Multi-messenger astronomy of gravitational-wave transients in the "Automatic Public Alert" Era

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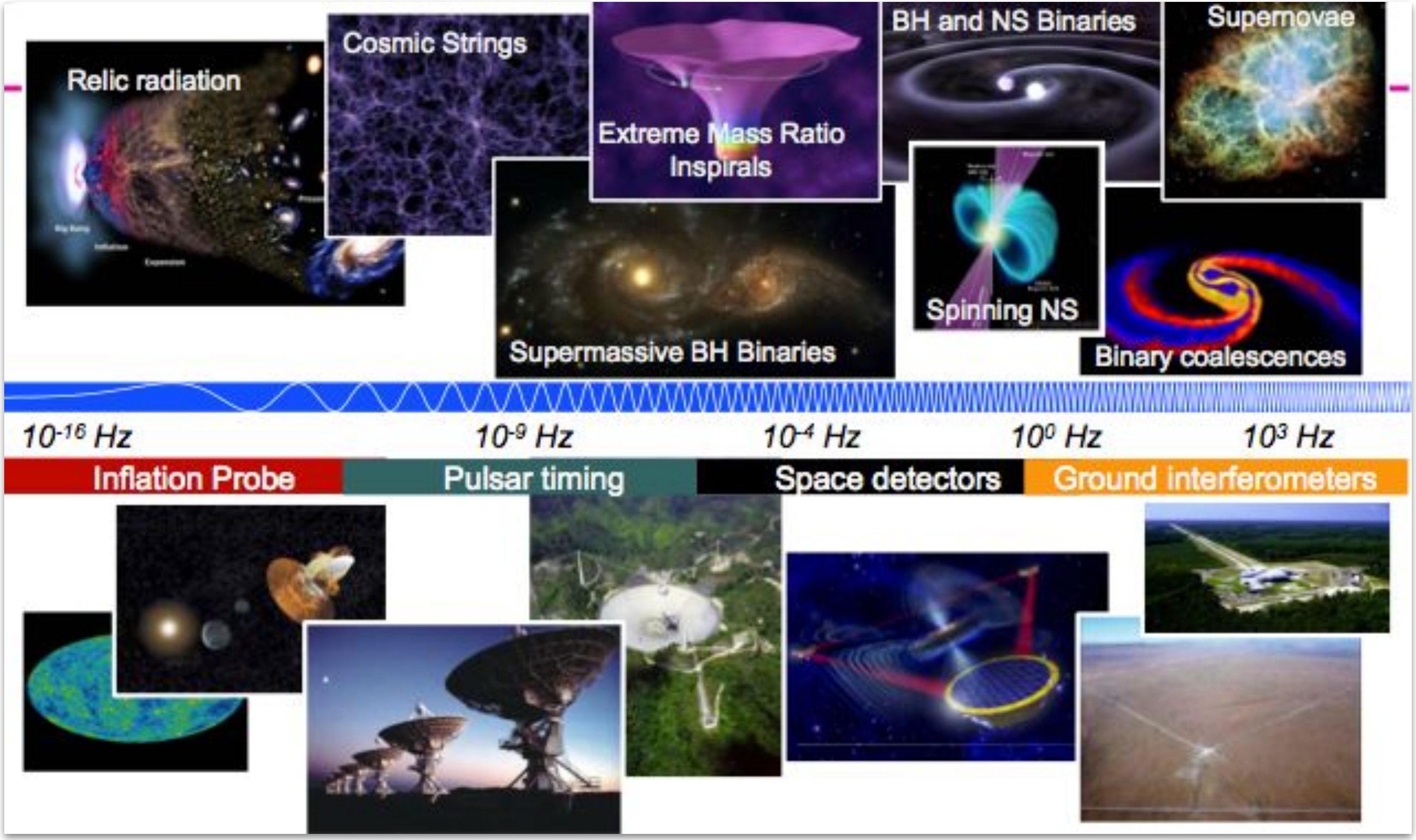
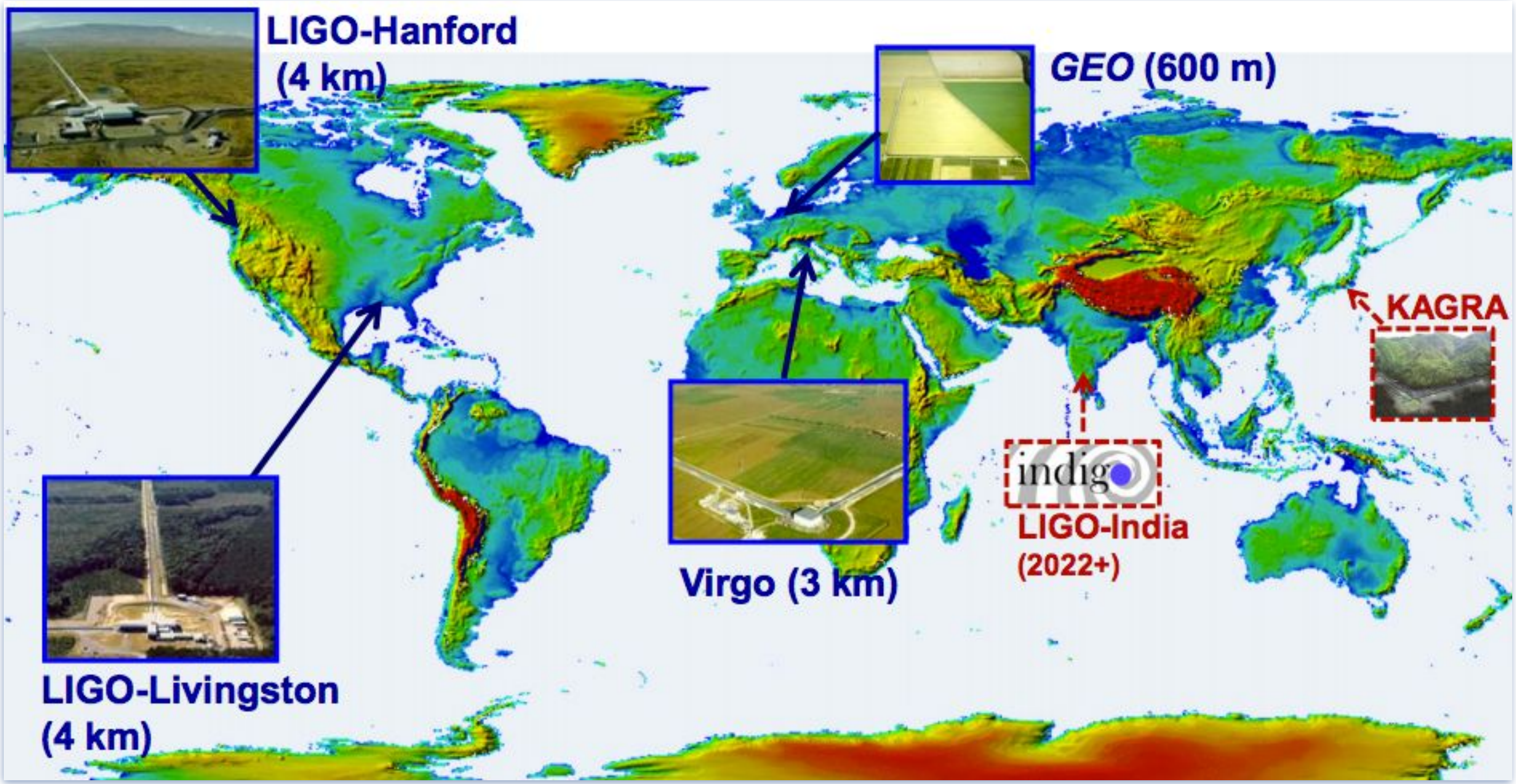
LIGO VIRGO

GW sources



Relic radiation
Cosmic Strings
Extreme Mass Ratio Inspirals
BH and NS Binaries
Supernovae
Spinning NS
Supermassive BH Binaries
Binary coalescences
10-16 Hz
10-9 Hz
10-4 Hz
100 Hz
103 Hz
Inflation Probe
Pulsar timing
Space detectors
Ground interferometers

