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# **LIGO/Virgo/KAGRA Public Alerts User Guide**

*Version 17.1+0.ge8ebe5d.dirty*

**LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration**

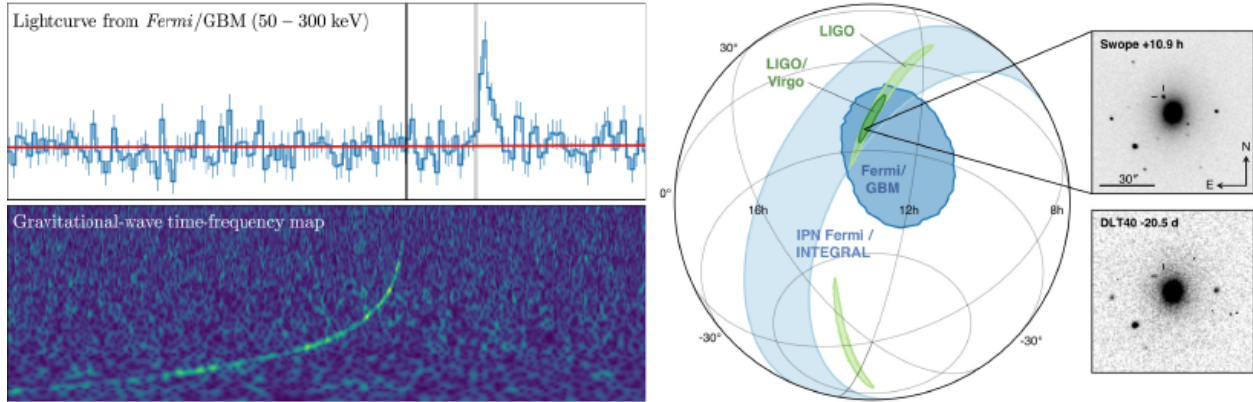
**Dec 15, 2022**



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Welcome to the LIGO/Virgo/KAGRA 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.

Four sites (*LHO*, *LLO*, *Virgo*, *KAGRA*) together form a global network of ground-based GW detectors. The *LIGO* Scientific Collaboration, the *Virgo* Collaboration, and the *KAGRA* Collaboration jointly analyze the data in real time to detect and localize transients from compact binary mergers and other sources. When a signal candidate is found, an alert is sent to astronomers in order to search for counterparts (electromagnetic waves or neutrinos).

**LIGO/Virgo/KAGRA alerts are public.** Alerts are distributed through NASA’s Gamma-ray Coordinates Network (*GCN*, <https://gcn.nasa.gov>) and Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics (*SCiMMA*, <https://scimma.org>). There are two types of alerts: human-readable *GCN Circulars* and machine-readable *Notices*. This 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 Notices and decoding GW sky maps.



## GETTING STARTED CHECKLIST

In addition to reading this user guide, we encourage you to sign up for certain e-mail lists and community resources. Make sure that you have completed the items on this checklist.

### 1.1 1. Read This User Guide

Pay particular attention to the [Alert Contents](#) section of this user guide to familiarize yourself with the contents of machine-readable LIGO/Virgo/KAGRA [Notices](#). Play with the [Sample Code](#) to receive example Notices and practice working with [sky localization maps](#).

### 1.2 2. Subscribe to GCN Circulars

Subscribe to [GCN Circulars](#) and review the [instructions for posting GCN Circulars](#). A [GCN Circular](#) is a short, public bulletin to rapidly report an astronomical observation. GCN Circulars are distributed by email and [archived online](#).<sup>1</sup> LIGO/Virgo/KAGRA uses GCN Circulars to announce detections, and the astronomy community expects participants to promptly disseminate preliminary reports of follow-up observations of LIGO/Virgo/KAGRA counterparts using GCN Circulars as well.

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#### Important

GCN Circulars can only be posted from registered email addresses. You *must* sign up for GCN Circulars *in advance* in order to post to the list.

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### 1.3 3. Join the OpenLVEM Community

Sign up to the OpenLVEM mailing list by following the [OpenLVEM instructions](#). LIGO/Virgo/KAGRA will use this list to make announcements and solicit input. It is also a great place to ask questions or discuss issues related to LIGO/Virgo/KAGRA public alerts. Documents relating to teleconferences and in-person meetings are available at [OpenLVEM wiki](#).

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<sup>1</sup> GCN Circulars are similar to [Astronomer's Telegrams](#) (ATels). By longstanding convention, the gamma-ray burst and gravitational-wave astronomy communities use GCNs, whereas the supernova community uses ATels.

## 1.4 4. Visit GraceDB

Familiarize yourself with [GraceDB](#), LIGO/Virgo/KAGRA's online portal for alerts and real-time results.



## OBSERVING CAPABILITIES

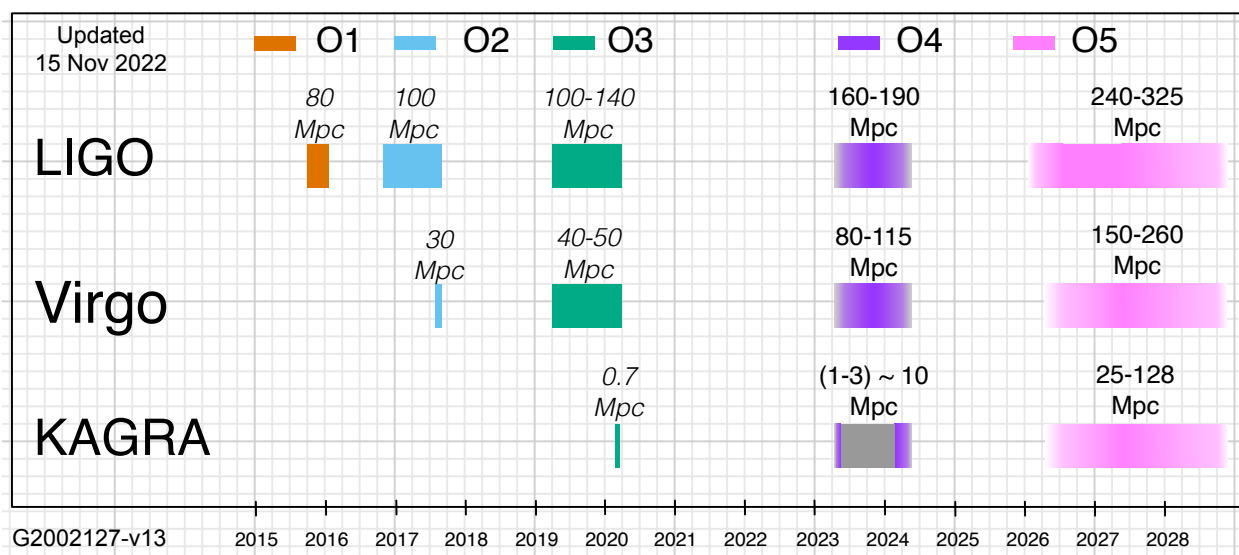
This section summarizes the projected observing capabilities of the global gravitational-wave detector network as of March 2023, superseding the Living Review<sup>1</sup> on prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo, and KAGRA.

### 2.1 Timeline

#### Note

Check the [LIGO, Virgo, and KAGRA Observing Run Plans](#) for the latest details on scheduling of the next observing run, which are summarized here.

The gravitational-wave observing schedule is divided into Observing Runs or epochs of months to years of operation at fixed sensitivity, down time for construction and commissioning, and transitional Engineering Runs between commissioning and observing runs. The long-term observing schedule is shown below. Since *BNS* mergers are a well-studied class of gravitational-wave signals, this figure gives the *BNS range for highly confident detections* in each observing run.



During O4, we expect that four facilities (*LHO*, *LLO*, *Virgo*, and *KAGRA*) will observe for one year. *LHO*, *LLO*, and *Virgo* will have a one-month commissioning break in the middle of the run. *KAGRA* will begin the run with *LIGO*

<sup>1</sup> Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2020, *Living Rev. Rel.*, 23, 3. doi:10.1007/s41114-020-00026-9

and Virgo and then return to extended commissioning to re-join with greater sensitivity toward the end of O4.

## 2.2 Live Status

There are a handful of public web pages that report live status of the LIGO/Virgo/KAGRA detectors and alert infrastructure.

- **Detector Status Portal:** Daily summary of detector performance.  
[https://www.gw-openscience.org/detector\\_status/](https://www.gw-openscience.org/detector_status/)
- **GWStat:** Real-time detector up/down status.  
<https://ldas-jobs.ligo.caltech.edu/~gwistat/gwistat/gwistat.html>
- **LIGO Data Grid Status:** Live dashboard showing up/down status of the detectors and online analyses. Status of the LIGO/Virgo/KAGRA alert pipeline is indicated by the “EMFollow” box.  
<https://monitor.ligo.org/gwstatus>

## 2.3 Public Alert Rate and Localization Accuracy

Here we provide predicted public alert rates, distances, and localization uncertainties for *BNS*, *NSBH*, and *BBH* mergers in O4 and O5, based on a Monte Carlo simulation of detection and localization of events.

The methodology of the simulation is the same as described in <sup>Page 5, 1</sup> and <sup>2</sup>, although the GW detector network configurations, sensitivity curves, astrophysical rates, and mass and spin distributions have been updated.

**Source code to reproduce these simulations** is available at <https://github.com/lpsinger/observing-scenarios-simulations/tree/v2> or <https://doi.org/10.5281/zenodo.5206852>.

