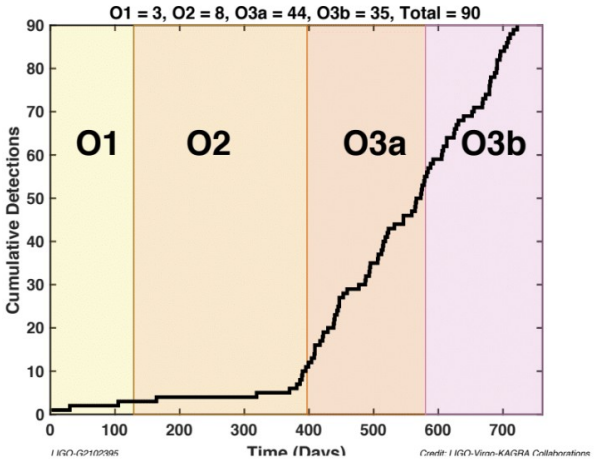
3.3 TB (16 kHz)

LIGO & Virgo

O3
1 yr
275 days
coincident

Kagra & GEO

6.6 TB (16 kHz)



2015 2016 2017 2018 2019 2020 2021

LIGO

O1
3 detections

O2
8 detections
GWTC-1

Virgo

LIGO & Virgo

O3

O3a
44 detections
GWTC-2.1

O3b
35 detections
GWTC-3

http://arxiv.org/abs/2010.14527
http://arxiv.org/abs/2108.01045
http://arxiv.org/abs/2111.03606

gw-openscience.org

- GW Open Science Center
  - Started in 2011 by Caltech under NSF impulse
- Public release policy – Cadence & proprietary period
  - Data Management Plan – https://dcc.ligo.org/LIGO-M1000066/public
  - LIGO Virgo MOU – https://dcc.ligo.org/LIGO-M060038/public

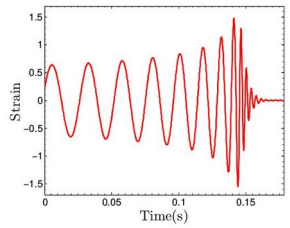
*Releases will occur every 6 months, in blocks of 6 months of data, with a latency of **18 months** from the end of acquisition of each observing block*

- So far data from LIGO, Virgo, GEO and KAGRA have been released according to this schedule

  O1: released in 2018

  O2: released in Feb 2019

  O3: released in Apr 2021 and Oct 2021 NEW



Livingston

Hanford

raw data

Virgo

LVK ONLINE ANALYSIS

Data aggregation, calibration, storing (Cascina, CIT)

$h_H(t)$
$h_L(t)$
$h_V(t)$

Detection pipelines (GstLAL, MBTA, PyCBC, SPIIR, ...)

triggers

Low latency Alert System + Enrichment + Vetting

events

GCN

$h_H(t)$
$h_L(t)$
$h_V(t)$

triggers

Enrichment + Analysis

events

Papers
GWOSC

LVK OFFLINE ANALYSIS

Livingston

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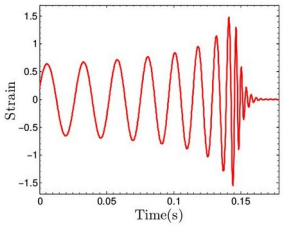
raw data



Data aggregation, calibration, storing (Cascina, CIT)

$h_H(t)$
$h_L(t)$
$h_V(t)$

GWOSC

$h_H(t)$
$h_L(t)$
$h_V(t)$

External detection pipelines (OGC, IAS, ...)