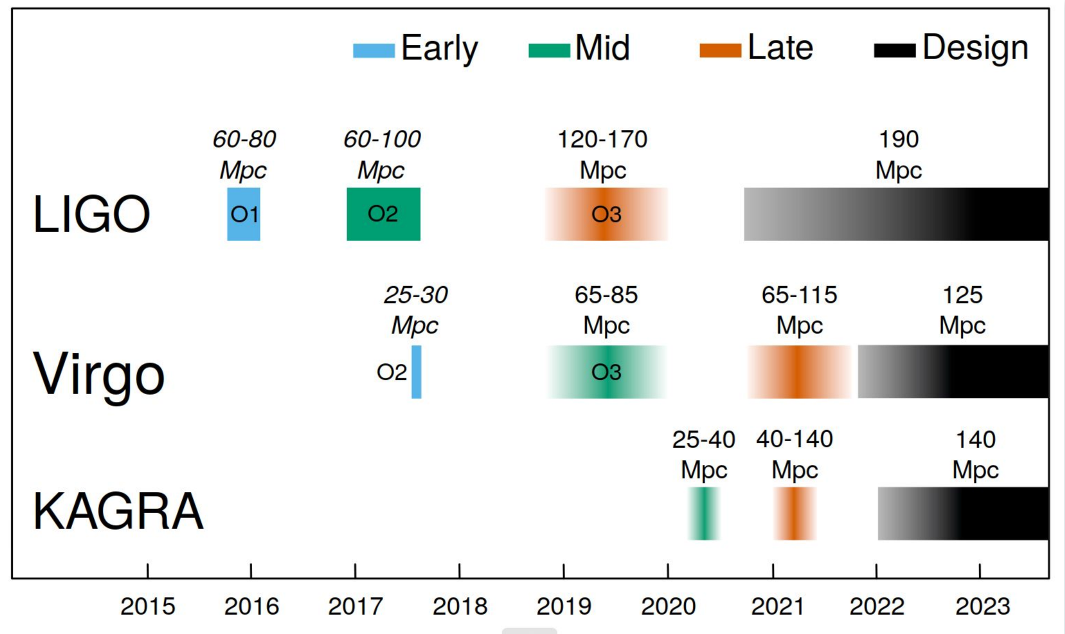
Interferometer Network



Timeline

The gravitational-wave observing schedules is divided into

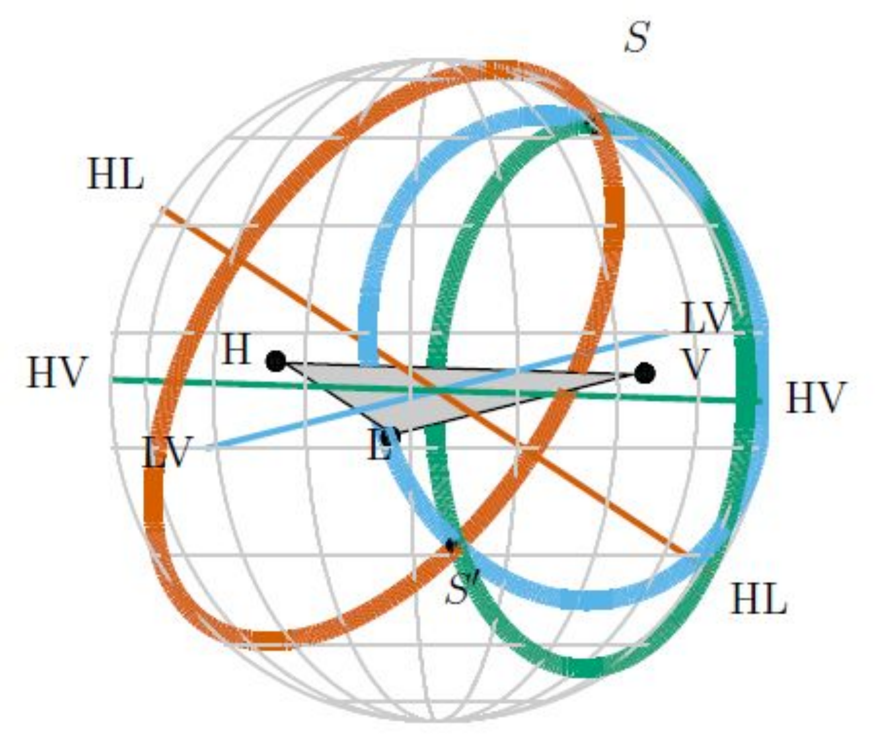
- **Observing Runs**, epochs of months to years of operation at fixed sensitivity.
- **Down time** for construction and commissioning.
- Transitional **Engineering Runs** between commissioning and observing runs.



During O3, we expect that all three detectors will observe continuously and without significant interruptions for one year. It is possible that the Japanese KAGRA detector may come online and become part of the joint gravitational-wave analysis at some point during O3.

Sky Localization

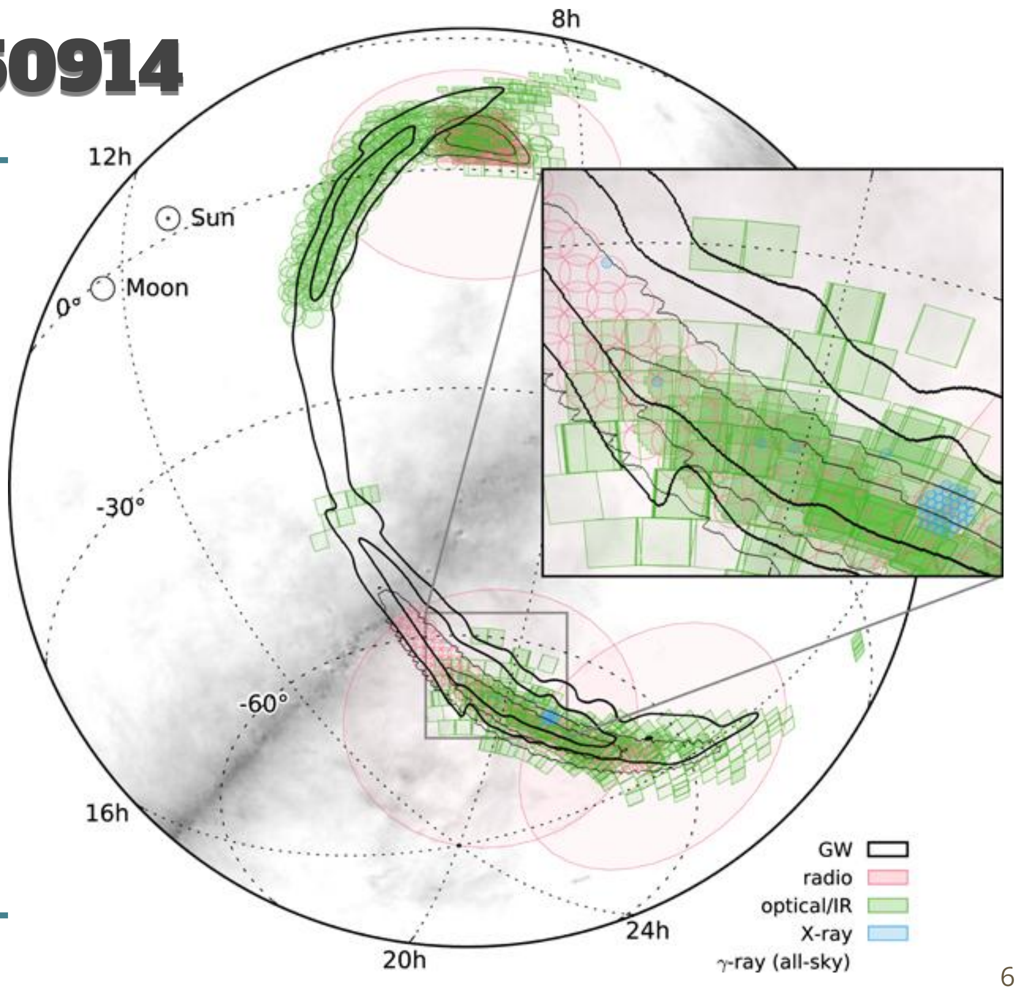
- Source localization using only timing for a two-site network yields an annulus on the sky. Additional information such as signal amplitude, spin, and precession effects resolve this to only parts of the annulus, but even then sources will only be localized to regions of hundreds to thousands of square degrees.
- For three detectors, the time delays restrict the source to two sky regions which are mirror images with respect to the plane passing through the three sites.
- With four or more detectors, timing information alone is sufficient to localize to a single sky region, and the additional baselines help to limit the region to under 10 deg^2 for some signals.



EM-FollowUP of GW150914

On September 14, 2015 at 09:50:45 UTC, the LIGO/Virgo Collaboration made the first direct detection of an astrophysical gravitational-wave (GW) signal that turned out to be from a binary black hole (BBH) merger - **GW150914.**

Twenty-five participating teams of observers responded to the GW alert to mobilize satellites and ground-based telescopes spanning 19 orders of magnitude in EM wavelength. The Figure shows the footprints of all reported observations in comparison with the 50% and 90% credible levels of the initially distributed GW localization maps.



High-energy followUP of GW150914

No stellar-BBH EM emission expected due to the absence of the accreting material.

However some mechanisms that could produce unusual presence of matter around BHs recently discussed (*e.g.* Loeb 2016; Perna et al. 2016; Murase et al. 2016, Bartosetal.2016)

- Fermi-GBM, INTEGRAL, IPN **archival search** to detect prompt emission
- Fermi-LAT, MAXI, Swift-XRT to detect afterglow emission

From Abbott et al. 2016, arXiv:1602.08492

Instrument	Band[a]	Depth[b]	Time[c]	Area (deg^2)	Contained probability (%) cWB	LIB	BSTR.	LALInf.	GCN
		erg cm^{-2} s^{-1}	Gamma-ray						
Fermi LAT	20 MeV–300 GeV	1.7×10^{-9}	(every 3 hr)	—	100	100	100	100	18709
Fermi GBM	8 keV–40 MeV	$0.7–5 \times 10^{-7}$ (0.1–1 MeV)	(archival)	—	100	100	100	100	18339
INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100	18354
IPN	15 keV–10 MeV	1×10^{-9}	(archival)	—	100	100	100	100	—
			X-ray						
MAXI/GSC	2–20 keV	1×10^{-9}	(archival)	17900	95	89	92	84	19013
Swift XRT	0.3–10 keV	5×10^{-13} (gal.)	2.3, 1, 1	0.6	0.03	0.18	0.04	0.05	18331
		$2–4 \times 10^{-12}$ (LMC)	3.4, 1, 1	4.1	1.2	1.9	0.16	0.26	18346

Evans et al. arXiv:1602.03868

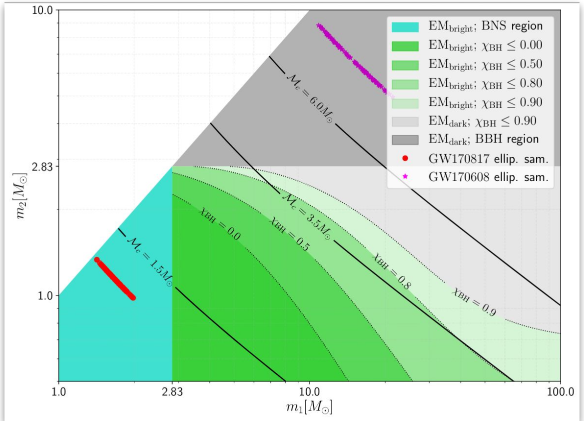
Integral:
no signal but stringent upper limit
Savchenko et al. arXiv:1602.04180

Fermi-GBM sub-threshold search:
weak signal 0.4s after the event (t=1s)
Connaughton et al. arXiv:1602.03920

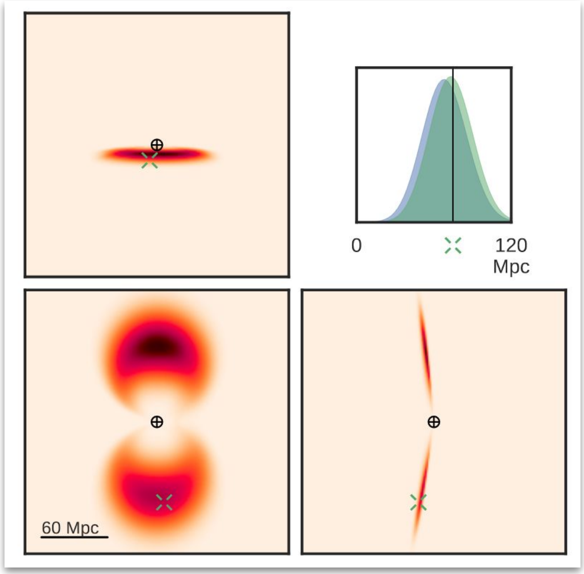
In O2 followUp campain (see next slides), no significant counterpart associated with BBH events was discovered; the most promising candidate was a weak gamma-ray transient found by AGILE during GW170104 lasting 32ms and occuring 0.5 s before the GW event (Verrecchia et al. 2017) but not confirmed by other instruments.

Low Latency campaign in O2

Source Classification, 3D skymap and ...