**Sky localization FITS files** from these simulations are provided at [doi:10.5281/zenodo.7026209](https://doi.org/10.5281/zenodo.7026209).

### 2.3.1 Detection Threshold

The network *SNR* threshold for detection was set to 8 in order to approximately reproduce the rate of *public alerts that were sent in O3* (see<sup>2</sup>).

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#### Important

**This section predicts the rate of public alerts, not the rate of highly confident detections. Most public alerts do not survive as confident detections in the authoritative end-of-run LIGO/Virgo/KAGRA compact binary catalogs.**

Previous versions of this User Guide used a network SNR threshold of 12, which roughly corresponds to the single-detector SNR threshold that is assumed for the canonical BNS *range* shown in the timeline figure above.

The change in the detection threshold from 12 to 8 accounts for an increase in the predicted number of events by a factor of  $\sim (12/8)^3 = 3.375$  over previous versions of this User Guide.

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<sup>2</sup> Petrov, P., Singer, L. P., Coughlin, M. W., et al. 2022, *Astrophys. J.* 924, 54. [doi:https://doi.org/10.3847/1538-4357/ac366d](https://doi.org/10.3847/1538-4357/ac366d)

### 2.3.2 Detector Network

The detector sensitivity curves used for the simulation are available in [LIGO-T2200043-v3](#). The filenames for each detector and observing run are given in the table below.

Detector	Observing run	
	O4	O5
<i>LHO, LLO</i>	aligo_04high.txt	AplusDesign.txt
<i>Virgo</i>	avirgo_04high_NEW.txt	avirgo_05low_NEW.txt
<i>KAGRA</i>	kagra_10Mpc.txt	kagra_128Mpc.txt

These noise curves correspond to the high ends of the BNS ranges shown in the timeline figure above, with the exception of Virgo in O5, for which it represents the low end.

We assume that each detector has an independent observing duty cycle of 70%.

### 2.3.3 Source Distribution

We draw masses and spins of compact objects from a global maximum *a posteriori* fit of all O3 compact binary observations<sup>3</sup>. The distribution and its parameters are described below.

#### Masses

The 1D source-frame component mass distribution is the “Power Law + Dip + Break” model based on<sup>4</sup>, and is given by:

$$p(m|\lambda) \propto l(m|M_{\max}, \eta_{\max}) \times h(m|M_{\min}, \eta_{\min}) \times n(m|M_{\text{low}}^{\text{gap}}, M_{\text{high}}^{\text{gap}}, \eta_{\text{low}}, \eta_{\text{high}}, A) \\ \times \begin{cases} \left(\frac{m}{M_{\text{high}}^{\text{gap}}}\right)^{\alpha_1} & \text{if } m < M_{\text{high}}^{\text{gap}} \\ \left(\frac{m}{M_{\text{high}}^{\text{gap}}}\right)^{\alpha_2} & \text{if } m \geq M_{\text{high}}^{\text{gap}} \end{cases},$$

defined for  $1 \leq m/M_{\odot} \leq 100$ . It consists of four terms:

- a high-mass tapering function  $l(m|M_{\max}, \eta_{\max}) = (1 + (m/M_{\max})^{\eta_{\max}})^{-1}$ ,
- a low-mass tapering function  $h(m|M_{\min}, \eta_{\min}) = 1 - l(m|M_{\min}, \eta_{\min})$ ,
- a function  $n(m|M_{\text{low}}^{\text{gap}}, M_{\text{high}}^{\text{gap}}, \eta_{\text{low}}, \eta_{\text{high}}, A) = 1 - A l(m|M_{\text{high}}^{\text{gap}}, \eta_{\text{high}}) h(m|M_{\text{low}}^{\text{gap}}, \eta_{\text{low}})$  that suppresses masses in the hypothetical “mass gap” between NSs and BHs, and
- a piecewise power law.

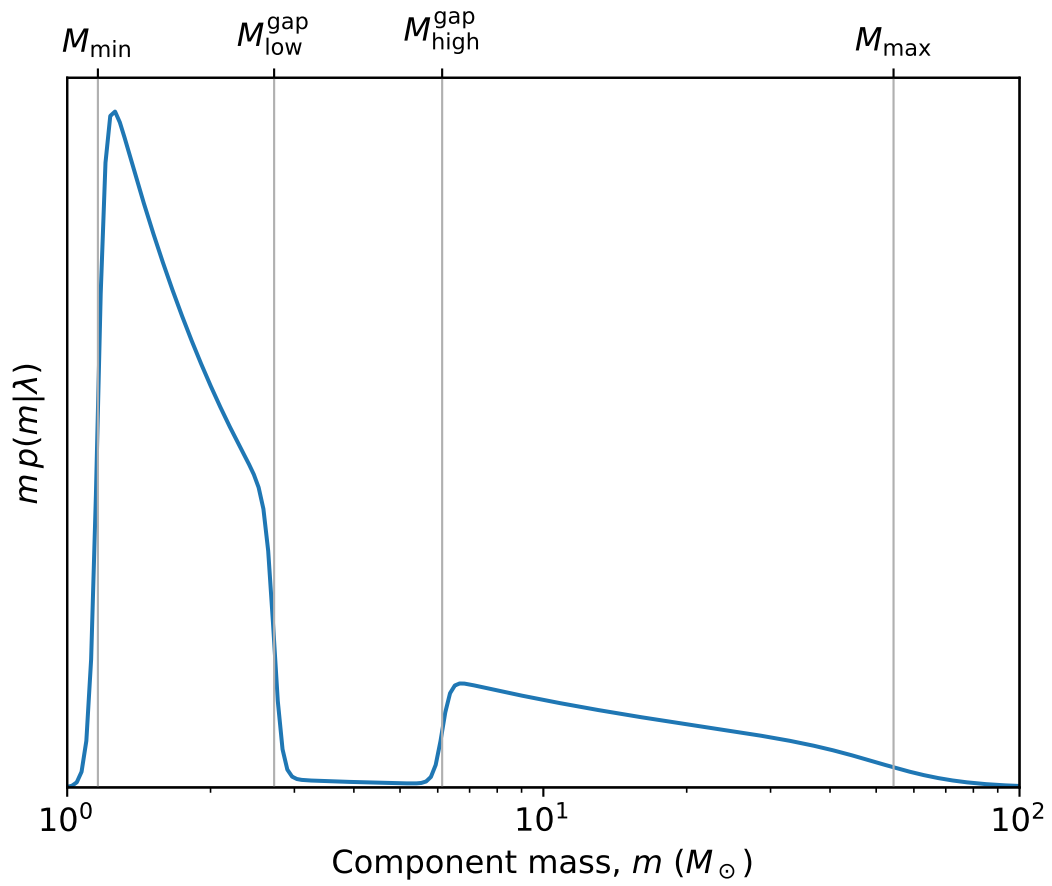
The joint 2D distribution of the primary mass  $m_1$  and the secondary mass  $m_2$  builds on the 1D component mass distribution and adds a pairing function that weights binaries by mass ratio:

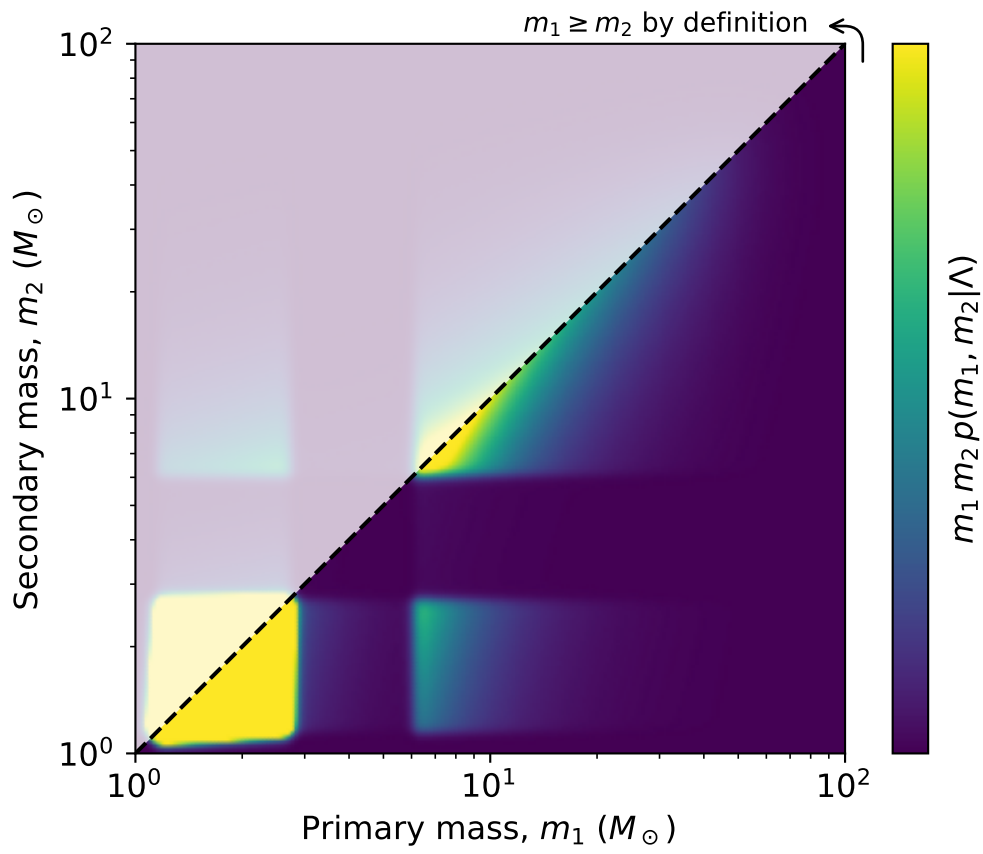
$$p(m_1, m_2|\Lambda) \propto p(m = m_1|\lambda) p(m = m_2|\lambda) \left(\frac{m_2}{m_1}\right)^{\beta},$$

defined for  $(m_1 \geq m_2) \cap ((m_1 \leq 60M_{\odot}) \cup (m_2 \geq 2.5M_{\odot}))$ . The two figures below show the 1D and joint 2D component mass distributions.