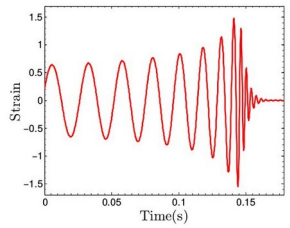
triggers

Enrichment, Analysis

events

Papers
GWOSC

EXTERNAL OFFLINE ANALYSIS



Livingston

Hanford

raw data

Virgo

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triggers

triggers

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Enrichment + Analysis

events

events

GCN

Papers
GWOSC

LVK OFFLINE ANALYSIS

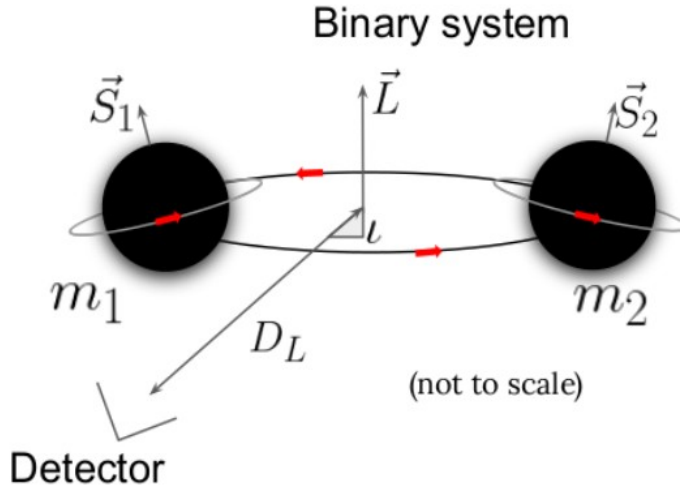
Pipeline triggers & Events

- Search pipelines deliver triggers (candidate events)
  - Very crude estimate of the source parameters (best fit template)
  - No uncertainty (error bar)
  - Some parameters are more relevant than others – Need to “marginalize” over irrelevant parameters
  - Non-trivial coupling between parameters
  - Model comparison and selection
- Triggers can be enriched through Bayesian analysis

Parameter estimation

The signal from a binary system made up of black holes will be described by fifteen parameters

- Intrinsic parameters:
  - Component Masses: m_1 m_2
  - Component spins in each direction: s_{1x} s_{1y} s_{1z} s_{2x} s_{2y} s_{2z}
- Extrinsic Parameters:
  - Location: Right Ascension and Declination
  - Inclination angle between line of sight and orbital plane, ι
  - Polarisation angle,
  - Phase at coalescence
  - Luminosity distance, D_L
  - Time of coalescence



TAP server

- DaCHS framework
- Currently: a staging server @ OVH (http://vps-fe1543c2.vps.ovh.net/__system__/adql/query/form)
- Production server: CC-IN2P3 green light from the science Virgo Czar and the technical support
- Public documentation: https://gwosc.docs.ligo.org/igwn-tap
- Non-yet published (fortunately because we changed the authority name from GWOSC to IGWN)
- Two schema: one for the triggers, one for the events
- Plain tables (no ObsCore)
- Deployment of Resource Descriptors via ansible (but not in a CI/CD)

Table 'triggers.all_triggers'

Release	Description	Catalog	#triggers
GWTC2p1	Deep Extended Catalog of Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run — Candidate Data Release. catalog paper	GWTC2p1-GSTLAL_AllSky	405
		GWTC2p1-MBTA_AllSky	320
		GWTC2p1-PYCBC_AllSky	337
		GWTC2p1-PYCBC_HighMass	329
GWTC3	Compact Binary Coalescences Observed by LIGO and Virgo during the Second Part of the Third Observing Run — Candidate Data Release. catalog paper	GWTC3-GSTLAL_AllSky	309
		GWTC3-MBTA_AllSky	264
		GWTC3-PYCBC_AllSky	284
		GWTC3-PYCBC_HighMass	325

Table 'triggers.all_triggers'

4-OGC	Fourth Open Gravitational-wave Catalog (4-OGC) of binary neutron star (BNS), binary black hole (BBH) and neutron star-black hole (NSBH) mergers. The catalog includes observations from 2015-2020 covering the first through third observing runs (O1, O2, O3a, O3b) of Advanced LIGO And Advanced Virgo. catalog paper	4-OGC	1424955
IAS-O3a	Candidates are identified using an updated version of the IAS pipeline (Venumadhav et al.), and events are declared according to criteria similar to those in the GWTC-2p1 catalog (Abbott et al.). The updated search is sensitive to a larger region of parameter space, applies a template prior that accounts for different search volume as a function of intrinsic parameters, and uses an improved coherent detection statistic that optimally combines data from the Hanford and Livingston detectors. catalog paper	IAS-O3a	1045