Different regimes of operation by the source classifier used in O2. The BNS region is shown in cyan.
Any system lying in this region is always considered to have an EM counterpart.
https://arxiv.org/pdf/1901.03310.pdf



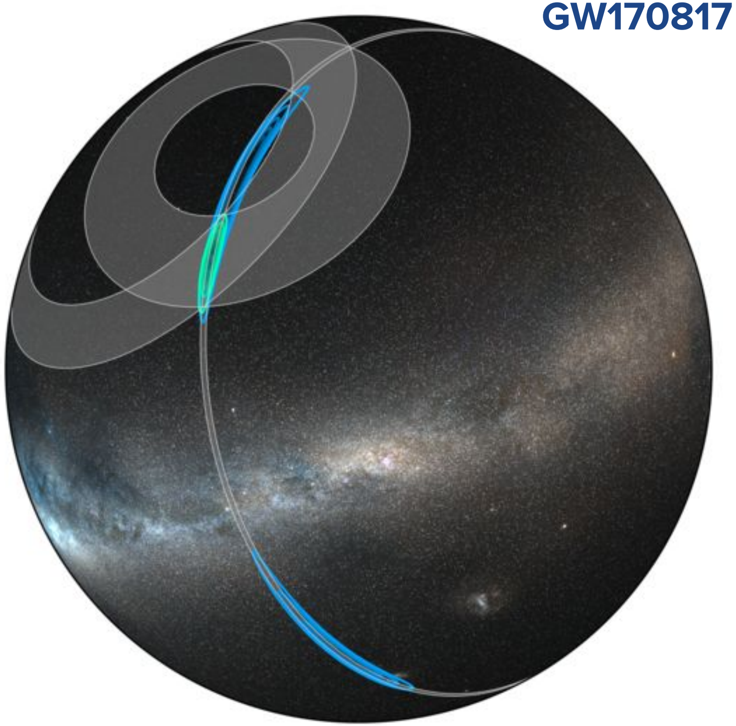
Marginal posterior probability distribution in the principal planes. *Singer at al., 2016*

Low Latency campaign in O2

... Virgo

GW170814

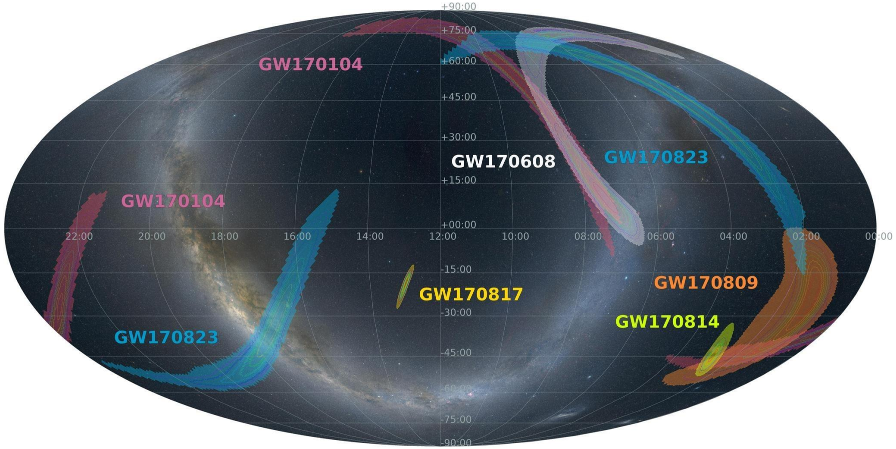
GW170817



Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

Low Latency campaign in O2

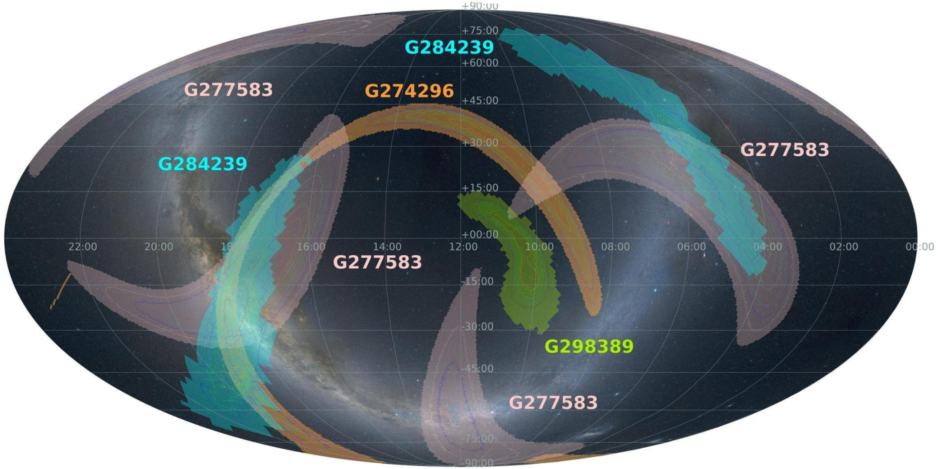
GW confident events

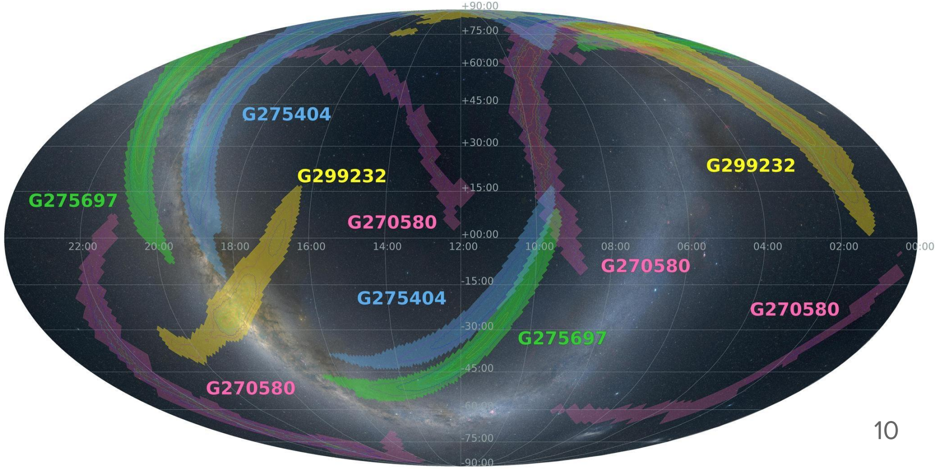


- 14 alerts were distributed.
- 6 events were declared as confident GW events.

GW candidates

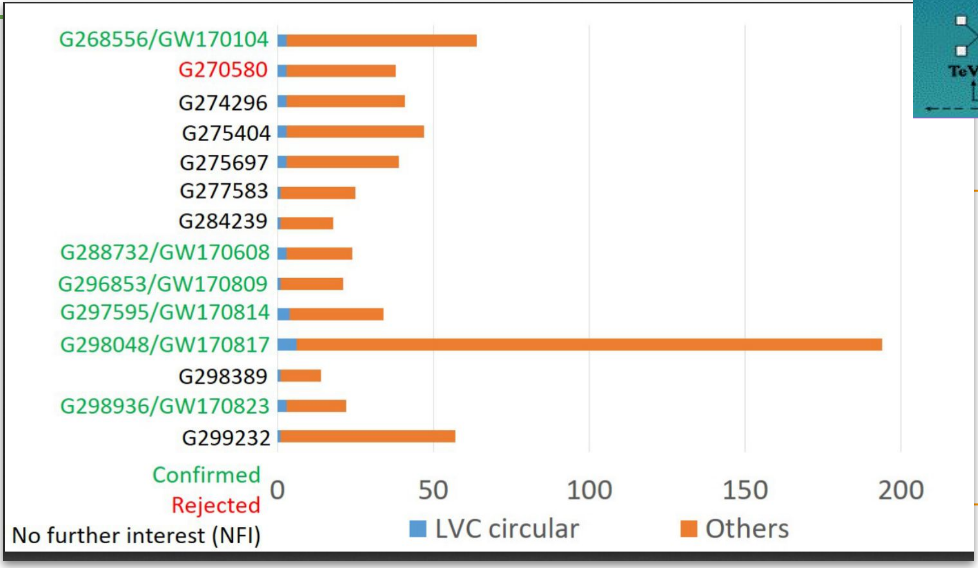
Marginally significant GW triggers

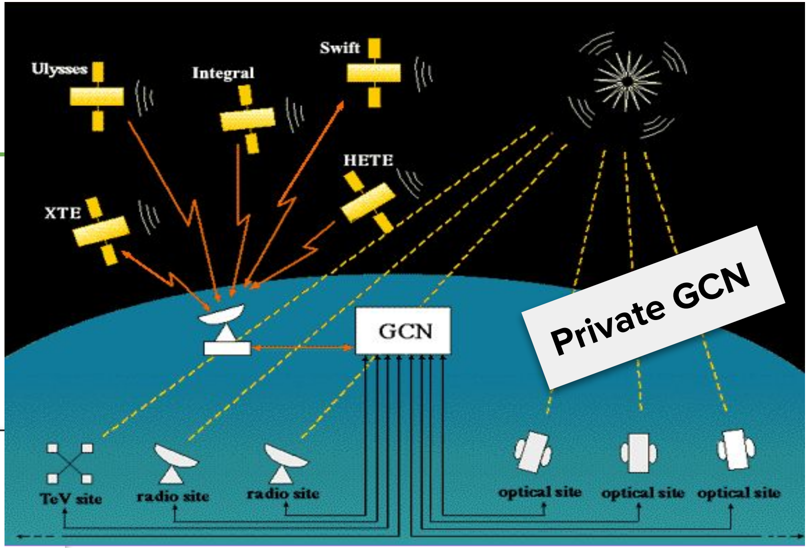




Exchange of information

More than 40 GCNs were generated for GW candidates that included a neutron star as one of the binary components - G275404, G275697, G298048 and G299232.





This underscores the importance of source classification during O3, when observers might want to allocate their valuable resources in the most efficient manner possible - see slide 23-24.