<sup>3</sup> LIGO Scientific Collaboration & Virgo Collaboration 2021, *The population of merging compact binaries inferred using gravitational waves through GWTC-3*. arXiv:2111.03634

<sup>4</sup> Farah, A., Fishbach, M., et al. 2022, *Bridging the Gap: Categorizing Gravitational-wave Events at the Transition between Neutron Stars and Black Holes*. *Astrophys. J.*, 931, 108. doi:10.3847/1538-4357/ac5f03





## Spins

The spins of the binary component objects are isotropically oriented. Component objects with masses less than  $2.5 M_{\odot}$  have spin magnitudes that are uniformly distributed from 0 to 0.4, and components with greater masses have spin magnitudes that are uniformly distributed from 0 to 1.

## Sky Location, orientation

Sources are isotropically distributed on the sky and have isotropically oriented orbital planes.

## Redshift

Sources are uniformly distributed in differential comoving volume per unit proper time.

## Rate

The total rate density of mergers, integrated across all masses and spins, is set to  $240^{+270}_{-140} \text{ Gpc}^{-3} \text{ yr}^{-1}$  ([Page 7, 3](#), Table II, first row, last column).

## Parameters

The parameters of the mass and spin distribution are given below.

Parameter	Description	Value
$\alpha_1$	Spectral index for the power law of the mass distribution at low mass	-2.16
$\alpha_2$	Spectral index for the power law of the mass distribution at high mass	-1.46
A	Lower mass gap depth	0.97
$M_{\text{low}}^{\text{gap}}$	Location of lower end of the mass gap	$2.72 M_{\odot}$
$M_{\text{high}}^{\text{gap}}$	Location of upper end of the mass gap	$6.13 M_{\odot}$
$\eta_{\text{low}}$	Parameter controlling how the rate tapers at the low end of the mass gap	50
$\eta_{\text{high}}$	Parameter controlling how the rate tapers at the high end of the mass gap	50
$\eta_{\text{min}}$	Parameter controlling tapering the power law at low mass	50
$\eta_{\text{max}}$	Parameter controlling tapering the power law at high mass	4.91
$\beta$	Spectral index for the power law-in-mass-ratio pairing function	1.89
$M_{\text{min}}$	Onset location of low-mass tapering	$1.16 M_{\odot}$
$M_{\text{max}}$	Onset location of high-mass tapering	$54.38 M_{\odot}$
$a_{\text{max,NS}}$	Maximum allowed component spin for objects with mass $< 2.5 M_{\odot}$	0.4
$a_{\text{max,BH}}$	Maximum allowed component spin for objects with mass $\geq 2.5 M_{\odot}$	1

## 2.3.4 Summary Statistics

The table below summarizes the estimated public alert rate and sky localization accuracy in O4 and O5. All values are given as a 5% to 95% confidence intervals.

Observing run	Network	Source class		
		<i>BNS</i>	<i>NSBH</i>	<i>BBH</i>
Merger rate per unit comoving volume per unit proper time (Gpc <sup>-3</sup> year <sup>-1</sup> , log-normal uncertainty)				
		210 <sup>+240</sup> <sub>-120</sub>	8.6 <sup>+9.7</sup> <sub>-5.0</sub>	17.1 <sup>+19.2</sup> <sub>-10.0</sub>
Sensitive volume: detection rate / merger rate (Gpc <sup>3</sup> , Monte Carlo uncertainty)				
O4	HKL	0.172 <sup>+0.013</sup> <sub>-0.012</sub>	0.78 <sup>+0.14</sup> <sub>-0.13</sub>	15.15 <sup>+0.42</sup> <sub>-0.41</sub>
O5	HKL	0.827 <sup>+0.044</sup> <sub>-0.042</sub>	3.65 <sup>+0.47</sup> <sub>-0.43</sub>	50.7 <sup>+1.2</sup> <sub>-1.2</sub>
Annual number of public alerts (log-normal merger rate uncertainty × Poisson counting uncertainty)				
O4	HKL	36 <sup>+49</sup> <sub>-22</sub>	6 <sup>+11</sup> <sub>-5</sub>	260 <sup>+330</sup> <sub>-150</sub>
O5	HKL	180 <sup>+220</sup> <sub>-100</sub>	31 <sup>+42</sup> <sub>-20</sub>	870 <sup>+1100</sup> <sub>-480</sub>
Median luminosity distance (Mpc, Monte Carlo uncertainty)				
O4	HKL	398 <sup>+15</sup> <sub>-14</sub>	770 <sup>+67</sup> <sub>-70</sub>	2685 <sup>+53</sup> <sub>-40</sub>
O5	HKL	738 <sup>+30</sup> <sub>-25</sub>	1318 <sup>+71</sup> <sub>-100</sub>	4607 <sup>+77</sup> <sub>-82</sub>
Median 90% credible area (deg <sup>2</sup> , Monte Carlo uncertainty)				
O4	HKL	1860 <sup>+250</sup> <sub>-170</sub>	2140 <sup>+480</sup> <sub>-530</sub>	1428 <sup>+60</sup> <sub>-55</sub>
O5	HKL	2050 <sup>+120</sup> <sub>-120</sub>	2000 <sup>+350</sup> <sub>-220</sub>	1256 <sup>+48</sup> <sub>-53</sub>
Median 90% credible comoving volume (10 <sup>3</sup> Mpc <sup>3</sup> , Monte Carlo uncertainty)				
O4	HKL	67.9 <sup>+11.3</sup> <sub>-9.9</sub>	232 <sup>+101</sup> <sub>-50</sub>	3400 <sup>+310</sup> <sub>-240</sub>
O5	HKL	376 <sup>+36</sup> <sub>-40</sub>	1350 <sup>+290</sup> <sub>-300</sub>	8580 <sup>+600</sup> <sub>-550</sub>

**Merger rate per unit comoving volume per unit proper time** is the astrophysical rate of mergers in the reference frame that is comoving with the Hubble flow. It is averaged over a distribution of masses and spins that is assumed to be non-evolving.

### Caution

The merger rate per comoving volume should not be confused with the binary formation rate, due to the time delay between formation and merger.

It should also not be confused with the merger rate per unit comoving volume per unit *observer* time. If the number density per unit comoving volume is  $n = dN/dV_C$ , and the merger rate per unit proper time  $\tau$  is  $R = dn/d\tau$ , then the merger rate per unit *observer* time is  $R/(1+z)$ , with the factor of  $1+z$  accounting for time dilation.

See<sup>5</sup> for further discussion of cosmological distance measures as they relate to sensitivity figures of merit for gravitational-wave detectors.

**Sensitive volume** is the quotient of the rate of detected events per unit observer time and the merger rate per unit comoving volume per unit proper time. The definition is given in the glossary entry for *sensitive volume*. To calculate

<sup>5</sup> Chen, H.-Y., Holz, D. E., et al. 2017, *Distance measures in gravitational-wave astrophysics and cosmology*. arXiv:1709.08079

the detection rate, multiply the merger rate by the sensitive volume.

The quoted confidence interval represents the uncertainty from the Monte Carlo simulation.

**Annual number of public alerts** is the number of alerts in one calendar year of observation. The quoted confidence interval incorporates both the log-normal distribution of the merger rate *and* Poisson counting statistics, but does not include the Monte Carlo error (which is negligible compared to the first two sources of uncertainty).

The remaining sections all give median values over the population of detectable events.

**Median luminosity distance** is the median luminosity distance in Mpc of detectable events. The quoted confidence interval represents the uncertainty from the Monte Carlo simulation.

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#### Note

Although the luminosity distances for BNSs in the table above are about twice as large as the BNS *ranges* in the figure in the *Timeline* section, the median luminosity distances should be better predictors of the typical distances of events that will be detectable during the corresponding observing runs.

The reason is that the BNS range is a characteristic distance for a single GW detector, not a network of detectors. LIGO, Virgo, and KAGRA as a network are sensitive to a greater fraction of the sky and a greater fraction of binary orientations than any single detector alone.

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**Median 90% credible area** is the area in  $\text{deg}^2$  of the smallest (not necessarily simply connected) region on the sky that has a 90% chance of containing the true location of the source.

**Median 90% credible volume** is the median comoving volume enclosed in the smallest region of space that has a 90% chance of containing the true location of the source.

### 2.3.5 Cumulative Histograms

Below are cumulative histograms of the 90% credible area, 90% credible comoving volume, and luminosity distance of detectable events in O3, O4, and O5.