Table 'triggers.all_triggers'

Name	Table Head	Description	Unit	UCD
name	Name	The unique identifier of the trigger, prefixed by the catalog name.	N/A	meta.id;meta.main
original_name	Original Name	The trigger identifier, as defined in the catalog. Useful to join the original catalog.	N/A	meta.id
release	Release	The release name, which may contain more than one catalog (ex: GWTC3).	N/A	meta.id
"catalog"	Catalog	The catalog name, equal to the release name if there is only one catalog in the release, or prefixed by the release name otherwise (ex: GWTC3-MBTA_AllSky).	N/A	meta.id;meta.table
pipeline	Pipeline	The name of the pipeline used in the analysis, in upper case (ex: GSTLAL, PYCBC).	N/A	meta.id;meta.software
network	Network	The interferometers, whose data were used to produce the trigger, in alphabetic order (ex: H1,L1,V1).	N/A	meta.id;instr
network_snr	Network SNR	The combined Signal-to-Noise ratio for the interferometers in the network.	N/A	stat.snr
H1_snr	H1 SNR	The Signal-to-Noise ratio for the Hanford 1 interferometer.	N/A	stat.snr
L1_snr	L1 SNR	The Signal-to-Noise ratio for the Livingston 1 interferometer.	N/A	stat.snr
V1_snr	V1 SNR	The Signal-to-Noise ratio for the Virgo 1 interferometer.	N/A	stat.snr

Table 'triggers.all_triggers'

ifar	Inverse FAR	The inverse false alarm rate.	yr	time.interval;stat.falsePositive
end_time_gps	End Time GPS	The GPS time of the merger. Precise definition may differ, depending on the catalog.	s	time.epoch
p_astro	P-astro	The bayesian probability of being astrophysical (or not being terrestrial).	N/A	stat.probability;src.class
mass_1	Mass 1	The detector-frame mass of the heavier object in the binary.	solMass	phys.mass
mass_2	Mass 2	The detector-frame mass of the lighter object in the binary.	solMass	phys.mass
spin_1z	Spin 1 (z)	The z-component of the heavier object's spin parameter in Euclidean coordinates.	N/A	phys.spinParameter
spin_2z	Spin 2 (z)	The z-component of the lighter object's spin parameter in Euclidean coordinates.	N/A	phys.spinParameter

Table 'events.all_events'

Release	Reference	Description
GWTC-1	link	A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs, 2015-2017.
GWTC-2.1	link	Deep Extended Catalog of Compact Binary Coalescences Observered by LIGO and VIRGO in the First Half of the Third Observing Run. This release contains an additional catalog (`GWTC-2.1-auxiliary`) for the events included in the GWTC-2 release that have been demoted after re-analysis.
GWTC-3	link	Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run.
O3-IMBH-marginal	link	This release includes data associated with marginal intermediate-mass black hole candidates in O3, initially published outside of main catalogs and O3 Discovery Papers.

Table 'events.all_events'

Name	Table Head	Description	Unit	UCD
name	Name	The unique identifier of the event.	N/A	meta.id;meta.main
release	Release	The data release in which the event has been published (ex: GWTC-2.1).	N/A	meta.id
"catalog"	Catalog	The data release catalog that contains the event (ex: GWTC-2.1-confident).	N/A	meta.id
network_matched_filter_snr	Network Matched Filter SNR	The matched filter signal to noise ratio in the gravitational wave detector network.	N/A	stat.snr
far	FAR	The false alarm rate.	yr**-1	arith.rate;stat.falsePositive
ifar	FAR^{-1}	The inverse false alarm rate.	yr	arith.interval;stat.falsePositive
geocent_time_gps	Merger Time GPS	The GPS merger time at the geocenter.	s	time.epoch
luminosity_distance	Lum. Distance	The luminosity distance of the source.	Mpc	pos.distance
redshift	Redshift	The redshift depending on specified cosmology.	N/A	src.redshift
mass_1_source	Mass 1	The source-frame mass of the heavier object in the binary.	solMass	phys.mass
mass_2_source	Mass 2	The source-frame mass of the lighter object in the binary.	solMass	phys.mass