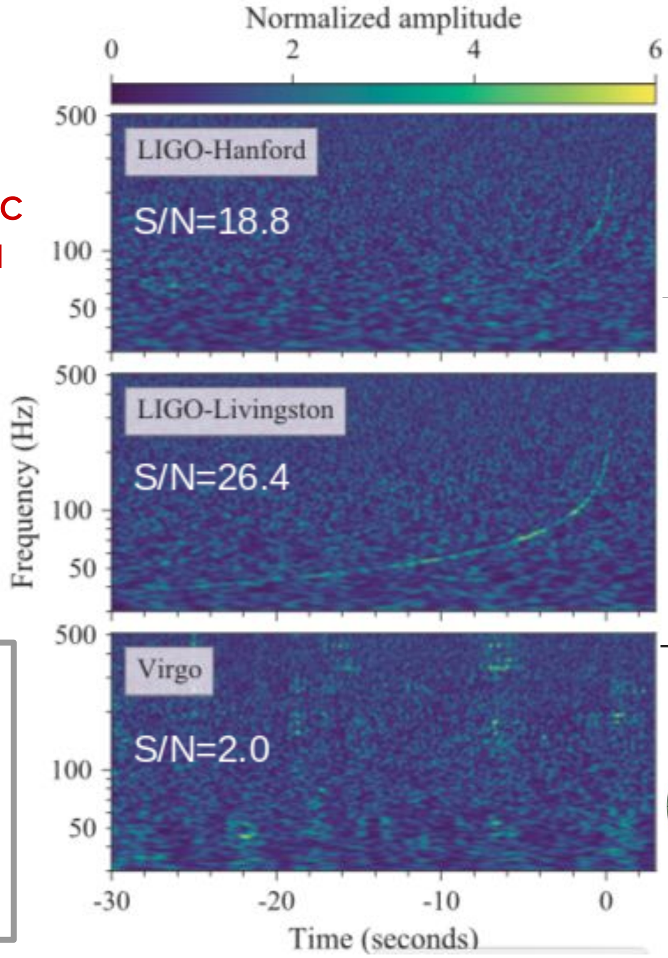
GW170817

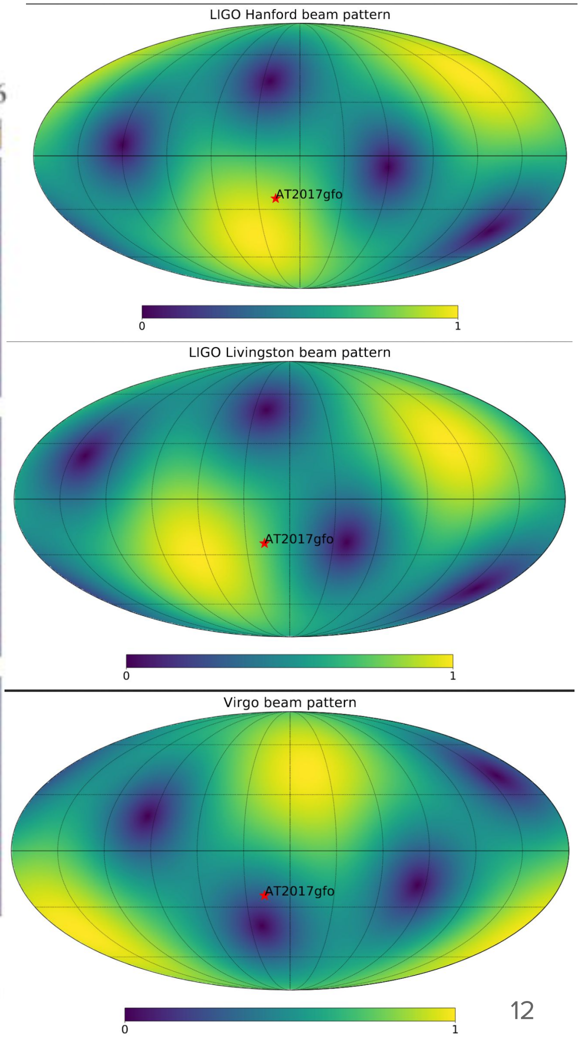
- ❑ On August 17, 2017, at 12:41:04 UTC a binary neutron star (BNS) inspiral signal GW170817) was observed.

- ❑ At the location of GW170817, the antenna pattern amplitude for V is 2.5 to 3 times lower than for H and L.

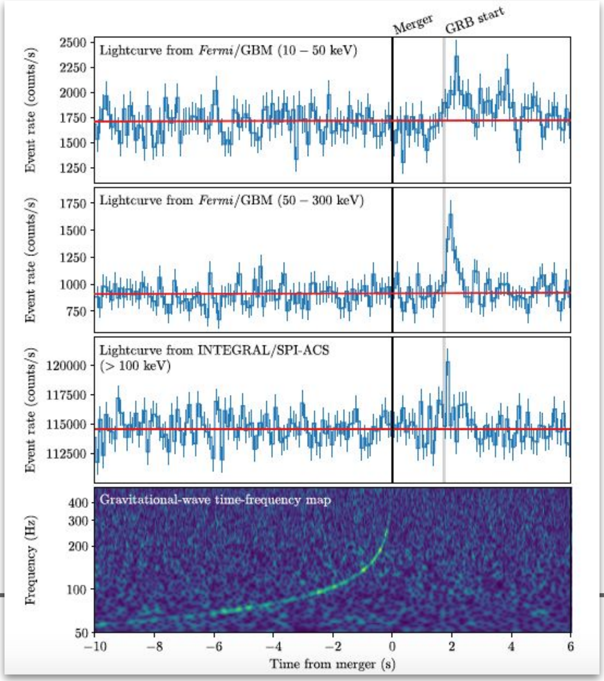
Antenna Patterns

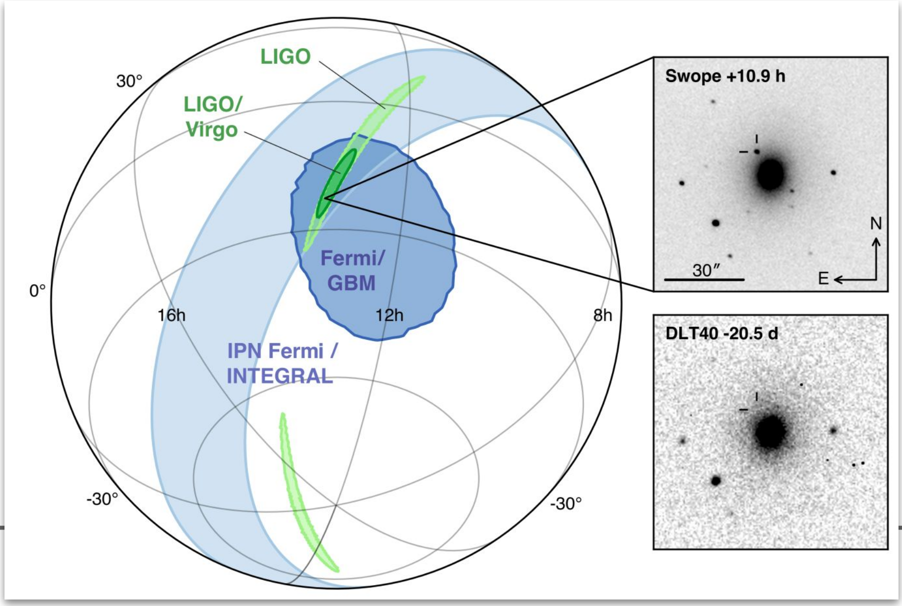
The antenna patterns represent the sensitivity of a detector to an event on the sky. The generic L-shaped detectors are most sensitive to signals coming from a direction perpendicular to the plane of its arms.





GW170817/GRB170817/AT2017gfo





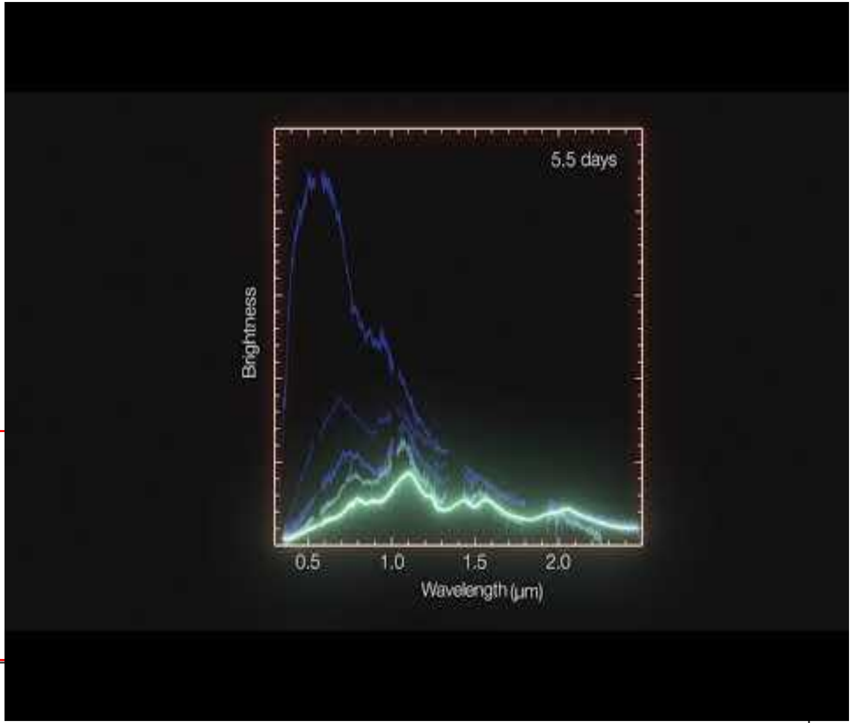
Less than two seconds later, the short gamma-ray burst (sGRB) GRB170817A was detected by two space-based instruments:the Gamma-ray Burst Monitor (GBM) on board Fermi (Goldstein et al. 2017), and the spectrometer anti-coincidence shield (SPI-ACS) on board INTEGRAL (Savchenko et al. 2017). This joint observation provided the first direct evidence that at least a fraction of sGRBs have a BNS system as progenitor, as predicted by Eichler et al. 1989; Paczynski 1986, 1991.

Animation of spectra of kilonova in NGC 4993

Credit: European Southern Observatory (ESO)

Credit: 1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

Swope and Magellan telescope optical and near-infrared images of the first optical counterpart to a gravitational wave source, SSS17a, in its galaxy, NGC 4993.



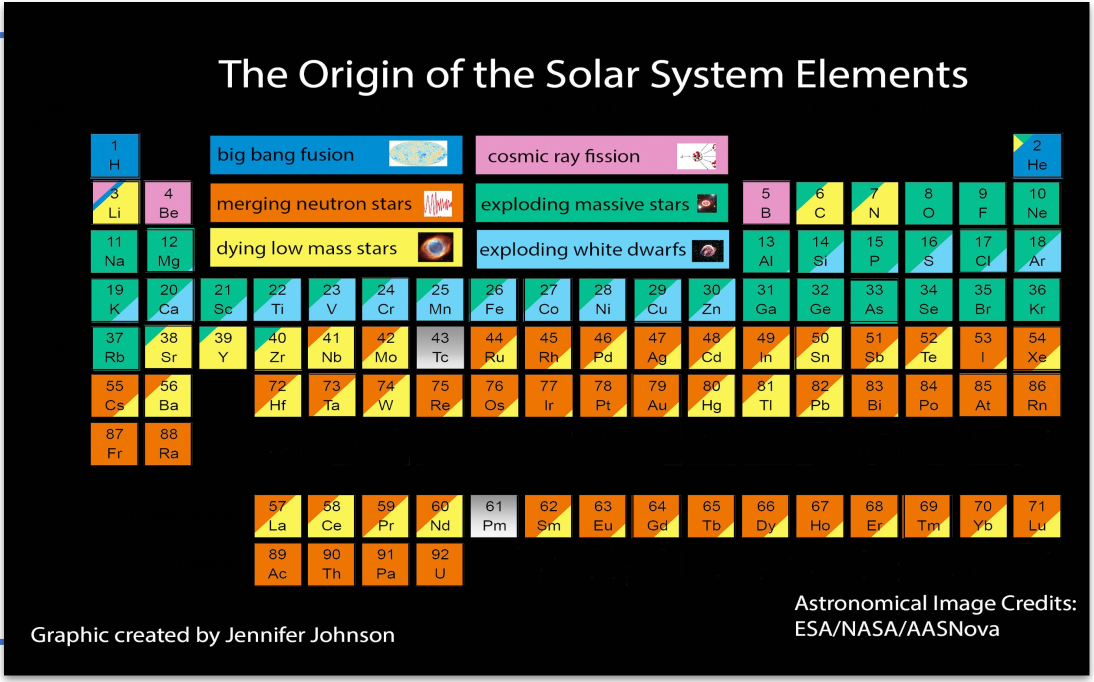
This animation is based on a series of spectra of the kilonova in NGC 4993 observed by the X-shooter instrument on ESO's Very Large Telescope in Chile. They cover a period of 12 days after the initial explosion on 17 August 2017. The kilonova is very blue initially but then brightens in the red and fades.