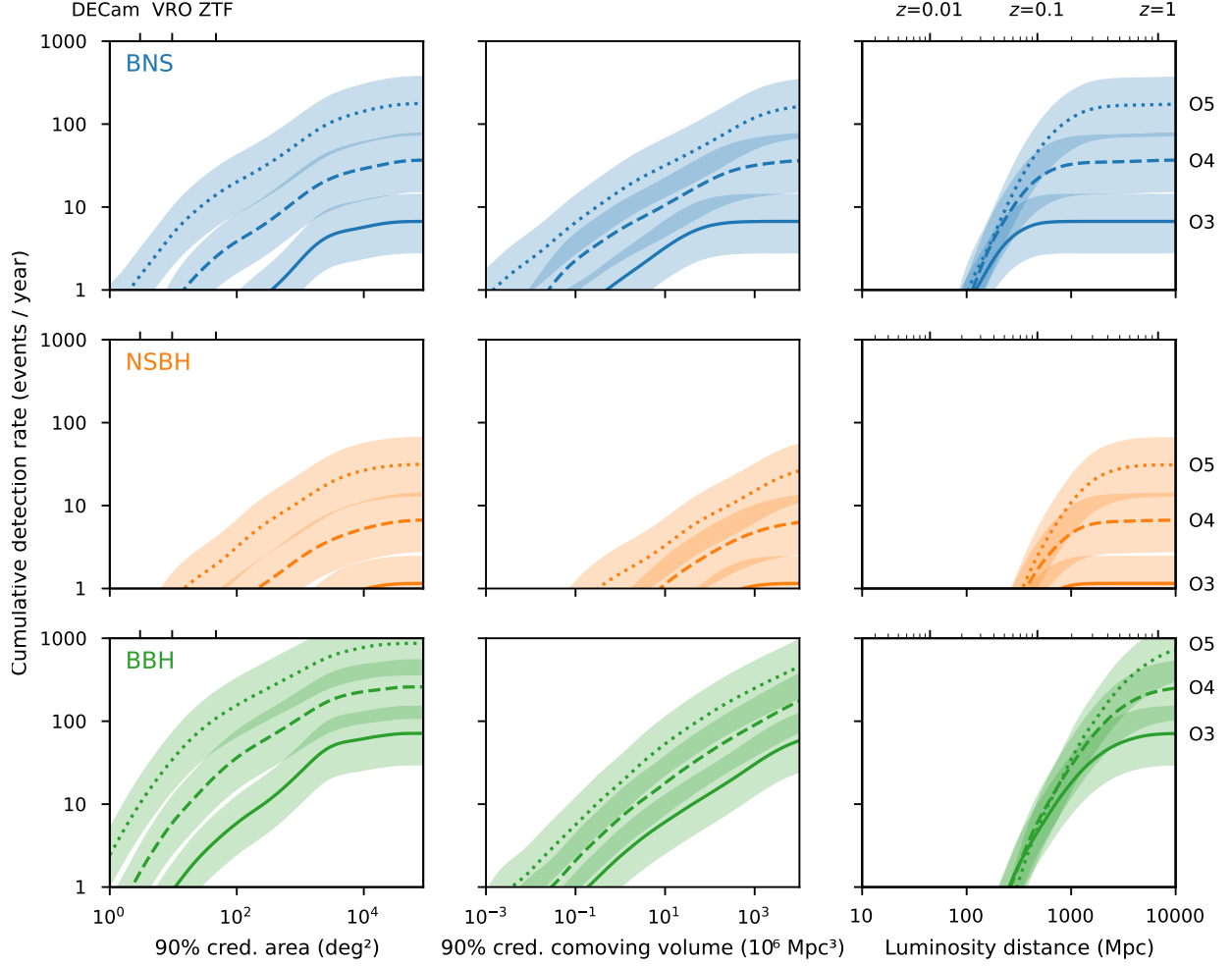


Fig. 1: Cumulative annual public alert rate of simulated mergers as a function of 90% credible area (left column), 90% credible comoving volume (middle column), or luminosity distance (right column). Rates are given for three sub-populations: BNS (top row), NSBH (middle row), and BBH (bottom row). The shaded bands give the inner 90% confidence interval including uncertainty in the estimated merger rate, Monte Carlo uncertainty from the finite sample size of the simulation, and Poisson fluctuations in the number of sources detected in one year.

This plot is based on Figure 2 of [Page 6, 2](#) but uses the simulations described above employing the mass and spin distributions from [Page 7, 3](#).



## DATA ANALYSIS

In this section we describe the different online searches looking for GW signals, the selection and vetting of candidates, and parameter estimation analysis.

When multiple candidates from different pipelines are close enough together in time, they will be considered as originating from the same physical event and will be grouped into a single *superevent*. See the following pages for technical details.

### 3.1 Online Pipelines

A number of search pipelines run in a low latency, online mode. These can be divided into two groups, modeled and unmodeled. The modeled (*CBC*) searches specifically look for signals from compact binary mergers of neutron stars and black holes (*BNS*, *NSBH*, and *BBH* systems). 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.

#### 3.1.1 False alarm rate and significance

Each search produces a set of candidate events time-stamped at or close to the estimated peak of GW strain amplitude. For binary merger candidates, this would be the time of merger.

Each candidate event is assigned a ranking statistic value by the search pipeline that produced it: higher statistic values correspond to a higher probability of astrophysical (signal), as opposed to terrestrial (noise) origin. The statistical significance of a candidate produced by a given pipeline is quantified by its *false alarm rate*. This is the expected number of events of noise origin produced by the pipeline with a higher ranking statistic than the candidate, per unit of time searched. Since each search pipeline has an independent method of generating and ranking events, and of estimating the noise background, the false alarm rates assigned for events in the same superevent will in general be different. For an alert to be sent automatically, we require at least one event to have a false alarm rate below the *alert threshold*.

### 3.1.2 Modeled Search

**GstLAL**, **MBTA**, **PyCBC Live** and **SPIIR** are matched-filtering based analysis pipelines that rapidly identify compact binary merger events, with  $\lesssim 1$  minute latencies. They use discrete banks of waveform templates to cover the target parameter space of compact binaries, with all pipelines covering the mass ranges corresponding to *BNS*, *NSBH*, and *BBH* systems.

A coincident analysis is performed by all pipelines, where candidate events are extracted separately from each detector via matched-filtering and later combined across detectors. **SPIIR** extracts candidates from each detector via matched-filtering and looks for coherent responses from the other detectors to provide source localization. Of the four pipelines, **GstLAL** and **MBTA** use several banks of matched filters to cover the detectors bandwidth, i.e., the templates are split across multiple frequency bands. All pipelines also implement different kinds of signal-based vetoes to reject instrumental transients that cause large *SNR* values but can otherwise be easily distinguished from compact binary coalescence signals.

**GstLAL**<sup>12</sup> is a matched-filter pipeline designed to find gravitational waves from compact binaries in low-latency. It uses a likelihood ratio, which increases monotonically with signal probability, to rank candidates, and then uses Monte Carlo sampling methods to estimate the distribution of likelihood-ratios in noise. This distribution can then be used to compute a *FAR* and p-value.

**MBTA**<sup>5</sup> constructs its background by making every possible coincidence from single detector triggers over a few hours of recent data. It then folds in the probability of a pair of triggers passing the time coincidence test.

**PyCBC Live**<sup>67</sup> estimates the noise background by performing time-shifted analyses using triggers from a few hours of recent data. Single-detector triggers from one detector are time shifted by every possible multiple of 100 ms, thus any resulting coincidence must be unphysical given the  $\sim 10$  ms light travel time between detectors. All such coincidences are recorded and assigned a ranking statistic. The false alarm rate is then estimated by counting accidental coincidences ranked higher than a given candidate, i.e. with a higher statistic value. When three detectors are observing at the time of a particular candidate, the most significant double coincidence is selected, and its false alarm rate is modified to take into account the data from the remaining detector.

**SPIIR**<sup>34</sup> applies summed parallel infinite impulse response (IIR) filters to approximate matched-filtering results. It selects high-*SNR* events from each detector and finds coherent responses from other detectors. It constructs a background statistical distribution by time-shifting detector data one hundred times over a week to evaluate foreground candidate significance.

### 3.1.3 Unmodeled Search

**cWB**<sup>89</sup> searches for and reconstructs gravitational-wave transient signals without relying on a specific waveform model. **cWB** searches for signals with durations of up to a few seconds that are coincident in multiple detectors. The analysis is performed on the time-frequency data obtained with a wavelet transform. **cWB** selects wavelet amplitudes above the fluctuations of the detector noise and groups them into clusters. Tuned versions for binary black holes (search name *BBH* and *IMBH*) choose time-frequency patterns with frequency increasing in time. For clusters correlated in multiple detectors, **cWB** reconstructs the direction to the source and the signal waveforms with the constrained maximum likelihood method. To assign detection significance to the found events, **cWB** ranks them by the coherent signal-to-noise ratio obtained from cross-correlation of the signal waveforms reconstructed in different detectors.