Table 'events.all_events' (cont.)

total_mass_source	Total Mass	The source-frame combined mass of the primary and secondary masses.	solMass	phys.mass
final_mass_source	Final Mass	The source-frame remnant mass estimated using the spins evolved to the ISCO frequency.	solMass	phys.mass
chirp_mass	Detector Chirp Mass	The detector-frame chirp mass.	solMass	phys.mass
chirp_mass_source	Chirp Mass	The source-frame chirp mass.	solMass	phys.mass
chi_eff	χeff	The effective inspiral spin parameter.	N/A	phys.inspiralSpinParameter
jsonurl	JSON URL	The URL of the JSON data.	N/A	meta.ref.url
reference	Reference	The reference identifying the data release.	N/A	meta.ref
version	Version	The version of the event entry.	N/A	meta.version

New UCDs

- `stat.falsePositive`:

Related to false alarm or false positive detection

- `stat.falseNegative`:

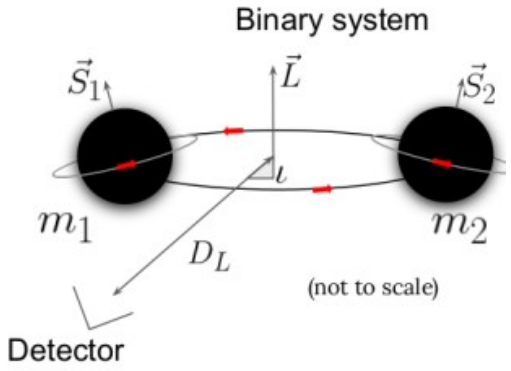
Related to missed or false negative detection

New UCDs in discussion

- `phys.spinParameter`

Related to the dimensionless compact object's spin parameter.

$$S = \frac{cJ}{GM^2} \qquad 0 \le S \le 1$$



- `phys.inspiralSpinParameter (or inspiralSpin):`

Related to the dimensionless compact binary inspiral spin parameter.

It measures the degree of alignment between the intrinsic angular momenta of the compact objects and the orbital angular momentum.

$$\chi_{eff} = \frac{m_1 S_1 \cos\left(\theta_{L,S_1}\right) + m_2 S_2 \cos\left(\theta_{L,S_2}\right)}{m_1 + m_2} \qquad -1 \le \chi_{eff} \le 1$$

-

Query examples

To match the pipeline triggers related to an event:

```
SELECT
    trig.*
FROM
    triggers.all_triggers AS trig
    INNER JOIN events.all_events AS ev
    ON ABS(trig.end_time_gps - ev.geocent_time_gps) < 1
WHERE
    ev.name = 'GW170817'
```

To cross-match the triggers from all catalogs with an inverse FAR greater than 2 hours, within a time window of 1 second:

```
SELECT t1.name, t2.name, ABS(t1.end_time_gps - t2.end_time_gps) AS "distance"
FROM
    triggers.all_triggers AS t1
    INNER JOIN triggers.all_triggers AS t2
    ON ABS(t1.end_time_gps - t2.end_time_gps) < 1
WHERE
        t1.ifar > 1. / 365 / 12
    AND t2.ifar > 1. / 365 / 12
    AND t1.end_time_gps < t2.end_time_gps
```

Future directions

- Include older pipeline triggers (from 01 and 02 observing runs)
- Add original trigger catalogs
- Conversion UTC / GPS
- Add skymaps
- Improve cross-match between triggers
- Searches in Multi-Order Coverage maps