Neutron star mergers as an origin of heavy elements

The cosmic origin of elements heavier than iron has long been uncertain.

Theoretical modelling shows that the matter that is expelled in the violent merger of two neutron stars can produce heavy elements such as gold and platinum in a process known as rapid neutron capture (r-process) nucleosynthesis.

The radioactive decay of isotopes of the heavy elements is predicted to power a distinctive thermal glow *the kilonova.*



OPA User Guide

Advanced LIGO and Advanced Virgo began their third observing run (O3) on April 1, 2019. For the first time, LIGO/Virgo alerts are public.

The document provides a brief overview of the procedures for vetting and sending GW alerts, describes their contents and format, and includes instructions and sample code for receiving GCN Notices and decoding GW sky maps.

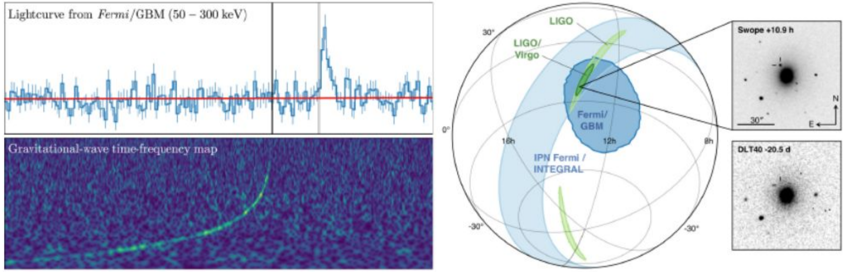
LSC LIGO Scientific Collaboration

VIRGO

Primer on public alerts for astronomers from the LIGO and Virgo gravitational-wave observatories.

Getting Started Checklist →

LIGO/Virgo Public Alerts User Guide



Navigation

- Getting Started Checklist
- Observing Capabilities
- Procedures
- Alert Contents
- Sample Code

- Change Log
- Glossary

Question? Issues? Feedback?

Email emfollow-userguide@support.ligo.org

Welcome to the LIGO/Virgo Public Alerts User Guide! This document is intended for both professional astronomers and science enthusiasts who are interested in receiving alerts and real-time data products related to gravitational-wave (GW) events.

Three sites (LHO, LLO, Virgo) together form a global network of ground-based GW detectors. The LIGO Scientific Collaboration and the Virgo Collaboration jointly analyze the data in real time to detect and localize transients from compact binary mergers and other sources. When a signal

https://emfollow.docs.ligo.org/userguide/

Sensitivity and Localization Accuracy

We expect 1–10 BNS events over the course of O3. For BNS events, the median localization accuracy of in terms of the 90% credible area will be 120–180 deg^2. 12–21% of BNS mergers will be localized to less than 20 deg^2.

Table 1
Plausible target detector sensitivities

	LIGO		Virgo		KAGRA	
	BNS	BBH	BNS	BBH	BNS	BBH
	range/ Mpc	range/ Mpc	range/ Mpc	range/ Mpc	range/ Mpc	range/ Mpc
Early	40–80	415–775	20–65	220–615	8–25	8–250
Mid	80–120	775–1110	65–85	615–790	25–40	250–405
Late	120–170	1110–1490	65–115	610–1030	40–140	405–1270
Design	190	1640	125	1130	140	1270

Detector	BNS Range (Mpc)	Burst Range (Mpc)
LIGO	120–170	75–90
Virgo	65–85	40–50
Kagra	8–25	

Name	FAR per years	Detectors	90% loc.	Distance (Mpc)
S190408an	1 / 1.127e+10	H1, L1, V1	387 deg^2	1473 +/ -358
S190412m	1 / 1.883e+19	H1, L1, V1	156 deg^2	812 +/- 194
S190421ar	1 / 2.1285	H1, L1	1917 deg^2	2281 +/- 697
S190425z	1 / 69834	L1, V1	7461 deg^2	155 +/- 45
S190426c	1 / 1.6276	H1, L1, V1	1262 deg^2	375 +/- 108

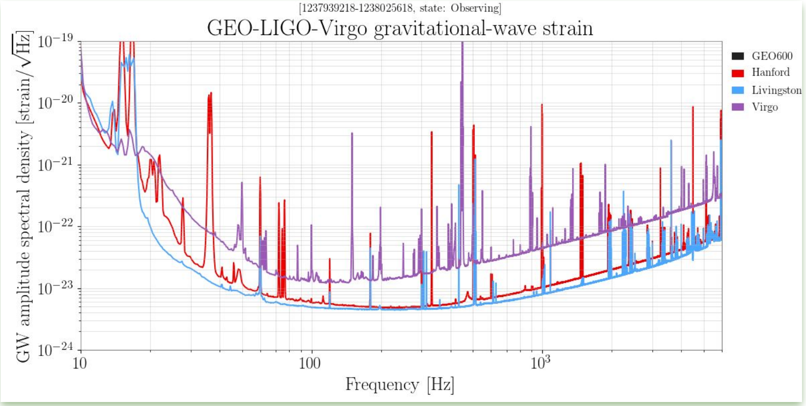
Name	FAR per years	Detectors	90% loc.	Distance (Mpc)
S190503bf	1 / 19.368	H1, L1, V1	448 deg^2	421 +/- 105
S190510g	1 / 3.5872	H1, L1, V1	3462 deg^2	269 +/- 108
S190512at	1 / 16.673	H1, L1, V1	399 deg^2	1331 +/- 341
S190513bm	1 / 84864	H1, L1, V1	691 deg^2	1987 +/- 501
S190517h	1 / 13.354	H1, L1, V1	939 deg^2	2950 +/- 1038
S190519bj	1 / 5.5578	H1, L1, V1	967 deg^2	3154 +/- 791
S190521g	1 / 8.3367	H1, L1, V1	765 deg^2	3931 +/- 953
S190521r	1 / 100.04	H1, L1	488 deg^2	1136 +/- 279

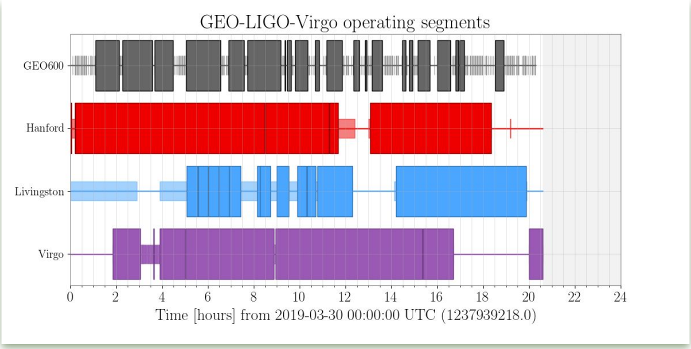
GW Candidate events issued so far from GraceDB

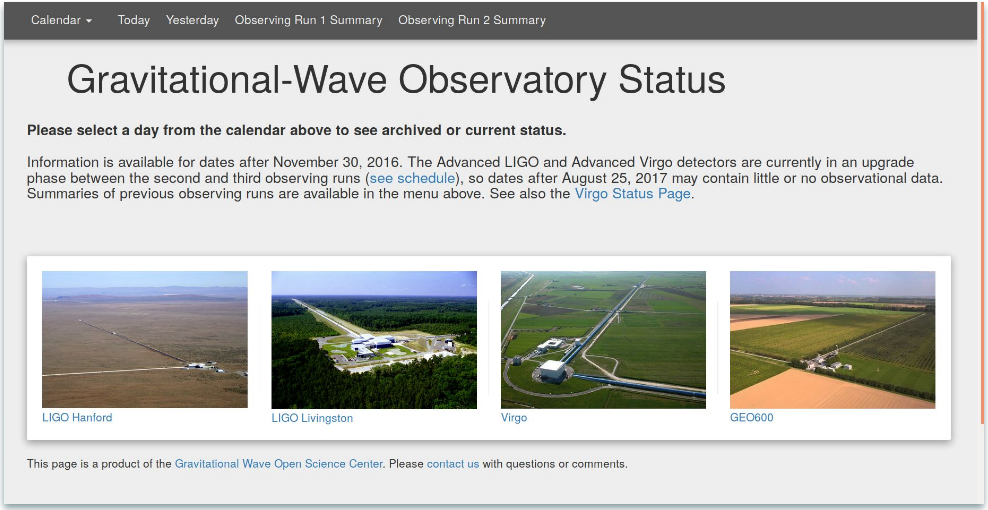
Artistic GW calendar created by Karelle Siellez

Live Status

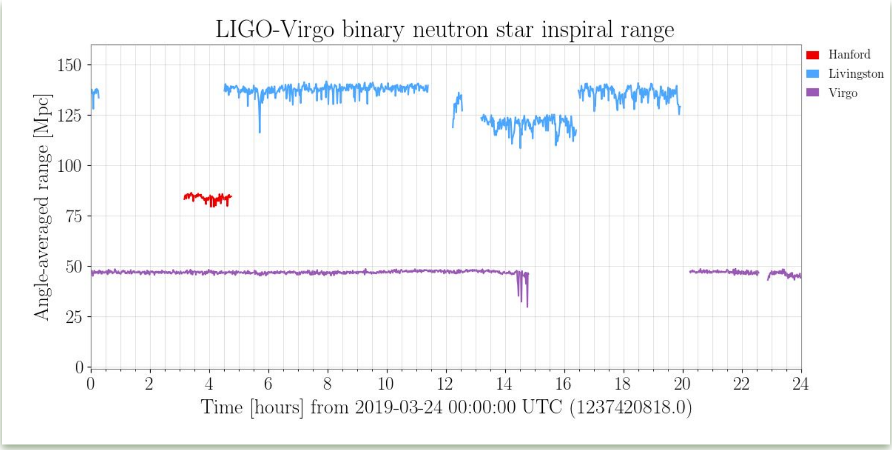
Detector Status Portal: Daily summary of detector performance