<sup>1</sup> Messick, C., Blackburn, K., Brady, P., et al. 2017, *Phys. Rev. D*, 95, 042001. doi:10.1103/PhysRevD.95.042001

<sup>2</sup> Sachdev, S., Caudill, S., Fong, H., et al. 2019. arXiv:1901.08580

<sup>5</sup> Adams, T., Buskulic, D., Germain, V., et al. 2016, *Class. Quantum Grav.*, 33, 175012. doi:10.1088/0264-9381/33/17/175012

<sup>6</sup> Nitz, A. H., Dal Canton, T., Davis, D. & Reyes, S. 2018, *Phys. Rev. D*, 98, 024050. doi:10.1103/PhysRevD.98.024050

<sup>7</sup> Dal Canton, T., & Harry, I. W. 2017. arXiv:1705.01845

<sup>3</sup> Hooper, S., Chung, S. K., Luan, J., et al. 2012, *Phys. Rev. D*, 86, 024012. doi:10.1103/PhysRevD.86.024012

<sup>4</sup> Chu, Q. 2017, Ph.D. Thesis, The University of Western Australia. <https://api.research-repository.uwa.edu.au/portalfiles/portal/18509751>

<sup>8</sup> Klimentenko, S., Mohanty, S., Rakhmanov, M., Mitselmakher, *Phys. Rev. D*, 72, 122002. doi:10.1103/PhysRevD.72.122002

<sup>9</sup> Klimentenko, S., Vedovato, G., Drago, M., et al. 2016, *Phys. Rev. D*, 93, 042004. doi:10.1103/PhysRevD.93.042004

**oLIB**<sup>10</sup> uses the Q transform to decompose GW strain data into several time-frequency planes of constant quality factors  $Q$ , where  $Q \sim \tau f_0$ . The pipeline flags data segments containing excess power and searches for clusters of these segments with identical  $f_0$  and  $Q$  spaced within 100 ms of each other. Coincidences among the detector network of clusters within a 10 ms light travel time window are then analyzed with a coherent (i.e., correlated across the detector network) signal model to identify possible GW candidate events.

#### Note

oLIB is not currently in operation.

### 3.1.4 Coincident with External Trigger Search

**RAVEN**<sup>11</sup> In addition, we will operate the Rapid On-Source VOEvent Coincidence Monitor (RAVEN), a fast search for coincidences between GW and non-GW events. RAVEN will process alerts for gamma-ray bursts (GRBs) from the Gamma-ray Burst Monitor (GBM) onboard Fermi, the Burst Alert Telescope (BAT) onboard the Neil Gehrels Swift Observatory, and the Mini-Calorimeter (MCAL) onboard AGILE, as well as galactic supernova alerts from the SNEWS collaboration. Two astronomical events are considered coincident if they are within a particular time window of each other, which varies depending on which two types of events are being considered (see the table below). Note that these time windows are centered on the GW, e.g., [-1,5] s means we consider GRBs up to one second before or up to 5 seconds after the GW.

Event Type	Time window (s)		Notice Type Considered ( <a href="#">see full list</a> )
	CBC	Burst	
GRB ( <i>Fermi</i> , <i>Swift</i> , <i>INTEGRAL</i> , <i>AGILE</i> )	[-1,5]	[-60,600]	FERMI_GBM_ALERT FERMI_GBM_FIN_POS FERMI_GBM_FLT_POS  FERMI_GBM_GND_POS  FERMI_GBM_SUBTHRESH  SWIFT_BAT_GRB_ALERT SWIFT_BAT_GRB_LC INTEGRAL_WAKEUP INTEGRAL_REFINED INTEGRAL_OFFLINE AGILE_MCAL_ALERT
Low-energy Neutrinos (SNEWS)	[-10,10]	[-10,10]	SNEWS

In addition, RAVEN will calculate coincident *FARs*, one including only timing information (temporal) and one including GRB/GW sky map information (space-time) as well. RAVEN is currently under review and is planned to be able

<sup>10</sup> Lynch, R., Vitale, S., Essick, R., Katsavounidis, E., & Robinet, F. 2017, *Phys. Rev. D*, 95, 104046. doi:10.1103/PhysRevD.95.104046

<sup>11</sup> Urban, A. L. 2016, Ph.D. Thesis. <https://dc.uwm.edu/etd/1218/>

to trigger preliminary alerts once this is finished.

**LLAMA**<sup>1213</sup> The [Low-Latency Algorithm for Multi-messenger Astrophysics](#) is an online search pipeline combining LIGO/Virgo/KAGRA GW triggers with High Energy Neutrino (HEN) triggers from IceCube. It finds temporally-coincident sub-threshold IceCube neutrinos and performs a detailed Bayesian significance calculation to find joint GW+HEN triggers.

## 3.2 Superevents

Superevents are an 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, sky localization, and classification.

The superevent accumulates event candidates from the *search pipelines* and updates its preferred event as more significant event candidates are reported (see [Selection of the Preferred Event](#)). The name of the superevent does not change. The naming scheme is described in the [alert contents](#) section. Once a preferred event candidate passes the public alert threshold (see [Alert Threshold](#)), it is frozen and a preliminary alert is queued using the data products of this preferred event. New event candidates are still allowed to be added to the superevent as the necessary annotations are completed. Once the preliminary alert is received by the GCN broker, the preferred event is revised after a *timeout* and a second preliminary notice is issued. Note that the latter is issued even if the preferred event candidate remains unchanged.

### 3.2.1 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:

1. A *publishable* event, meeting the public alert threshold, is given preference over one that does not meet the criteria.
2. An event from modeled [CBC](#) searches is preferred over an event from unmodeled Burst searches (see [Searches](#) for details on search pipelines).
3. In the case of multiple CBC events, three-interferometer events are preferred over two-interferometer events, and two-interferometer events are preferred over single-interferometer events.
4. In the case of multiple CBC events with the same number of participating interferometers, the event with the highest [SNR](#) is preferred. In the case of multiple Burst events, the event with the lowest [FAR](#) is preferred.

See also the [preferred event selection flow chart](#) in our software documentation.

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#### Note

- A Preliminary GCN is automatically issued for a superevent if the preferred event's [FAR](#) is less than the threshold value stated in the [Alert Threshold](#) section.
- A second Preliminary GCN is usually issued automatically after the first one is successfully dispatched to the GCN broker. However, this may not be sent if the superevent is vetoed on grounds of data quality before the alert is sent.
- An additional preliminary notice may be issued by human intervention in case of unexpected circumstances to help in time-sensitive follow-up operations.

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<sup>12</sup> Bartos, I., Veske, D., Keivani, A., et al. 2019, *Phys. Rev. D*, 100, 083017. doi:10.1103/PhysRevD.100.083017

<sup>13</sup> Countryman, S., Keivani, A., Bartos, I., et al. 2019. [arXiv:1901.05486](#)

- In case of an event created by a pipeline due to an *offline* analysis, no preliminary GCN will be sent.
- The *SNR* is used to select the preferred event among *CBC* candidates because higher *SNR* implies better sky location and parameter estimates from low-latency searches.

### 3.3 Candidate Vetting

*GWCElery* orchestrates and supervises performing basic data quality and detector state checks, grouping of events from individual pipelines into *superevents*, initiating automated *sky localization and parameter estimation*, inferring *classification and source properties*, and sending alerts.

A Data Quality Report is prepared that consists of a semi-automated detector characterization and data quality investigation for each event. It provides a variety of metrics based on auxiliary instrumental and environmental sensors that are used by a rapid response team in order to make a decision of whether to confirm or retract a candidate.

The rapid response team consists of commissioning, computing, and calibration experts from each of the detector sites, pipeline experts, detector characterization experts, and follow-up advocates.

### 3.4 Sky Localization and Parameter Estimation

Immediately after one of the *search pipelines* reports an event, sky localization and parameter estimation analyses begin. These analyses all use Bayesian inference to calculate the posterior probability distribution over the parameters (sky location, distance, and/or intrinsic properties of the source) given the observed gravitational-wave signal.

There are different parameter estimation methods for modeled (*CBC*) and unmodeled (*burst*) events. However, in both cases there is a rapid analysis that estimates only the sky localization, and is ready in seconds, and a refined analysis that explores a larger parameter space and completes up to hours or a day later.

#### 3.4.1 Modeled Events

**BAYESTAR**<sup>1</sup> is the rapid *CBC* sky localization algorithm. It reads in the matched-filter time series from the *search pipeline* and calculates the posterior probability distribution over the sky location and distance of the source by coherently modeling the response of the gravitational-wave detector network. It explores the parameter space using Gaussian quadrature, lookup tables, and sampling on an adaptively refined *HEALPix* grid. The sky localization takes tens of seconds and is included in the preliminary alert.

**LALInference**<sup>2</sup> is a full *CBC* parameter estimation pipeline. It explores a greatly expanded parameter space including sky location, distance, masses, and spins, and performs full forward modeling of the gravitational-wave signal and the strain calibration of the gravitational-wave detectors. It explores the parameter space using *MCMC* and nested sampling. For all events, there is an automated *LALInference* analysis that uses the least expensive *CBC* waveform models and completes within hours and may be included in a subsequent alert. More time-consuming analyses with more sophisticated waveform models are started at the discretion of human analysts, and will complete days or weeks later.

**Bilby**<sup>3</sup> is a next-generation python-based Bayesian inference parameter estimation code. *Bilby* provides a user-friendly and accessible interface with the latest stochastic sampling methods built-in. It can be used for gravitational-wave analyses to extract source properties of *CBC* events such as masses, spins, distance and sky location. These parameters are extracted by employing the use of stochastic sampling methods such as *MCMC* and nested sampling. An automated

<sup>1</sup> Singer, L. P., & Price, L. R. 2016, *Phys. Rev. D*, 93, 024013. doi:10.1103/PhysRevD.93.024013

<sup>2</sup> Veitch, J., Raymond, V., Farr, B., et al. 2015, *Phys. Rev. D*, 91, 042003. doi:10.1103/PhysRevD.91.042003

<sup>3</sup> Ashton, G., Hübner, M., Lasky, P. D., Talbot, C., et al. 2019, *Astropys. J. Supp.*, 241, 27. doi:10.3847/1538-4365/ab06fc

pipeline is used to perform a Bilby analysis on all CBC events. The automated parameter estimation pipeline uses less expensive default settings, including the use of simpler waveforms, to perform an initial analysis of the event. Further analyses with more complex waveforms are performed by a human analyst as needed.