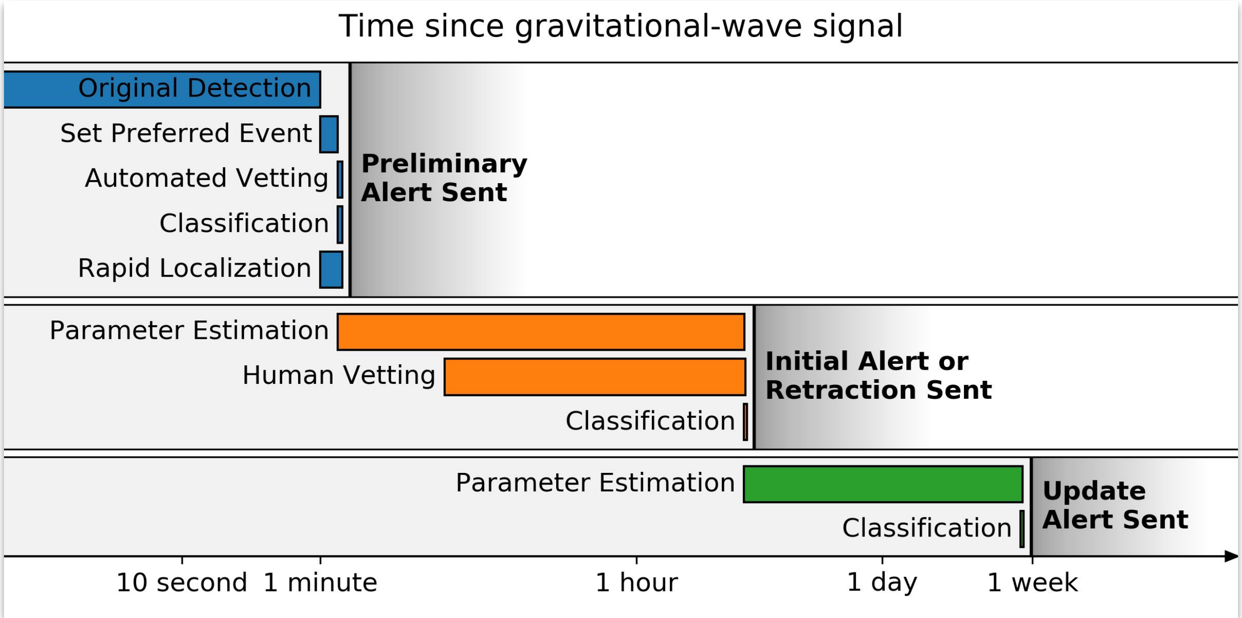
https://www.gw-openscience.org/detector_status



GCNs

- **Within 1 – 10 minutes after GW trigger time,** the first preliminary notice will be sent fully autonomously.
- **Within 24 hours after the GW trigger time** (possibly within 4 hours for BNS or NSBH sources, to be decided) the Initial notices and circulars will be distributed with an update for the sky localization area and the source classification. They are vetted by human instrument scientists and analysts.
- **Within a day,** black hole mergers will be fully vetted by experts and retraction or confirmation status will be reported.

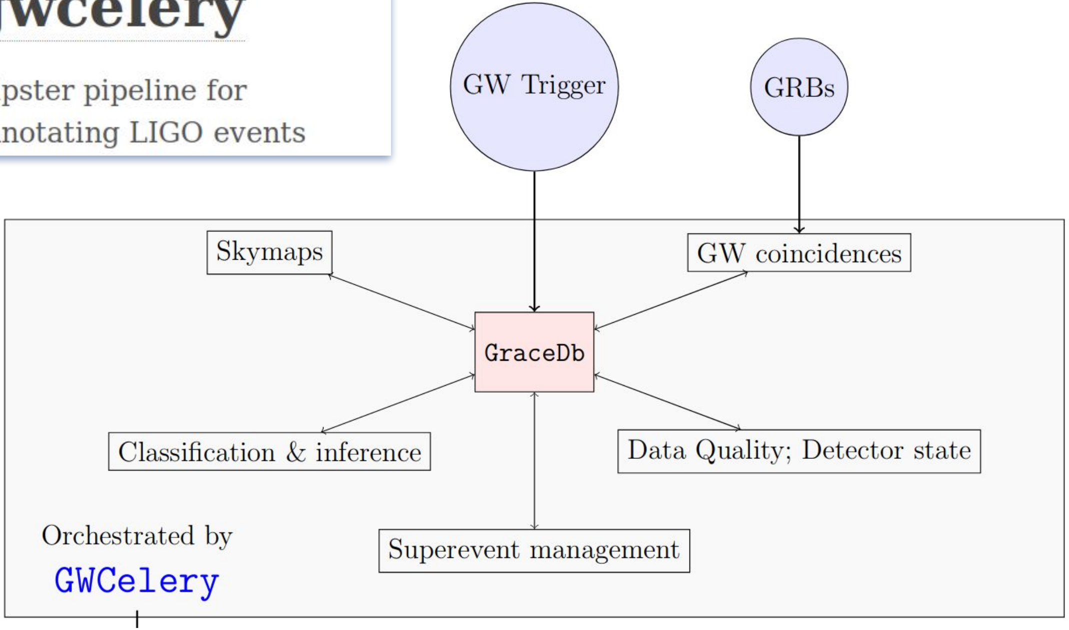
Update notice and circulars are sent whenever the sky localization area or significance accuracy improves.

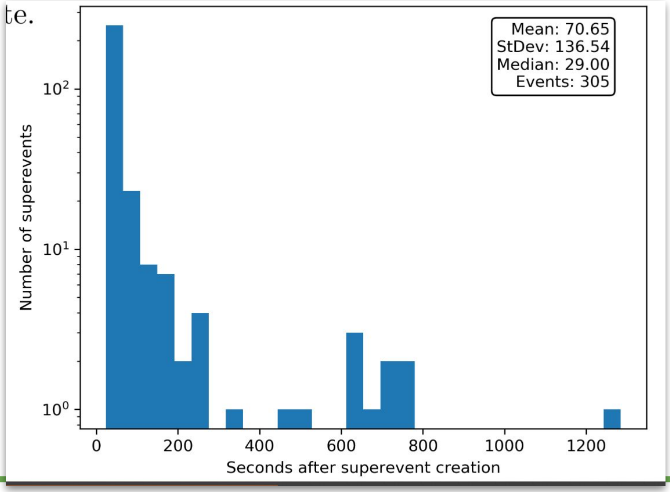


These alerts will be publicly available through the Gamma-ray Coordinates Network (GCN) via notices and circulars. Event candidates are publicly available in GraceDB.

At any time, we can promote an extraordinary candidate that does not pass our public alert thresholds if it is compellingly associated with a multimessenger signal (e.g. GRB, core-collapse SN). In this case, Initial notices and circulars will be distributed.

GWCelery is a simple and reliable package for annotating and orchestrating LIGO/Virgo alerts, built from widely used open source components.





Time between GWCelery superevent creation and GCN sending for 305 superevents, spanning over 7 weeks of replayed O2 data.
GWPAW 2018 - Poster from Geoffrey Mo et al.

In the first weeks the system encountered some technical issues that prevented automatic generation of alerts.

Online Pipelines

A number of search pipelines run in a low latency, online mode. These can be divided into two groups, modeled and unmodeled.

1. The modeled (CBC) searches specifically look for signals from compact binary mergers of neutron stars and black holes (BNS, NSBH, and BBH systems) Matched-filtering based → GstLAL, MBTAOnline, PyCBC Live and SPIIR.
2. The unmodeled (Burst) searches on the other hand, are capable of detecting signals from a wide variety of astrophysical sources in addition to compact binary mergers: core-collapse of massive stars, magnetar star-quakes, and more speculative sources such as intersecting cosmic strings or as-yet unknown GW sources. Excess power algorithm → cWB, Olib.

Classification for CBC events


```
- <Group type="Classification">
  - <Param name="BNS" dataType="float" value="0.0" ucd="stat.probability">
    - <Description>
        Probability that the source is a binary neutron star merger (both objects lighter than 3 solar masses)
      </Description>
    </Param>
  - <Param name="NSBH" dataType="float" value="0.0" ucd="stat.probability">
    - <Description>
        Probability that the source is a neutron star-black hole merger (primary heavier than 5 solar masses, secondary lighter than 3 solar
        masses)
      </Description>
    </Param>
  - <Param name="BBH" dataType="float" value="0.999332344055" ucd="stat.probability">
    - <Description>
        Probability that the source is a binary black hole merger (both objects heavier than 5 solar masses)
      </Description>
    </Param>
  - <Param name="MassGap" dataType="float" value="0.0" ucd="stat.probability">
    - <Description>
        Probability that the source has at least one object between 3 and 5 solar masses
      </Description>
    </Param>
  - <Param name="Terrestrial" dataType="float" value="0.00066765594519" ucd="stat.probability">
    - <Description>
        Probability that the source is terrestrial (i.e., a background noise fluctuation or a glitch)
      </Description>
    </Param>
  - <Description>
      Source classification: binary neutron star (BNS), neutron star-black hole (NSBH), binary black hole (BBH), MassGap, or terrestrial (noise)
    </Description>
  </Group>
```

Properties for CBC events


```xml
</Group>
- <Group type="Properties">
  - <Param name="HasNS" dataType="float" value="0.0" ucd="stat.probability">
    - <Description>
        Probability that at least one object in the binary has a mass that is less than 3 solar masses
      </Description>
    </Param>
  - <Param name="HasRemnant" dataType="float" value="0.0" ucd="stat.probability">
    - <Description>
        Probability that a nonzero mass was ejected outside the central remnant object
      </Description>
    </Param>
```


GCN example

TITLE: GCN CIRCULAR
NUMBER: 24632
SUBJECT: LIGO/Virgo S190521r: Identification of a GW compact binary merger candidate
DATE: 19/05/21 08:41:27 GMT
FROM: Shasvath J. Kapadia at U. of Wisconsin, Milwaukee <kapadia@uwm.edu>

The classification of the GW signal, in order of descending probability, is BBH (>99%), Terrestrial (<1%), BNS (<1%), NSBH (<1%), or MassGap (<1%).

Assuming the candidate is astrophysical in origin, there is strong evidence against the lighter compact object having a mass < 3 solar masses (HasNS: <1%). Using the masses and spins inferred from the signal, there is strong evidence against matter outside the final compact object (HasRemnant: <1%).

Asterics and MMA: a few examples

ASTERICS is a project supported by the European Commission Framework Programme Horizon 2020 Research and Innovation action under grant agreement n. 653477

Astronomy ESFRI & Research Infrastructure Cluster

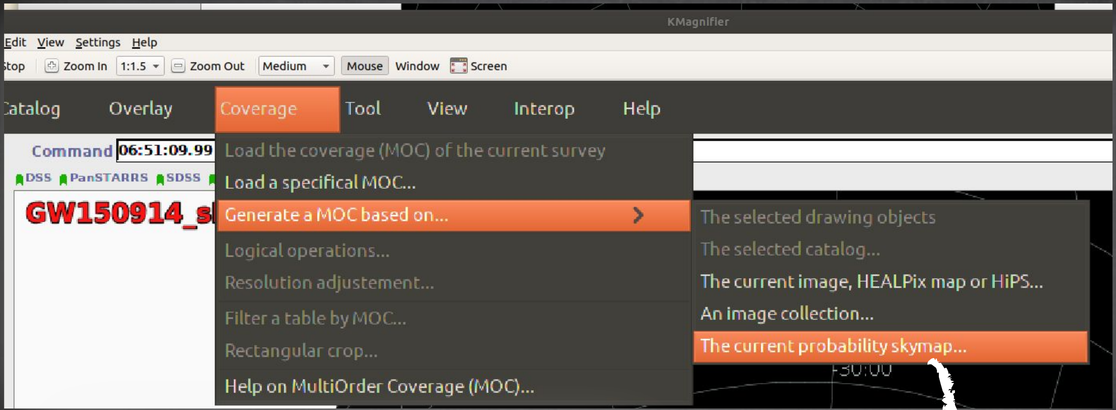
EGO - Virgo

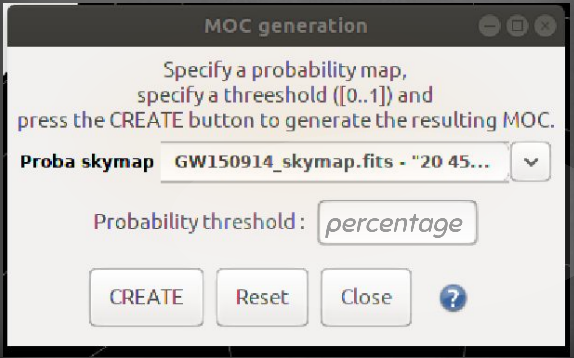
Data Access, Discovery and Interoperability (DADI)

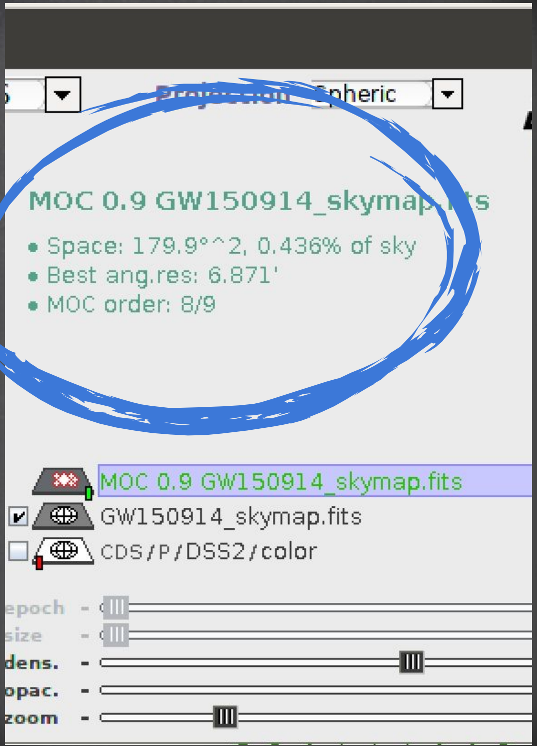
MMA Section

From credible region(s) to galaxy catalog queries

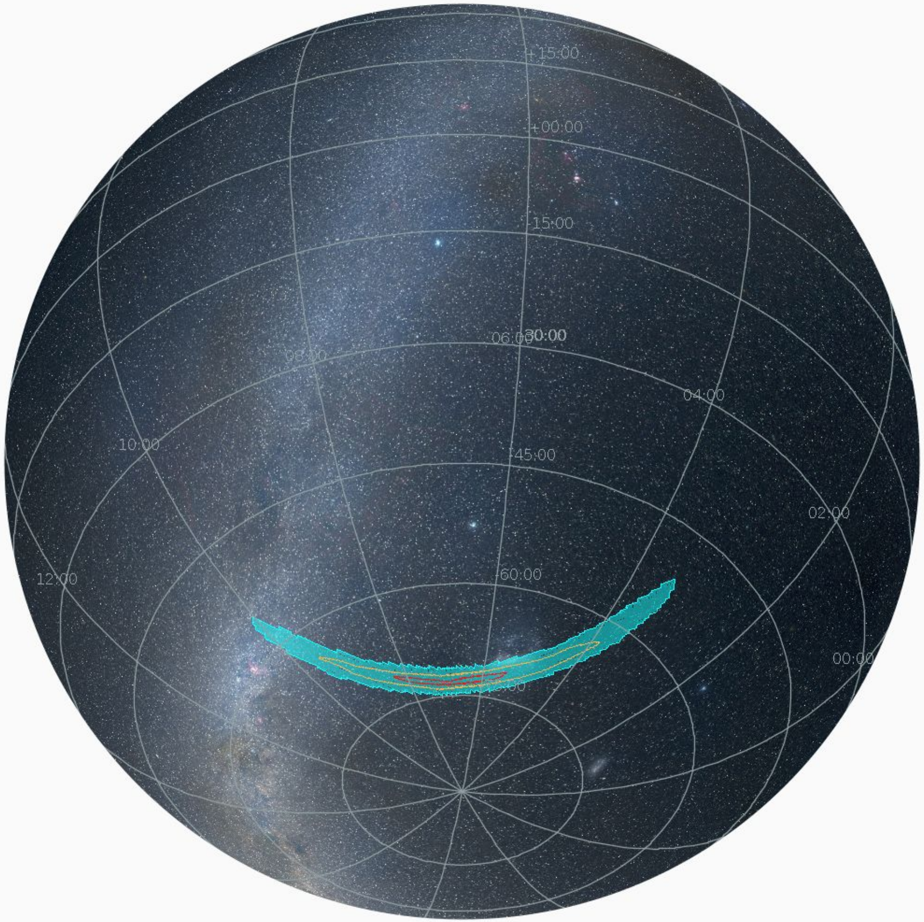
1. Confidence level(s)



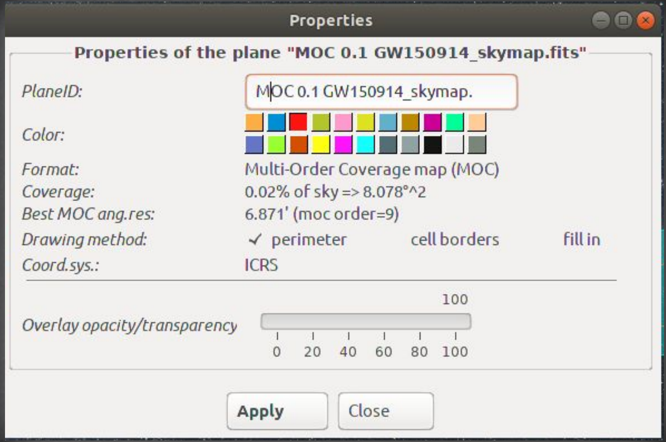




By leaving the cursor on the plane, the enclosed sky area in sq. deg. is quoted in the Aladin stack (see "Space" on the top right)



2. Properties



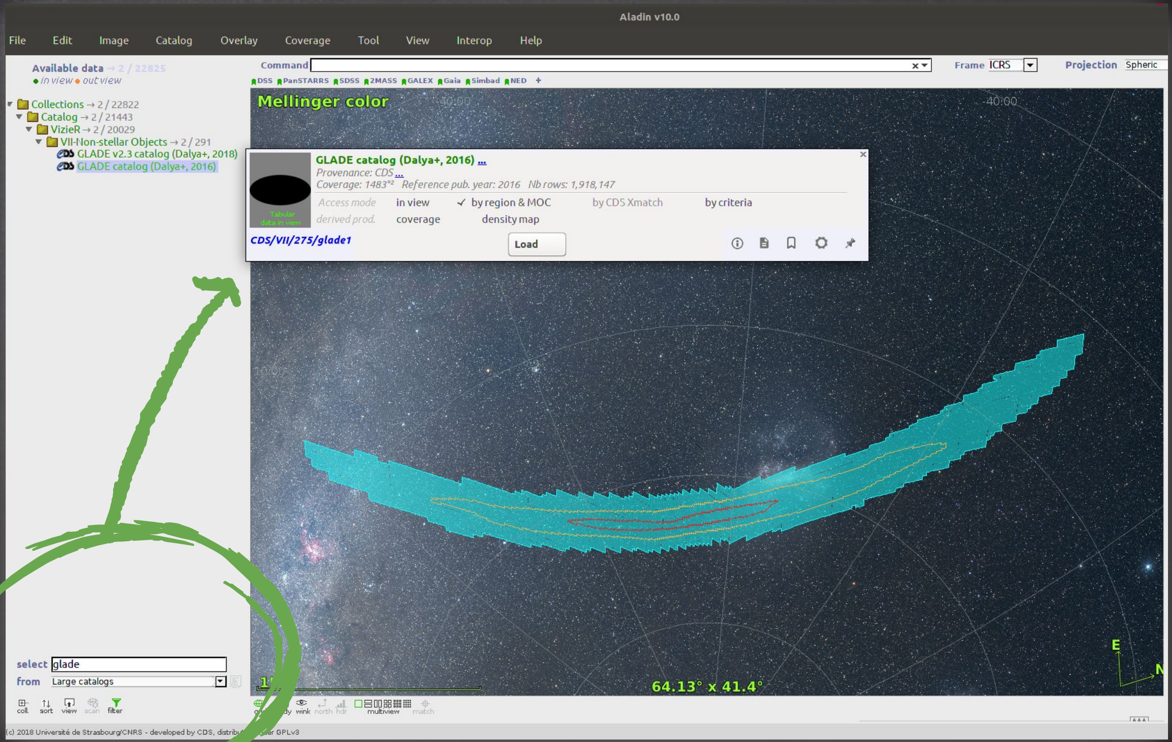
Display multiple confidence levels selecting "perimeter" as Drawing method

3. Queries

The Aladin data collections tree provides access to a large data collections.

For catalogues, you can load all sources in the GW sky localization (at any confidence regions).

For image surveys, you can access the HiPS images.



Multi Order Coverage MAP

- The MOC method is based on the HEALPix tessellation algorithm (Gorski et. al 2005) and it is essentially a simple way to map irregular and complex sky regions into hierarchically grouped predefined cells.