### 3.4.2 Unmodeled Events

**cWB**, the burst *search pipeline*, also performs a rapid sky localization based on its coherent reconstruction of the gravitational-wave signal using a wavelet basis and the response of the gravitational-wave detector network<sup>4</sup>. The cWB sky localization is included in the preliminary alert.

Refined sky localizations for unmodeled bursts are provided by two algorithms that use the same *MCMC* and nested sampling methodology as LALInference. **LALInference Burst (LIB)**<sup>5</sup> models the signal as a single sinusoidally modulated Gaussian. **BayesWave**<sup>6</sup> models the signal as a superposition of wavelets and jointly models the background with both a stationary noise component and glitches composed of wavelets that are present in individual detectors.

## 3.5 Inference

For *CBC* events, we calculate a number of quantities that are inferred from the signal. In preliminary alerts, these quantities are based on the candidate significance and the matched-filter estimates of the source parameters. Once parameter estimation has been completed, updated values will be provided based on samples drawn from the posterior probability distribution.

### 3.5.1 Classification

The classification consists of four numbers, summing to unity, that give the probability that the source is either a *BNS*, *NSBH*, *BBH* merger, or is of *Terrestrial* (i.e. a background fluctuation or a glitch) origin. See the *figure in the alert contents section* for the boundaries of the source classification categories in the  $(m_1, m_2)$  plane. The boundary between NSs and BHs is set to  $3M_\odot$ .

This assumes that terrestrial and astrophysical events occur as independent Poisson processes. A source-dependent weighting of matched-filter templates is used to compute the mean values of expected counts associated with each of these four categories. The mean values are updated weekly based on observed matched-filter count rates. They are then used to predict the category for new triggers uploaded by *search pipelines*.

For details, see<sup>1</sup>, especially Section II E. and Equation 18 therein.

### 3.5.2 Properties

The source properties consist of a set of numbers, each between zero and unity, that give the probabilities that the source satisfies certain conditions. These conditions are:

**HasNS**: At least one of the compact objects in the binary (that is, the less massive or *secondary* compact object) has a mass that is consistent with a neutron star. Specifically, we define this as the probability that the secondary mass satisfies  $m_2 \leq M_{\text{max}}$ , where  $M_{\text{max}}$  is the maximum mass allowed by the neutron star equation of state (*EOS*). Several NS EOSs are considered and the value is marginalized by weighting using the Bayes factors reported in<sup>2</sup>.

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<sup>4</sup> Klimentenko, S., Vedovato, G., Drago, M., et al. 2011, *Phys. Rev. D*, 83, 102001. doi:10.1103/PhysRevD.83.102001

<sup>5</sup> Lynch, R., Vitale, S., Essick, R., Katsavounidis, E., & Robinet, F. 2017, *Phys. Rev. D*, 95, 104046. doi:10.1103/PhysRevD.95.104046

<sup>6</sup> Cornish, N. J., & Littenberg, T. B. 2015, *Class. Quantum Grav.*, 32, 135012. doi:10.1088/0264-9381/32/13/135012

<sup>1</sup> Kapadia, S. J., Caudill, S., Creighton, J. D. E., et al., 2020, *Class. Quantum Grav.*, 37, 045007. doi:10.1088/1361-6382/ab5f2d

<sup>2</sup> Ghosh, S., Liu, X., Creighton, J., et. al., 2021, *Phys. Rev. D*, 104, 083003. doi:10.1103/PhysRevD.104.083003



**HasRemnant:** The source formed a nonzero mass outside the final remnant compact object. Specifically, the probability is calculated using the disk mass fitting formula from<sup>3</sup> (Equation 4). Several neutron star EOSs are considered to compute the remnant mass. The value is marginalized by weighting based on Bayes factors in reference mentioned above.

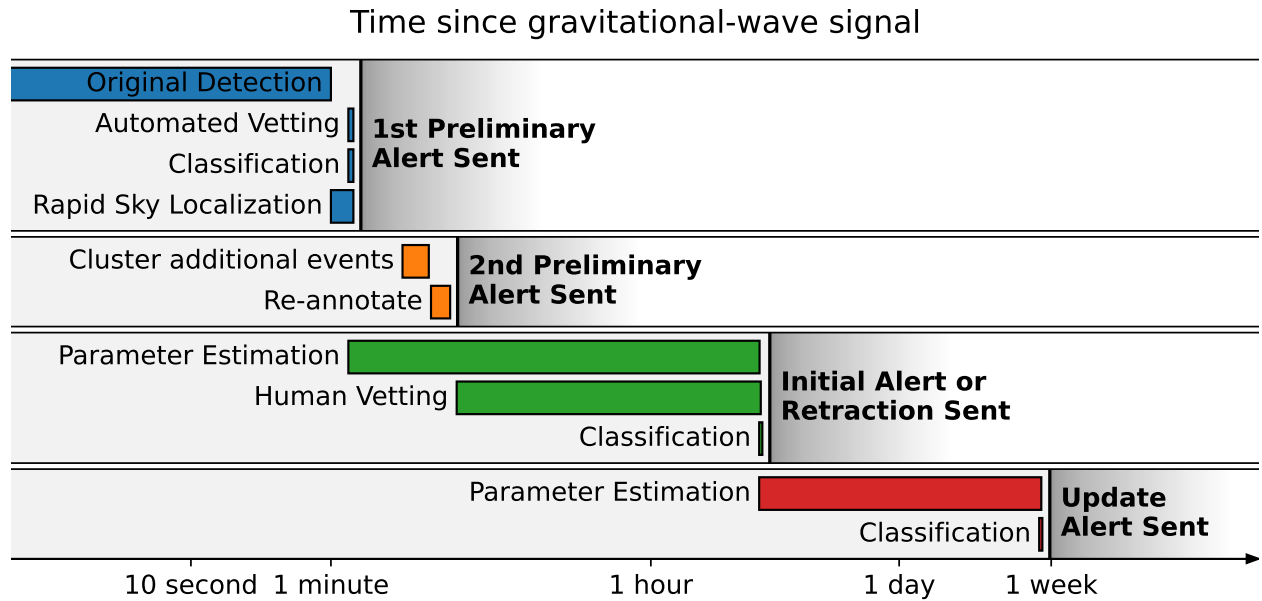
**HasMassGap:** At least one of the compact objects in the binary has a mass in the hypothetical “mass gap” between neutron stars and black holes, defined here as  $3M_{\odot} \leq m \leq 5M_{\odot}$ .

The mass values mentioned in this section are *source-frame mass*. The value reported in the *preliminary* alert is calculated using a supervised machine learning classifier on a feature space consisting of the masses, spins, and *SNR* of the best-matching template, described in<sup>4</sup>. This is to account for the uncertainty in the reported template parameters compared to the true parameters. The value reported in the *update* alerts uses the *online parameter estimation* to compute the value.

The timeline for distribution of alerts is described below.

### 3.6 Alert Timeline

Here, we describe the sequence of LIGO/Virgo/KAGRA alerts for a single event that will be distributed through the Gamma-ray Coordinates Network (*GCN*) via notices and circulars (see the *Alert Contents* and *Sample Code* sections for details).



**Within 1–10 minutes after GW trigger time**, the first and second *preliminary notices* will be sent fully autonomously. The trigger will be immediately and publicly visible in the *GraceDB* database. Since the procedure is fully automatic, some preliminary alerts may be retracted after human inspection for data quality, instrumental conditions, and pipeline behavior.

**Within 24 hours after the GW trigger time** (possibly within 4 hours for *BNS* or *NSBH* sources), the *Initial or Retraction notice and circular* will be distributed. It will include an updated sky localization and source classification. At this stage, the event will have been vetted by human instrument scientists and analysts. The candidate will either be **confirmed** by an Initial notice and circular or withdrawn by a Retraction notice and circular if the data quality is unsuitable.

<sup>3</sup> Foucart, F., Hinderer, T. & Nissanke, S. 2018, *Phys. Rev. D*, 98, 081501. doi:10.1103/PhysRevD.98.081501

<sup>4</sup> Chatterjee, D., Ghosh, S., Brady, P. R., et al. 2020, *Astrophys. J.*, 896, 54. doi:10.3847/1538-4357/ab8dbe

**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 (e.g. as a result of improved calibration, glitch removal, or computationally deeper parameter estimation). Updates will be sent up until the position is determined more accurately by public announcement of an unambiguous counterpart. At that point, there will be no further sky localization updates until the publication of the event in a peer-reviewed journal.

**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.

## 3.7 Alert Threshold

Automated preliminary alerts are sent for all events that pass a false alarm rate (*FAR*) threshold. The *FAR* threshold is  $3.8 \times 10^{-8}$  Hz (one per 10 months) for *CBC* searches and is  $7.9 \times 10^{-9}$  (one per 4 years) for unmodeled burst searches. Since there are 4 independent *CBC* searches and 3 independent *burst* searches, as well as a coincidence search *RAVEN* that looks at the results from both the aforementioned *CBC* and *burst* searches, the effective rate of false alarms for *CBC* sources is  $1.9 \times 10^{-7}$  Hz (one per 2 months), and for unmodeled bursts is  $3.2 \times 10^{-8}$  Hz (one per year).