- The operation between the MOC maps (union, intersection, subtraction, difference) are very fast even for very complex regions.

- Some dataserver, such as VizieR, can be queried by MOC in order to return data (galaxy catalogs/list of images) only inside the MOC coverage.

Fernique et al., 2014

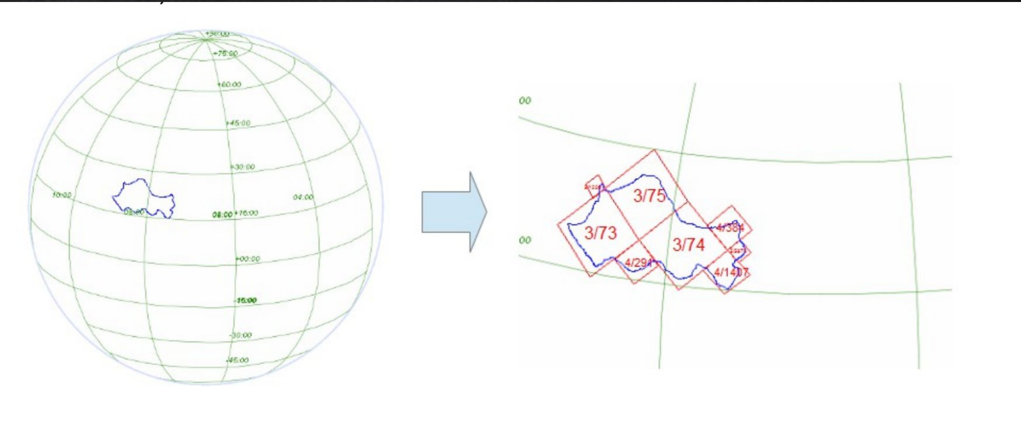
MOC Basic Algorithm

Each MOC cell is defined by two numbers: the hierarchy level (HEALPix order) and the pixel index (HEALPix npix).

The NUNIQ scheme defines an algorithm for packing an (ORDER, NPIX) pair into a single integer for compactness:

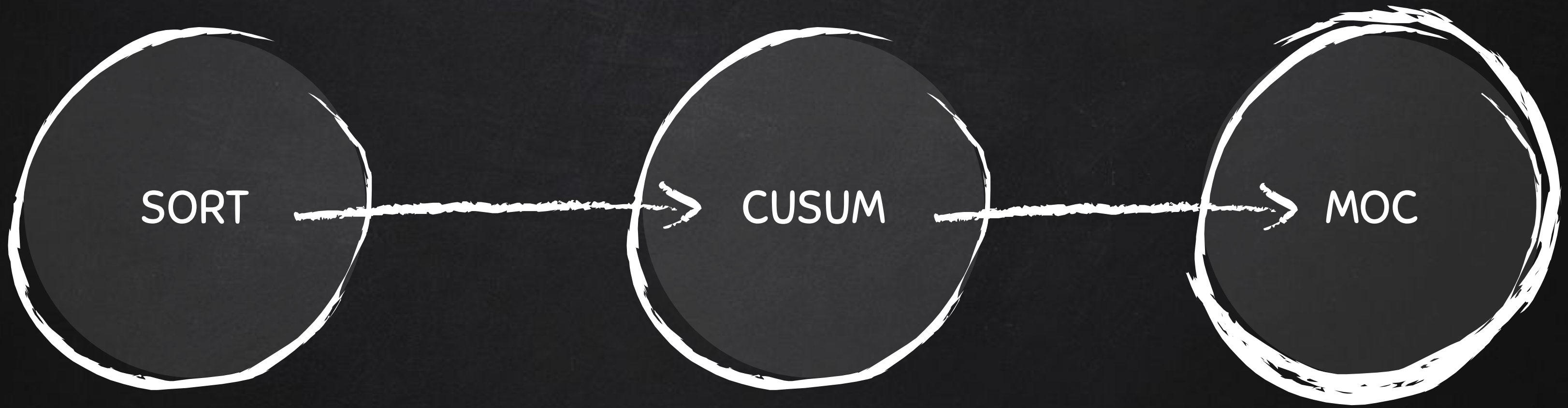
$$uniq = 4 \times 4^{order} + npix$$

Fernique et al., 2014



A MOC can thus be represented as a flat list of integers (in this example, 8 of them) and stored in a single-column FITS table.

GW Sky localization area is the confidence region that encloses a given percentage of the localization probability.



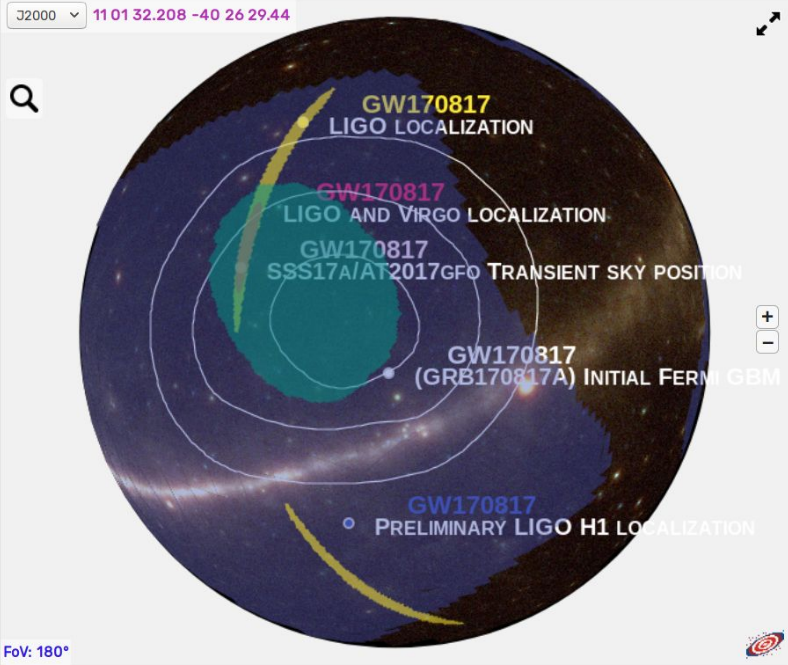
More details about the computational time in slide 13.

Interactive Detection Page

www.virgo-gw.eu/skymap.html

Interactive Detection Skymap

J2000 11 01 32.208 -40 26 29.44



Using the skymap

Click on the various options below to display information relating to each detection.

Detection	Sky localisation	Label	Pop-up info
GW170817 - H1 only	☑	☑	☑
GW170817 - L1/H1 only	☑	☑	☑
GW170817 - L1/H1/V1	☑	☑	☐
GW170817 - Refined skymap	☐	☐	☐
GW170817 - (GRB170817A) Initial Fermi GBM localization	☑	☑	☑
GW170817 - (GRB170817A) Final Fermi GBM localization	☑	☐	☐
GW170817 - SSS17a/AT2017gfo Transient sky position		☑	☑
GW170814 - H1/L1	☐	☐	☐
GW170814 - H1/L1/V1	☐	☐	☐
GW170814 - Refined skymap	☐	☐	☐
GW170608 - Refined LIGO localization	☐	☐	☐
GW170104 - Refined LIGO localization	☐	☐	☐

Backgrounds

If you want to see the extension of these sky regions through the constellations you can

Sonification Project

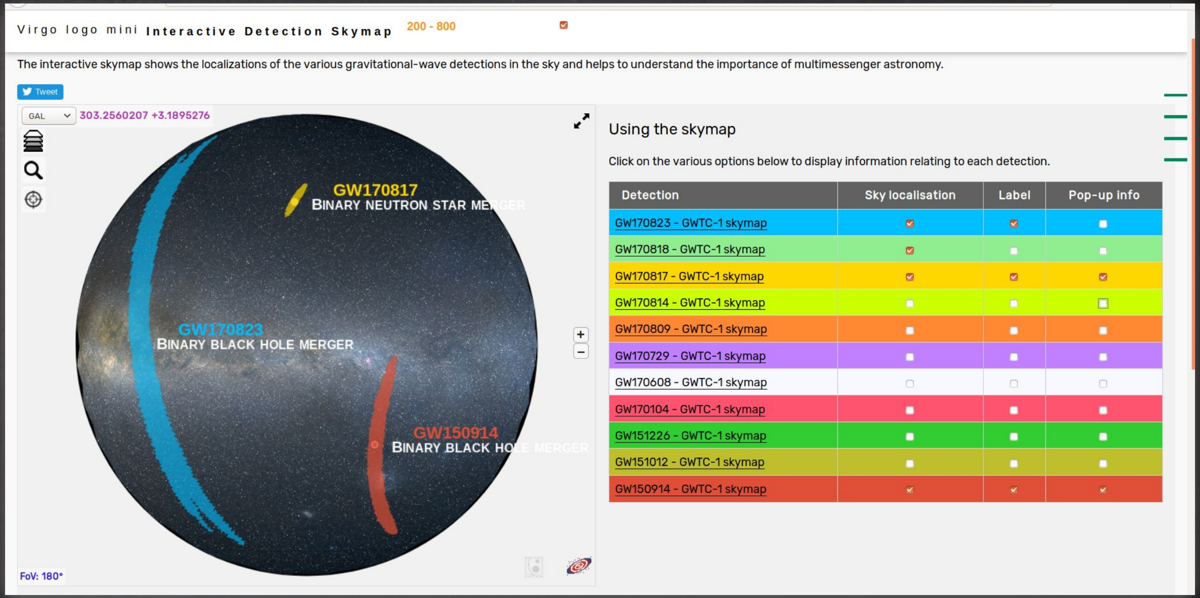
The frequency is mapped to the galactic latitude of the mouse cursor location with a stereo spatialization (left/right speaker) for the galactic longitude.

A specific chord is played when the cursor enters or leaves the coverage of the sky localization.

An audio file is added to explain the nature of each event and the main properties.

The user can modify the frequency range or exclude the sound system with a check button.

An automatic tour will be added using the AladinLite Plugin developed by Tamara Clvera.



SuperEvent

Superevents are a new abstraction to unify gravitational-wave candidates from multiple search pipelines. Each superevent is intended to represent a single astrophysical event. A superevent consists of one or more event candidates, possibly from different pipelines, that are neighbors in time. At any given time, one event belonging to the superevent is identified as the preferred event. The superevent inherits properties from the preferred event such as time, significance, localization, and classification.

Selection of the Preferred Event When multiple online searches report events at the same time, the preferred event is decided by applying the following rules, in order:

- Events that are detected in multiple interferometers are preferred over an events from a single interferometer.
- Events from modeled CBC searches are preferred over events from unmodeled Burst searches
- In the case of multiple CBC events, the event with the highest signal to noise ratio (SNR) is preferred.
- In the case of multiple Burst events, the event with the lowest false alarm rate (FAR) is preferred.