## ALERT CONTENTS

Public LIGO/Virgo/KAGRA alerts are distributed using NASA’s General Coordinates Network (*GCN*, <https://gcn.nasa.gov>) and Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics (*SCiMMA*, <https://scimma.org>). There are two types of alerts:

**Notices** are machine-readable packets. They are available as *JSON*, *Avro*, *VOEvent* XML, and several other legacy formats. See the *Sample Code* section for instructions on receiving notices, which are available via *Kafka* and *VOEvent* brokers.

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### Warning

The JSON, Avro, and VOEvent formats are fully supported, but the legacy text, binary, and email formats are not.

The VOEvent XML alerts are official data products of LIGO/Virgo/KAGRA. GCN produces several other legacy formats from them, in particular a text-based “full format” and binary format. LIGO/Virgo/KAGRA performs only limited quality control of the legacy formats.

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**GCN Circulars** are short human-readable astronomical bulletins. They are written in a certain well-established format and style. You can [subscribe to GCN Circulars](#) to receive and post them by email, or you can view them in the public GCN Circulars archive.

## 4.1 Notice Types

For each event, there are up to five kinds of Notices:

An **Early Warning Notice** may be issued for *CBC* events up to tens of seconds *before* merger. The candidate must have passed some automated data quality checks, but it may later be *retracted* after human vetting. There is no accompanying GCN Circular at this stage. Early Warning alerts are an experimental feature in *O3*. Early Warning alerts are only possible for exceptionally loud and nearby *CBC* events, and are expected to be rare.

A **Preliminary Notice** is issued automatically within minutes *after* a gravitational-wave candidate is detected. Like an **Early Warning Notice**, the candidate must have passed automated data quality checks, but it may later be *retracted*, and there is no accompanying GCN Circular.

An **Initial Notice** is issued after human vetting (see *Candidate Vetting*). If the signal does not pass human vetting (e.g., it is a glitch), then instead of an initial alert there will be a *retraction*. The initial alert is also accompanied by a GCN Circular, which should be considered as the first formal publication of the candidate and can be cited as such.

An **Update Notice** is issued whenever further analysis leads to improved estimates of the sky localization, significance, or classification. There may be multiple updates for a given event, and updates may be issued hours, days, or even weeks after the event.

Lastly, a **Retraction Notice** is issued if the candidate is rejected as a result of vetting by human instrument scientists and data analysts. A retraction indicates that the candidate has been withdrawn because it is probably not astrophysical.

All types of Notices *except for Retraction notices* contain the following information, which are described in further detail below:

- *Name*: a unique identifier for the candidate
- *Significance*: estimated false alarm rate (*FAR*)
- *Sky localization*: inferred sky position and (*CBC* candidates only) distance
- *Inference*: (*CBC* candidates only) inferred source classification and properties

Of the above fields, Retraction notices provide only the name.

Initial and Update notices are accompanied by human-readable GCN Circulars, which restate all of the above information and also may include a *data quality assessment*.

## 4.2 Notice Formats

Notices essentially come in two different formats: a format that is distributed over *Kafka* and a different format that is distributed using VOEvent brokers. These two formats contain the same information about the candidate but contain different metadata and follow different schema.

### 4.2.1 Kafka Notice (GCN, SCiMMA)

Public LIGO/Virgo/KAGRA notices distributed over Kafka as either *JSON* or *Avro* follow the format of the table below. The `event` field will be null in retraction notices; the `external_coinc` field will only be non-null in the event of a coincidence between a gravitational-wave candidate and an alert from a third party.

---

#### Important

The sky map field stores the raw byte-string representation of the sky localization file (described below) in Avro notices, but stores the *Base64 encoded* byte-string representation in JSON notices.

---

JSON

Avro

alert_type	{ <i>EarlyWarning, Preliminary, Initial, Update, Retraction</i> }	
time_created	Time notice was created (UTC, ISO-8601) 2018-11-01T22:34:20Z	
superevent_id	GraceDB ID: [{ <i>T, M</i> }] <i>SYMMDD</i> abc. Example: MS181101abc	
event		
time	Time of event (UTC, ISO-8601), e.g. 2018-11-01T22:22:46.654Z	
far	Estimated <i>FAR</i> in Hz	
instruments	List of detectors, e.g. ['H1', 'L1', 'V1'] whose data have been used by the <i>online pipeline</i> that has produced the preferred event for that particular <i>superevent</i>	
skymap	The contents of a sky map in a multi-order FITS format as a Base64-encoded string.	
search	{ <i>AllSky, AllSkyLong, BBH, EarlyWarning, HighMass, IMBH, MDC</i> }	
group	CBC	Burst
pipeline	{ <i>gstlal, MBTAOnline, pycbc, spiir</i> }	{ <i>CWB, oLIB</i> }
event.properties		
HasNS, HasRemnant, HasMassGap	Probability, under the assumption that the source is not noise, that at least one of the compact objects was a neutron star, that the system ejected a non-zero amount of neutron star matter, and that at least one of the compact objects has mass in the range 3-5 solar masses, respectively	N/A
event.classification		
BNS, NSBH, BBH, Noise	Probability that the source is a <i>BNS</i> , <i>NSBH</i> , <i>BBH</i> , or <i>Terrestrial</i> (i.e, noise) respectively	N/A
external_coinc		
gc_nnotice_id	{583417860, 583327924}	
ivorn	External IVORN identification field	
observatory	{ <i>Fermi, Swift</i> }	
search	{ <i>GRB, SubGRB</i> }	
time_difference	Time between source and external event in seconds	
time_coincidence	Estimated coincidence false alarm rate in Hz using timing	
time_sky_position	Estimated coincidence false alarm rate in Hz using timing and sky position	

alert_type	{ <i>EarlyWarning, Preliminary, Initial, Update, Retraction</i> }	
time_created	Time notice was created (UTC, ISO-8601) 2018-11-01T22:34:20Z	
superevent_id	GraceDB ID: [{ <i>T, M</i> }] <i>SYMMDD</i> abc. Example: MS181101abc	
event		
time	Time of event (UTC, ISO-8601), e.g. 2018-11-01T22:22:46.654Z	
far	Estimated <i>FAR</i> in Hz	
instruments	List of detectors, e.g. ['H1', 'L1', 'V1'] whose data have been used by the <i>online pipeline</i> that has produced the preferred event for that particular <i>superevent</i>	
skymap	The contents of a sky map in a multi-order FITS format as a byte-string.	
search	{ <i>AllSky, AllSkyLong, BBH, EarlyWarning, HighMass, IMBH, MDC</i> }	
group	CBC	Burst
pipeline	{ <i>gstlal, MBTAOnline, pycbc, spiir</i> }	{ <i>CWB, oLIB</i> }
event.properties		
HasNS, HasRemnant, Has-MassGap	Probability, under the assumption that the source is not noise, that at least one of the compact objects was a neutron star, that the system ejected a non-zero amount of neutron star matter, and that at least one of the compact objects has mass in the range 3-5 solar masses, respectively	N/A
event.classification		
BNS, NSBH, BBH, Noise	Probability that the source is a <i>BNS, NSBH, BBH</i> , or <i>Terrestrial</i> (i.e, noise) respectively	N/A
external_coinc		
gc_nnotice_id	{583417860, 583327924}	
ivorn	External IVORN identification field	
observatory	{ <i>Fermi, Swift</i> }	
search	{ <i>GRB, SubGRB</i> }	
time_difference	Time between source and external event in seconds	
time_coincidence	Estimated coincidence false alarm rate in Hz using timing	
time_sky_position	Estimated coincidence false alarm rate in Hz using timing and sky position	

#### 4.2.2 VOEvent Notice (GCN Classic)

The table below is a representation of the contents of a LIGO/Virgo/KAGRA GCN Notice.

Root		
IVORN	ivo://gwnet/LVC#[{T,M}]SYMMDDabc-{1,2,3}-{EarlyWarning,Preliminary,Initial,Update,Retraction}	
Role	{observation,test}	
Who		
Date	Time sent (UTC, ISO-8601), e.g. 2018-11-01T22:34:49	
Author	LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration	
What		
GraceID	GraceDB ID: [{T,M}]SYMMDDabc. Example: MS181101abc	
Packet Type	GCN Notice type: {Preliminary,Initial,Update,Retraction}	
Notice Type	Numerical equivalent of GCN Notice type: {150,151,152,164}	
FAR	Estimated FAR in Hz	
Sky Map	Versioned URL of HEALPix FITS sky localization file in the format https://gracedb.ligo.org/api/superevents/{T,M}]SYMMDDabc/files/{bayestar,LALInference,cWB}.multiorder.fits,[0-8]. Example: https://gracedb.ligo.org/api/superevents/S190901ap/files/bayestar.multiorder.fits,0	
Group	CBC	Burst
Pipeline	{gstlal,MBTA,pycbc,spiiir}	{CWB,oLIB}
Central-Freq	N/A	Central frequency in Hz
Duration		Duration of burst in s
BNS, NSBH, BBH, Noise	Probability that the source is a BNS, NSBH, BBH, or Terrestrial (i.e, noise) respectively	N/A
HasNS, Has-Remnant, Has-Mass-Gap	Probability, under the assumption that the source is not noise, that at least one of the compact objects was a neutron star, that the system ejected a non-zero amount of neutron star matter, and that at least one of the compact objects has mass in the range 3-5 solar masses, respectively	
When	Time of signal (UTC, ISO-8601), e.g. 2018-11-01T22:22:46.654437	
How	List of detectors, e.g. H1: LIGO Hanford 4 km gravitational wave detector, L1: LIGO Livingston 4 km gravitational wave detector and V1: Virgo 3 km gravitational wave detector K1: KAGRA 3 km gravitational wave detector whose data have been used by the online pipeline that has produced the preferred event for that particular superevent	

In the event of a coincidence between a gravitational-wave candidate and an alert from a third party (e.g. a gamma-ray burst or neutrino trigger), the following fields will also be present:

External GCN Notice ID	<code>{583417860, 583327924}</code>
External IVORN	External IVORN identification field
External Observatory	<code>{Fermi, Swift}</code>
External Search	<code>{GRB, SubGRB}</code>
Time Coincidence FAR	Estimated coincidence false alarm rate in Hz using timing
Time and Sky Position Coincidence FAR	Estimated coincidence false alarm rate in Hz using timing and sky position
Combined Sky Map	URL of combined GW-External HEALPix FITS sky localization file
Time Difference	Time between source and external event in seconds

## 4.3 Notice Contents

### 4.3.1 Name

The name of an event is its *GraceDB* ID (sometimes called the *superevent* ID), a uniquely assigned identifier such as MS181101abc. A GraceDB ID has three parts:

- Prefix: S for normal candidates and MS or TS for mock or test events respectively. The S stands for *superevent*.
- Date: The six-digit UTC date of the event consisting of a two-digit year, month, and day of month.
- Suffix: A lowercase alphabetic string that is incremented automatically (a, b, ..., z, aa, ab, ... az, aaa, etc.) whenever a candidate on a given date is added to GraceDB.

### 4.3.2 Significance

The significance of the event is quantified by its *false alarm rate*: the expected rate of events from the pipeline that produced the preferred event with equal or higher ranking statistics, in the absence of any astrophysical signal (see *false alarm rate (FAR)*).

### 4.3.3 Sky Localization

The sky localization consists of the posterior probability distribution of the source’s sky position and (for *CBC* events only) luminosity distance. The Classic GCN Notice and Circular will provide a URL for the sky localization file stored in GraceDB, notices delivered over Kafka will provide byte-string representations of the localization file content. Avro notices will provide the raw bytes, JSON notices will provide *base64 encoded* bytes. The sky localization is saved in a *FITS* file as a *HEALPix*<sup>1</sup> all-sky image. See our *sample code* for instructions on working with sky localization files.

The sky map URL will generally be of the form `https://gracedb.ligo.org/api/superevents/sid/files/method.multiorder.fits,v`, where *sid* is the *superevent* ID, *method* is the sky localization algorithm (usually bayestar, LALInference, or cWB), and *v* is an integer that uniquely identifies different versions of the localization. The version number is automatically assigned by GraceDB, starting from 0, and increments for each file of the same name. For example, the first FITS file with the name bayestar.multiorder.fits becomes bayestar.multiorder.fits,0, then the next one is bayestar.multiorder.fits,1, and so on. The filename without the version suffix, such as bayestar.multiorder.fits, always points to the most recent version.

---

#### Important

We generally provide localizations in two HEALPix formats, distinguished by file extension:

<sup>1</sup> Górski, K.M., Hivon, E., Banday, A.J., et al. 2005, *Astrophys. J.*, 622, 759. doi:10.1086/427976



### \*.multiorder.fits

A new variant of the HEALPix format that is designed to overcome limitations of the \*.fits.gz format for well-localized events from three-detector operations and future gravitational-wave facilities (see rationale in [LIGO-G1800186](#)). It uses HEALPix [explicit indexing](#) and the [NUNIQ numbering scheme](#), which is closely related to [multi-order coverage \(MOC\) maps](#) in Aladin. This is the new format that is used by the LIGO/Virgo/KAGRA low-latency alert pipeline. **This is the primary and preferred format, and the only format that is explicitly listed in the GCN Notices and Circulars.** See the section [Working with Multi-Order Sky Maps](#) for details.

### \*.fits.gz

A subset of the standard HEALPix-in-FITS format (see semi-official specifications [from the HEALPix team](#) and [from the gamma-ray community](#)) that is recognized by a wide variety of astronomical imaging programs including DS9 and Aladin. It uses HEALPix [implicit indexing](#) and the [NESTED numbering scheme](#). See the section [Working with Flat Resolution Sky Maps](#) for details.

Both formats always use celestial (equatorial, J2000) coordinates.

## 4.3.4 Inference

The inference section is present for [CBC](#) events *only*. It has two parts:

**Classification:** Four numbers, summing to unity, giving probability that the source belongs to the following five mutually exclusive categories:

- [BNS](#) merger
- [NSBH](#) merger
- [BBH](#) merger
- [Terrestrial](#) (i.e., a chance background fluctuation or a glitch)

The figure below shows the extent of the three astrophysical categories (BNS, NSBH, and BBH) in terms of the component masses  $m_1$  and  $m_2$ .

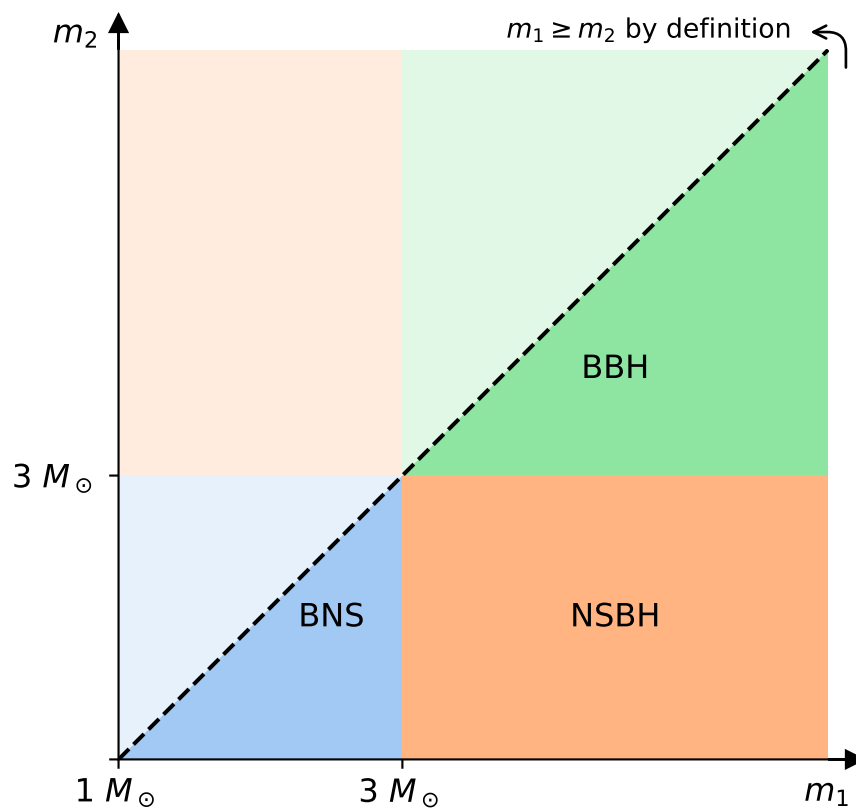
### Note

By convention, the component masses are defined such that  $m_1 \geq m_2$ , so that the [primary](#) compact object in the binary (i.e., component 1), is always more massive than the [secondary](#) compact object (i.e., component 2).

In the mass diagram below, the upper diagonal region  $m_1 < m_2$  is lightly shaded in order to indicate that the definitions of four mass classes (BNS, NSBH, BBH) are *symmetric* in  $m_1$  and  $m_2$ .

**Properties:** Probabilities that the source has each of the following properties, *assuming that it is not noise* (e.g., assuming that it is a BNS, NSBH, or BBH merger):

- **HasNS:** The mass of one or more of the binary's two companion compact objects is consistent with a neutron star. Equivalently, the mass of the *secondary* or less massive compact object is consistent with a neutron star. The upper limit of the neutron star mass is marginalized over several neutron star equations of state ([EOS](#)).
- **HasRemnant:** A non-zero amount of neutron star material remained outside the final remnant compact object (a necessary but not sufficient condition to produce certain kinds of electromagnetic emission such as a short [GRB](#) or a kilonova). Several neutron star EOSs are considered to compute the remnant mass and are marginalized over.



- **HasMassGap:** The mass of one or more of the binary’s two companion object lies in the hypothetical “mass gap” between neutron stars and black holes, defined here as  $3M_{\odot} \leq m \leq 5M_{\odot}$ .

All of the quantities in the Classification and Properties sections are model dependent to some extent: the Classification section takes into consideration prior knowledge of astrophysical compact binary merger rates from previous LIGO/Virgo/KAGRA observations, and both the Classification and Properties sections depend on details of neutron star physics (e.g. maximum NS mass, equation of state). See the earlier subsection of the [Data Analysis](#) section for implementation details.

## 4.4 Circular Contents

The following information will be present in the human-readable GCN Circulars.

### 4.4.1 Data Quality Assessment

Circulars may contain concise descriptions of any instrument or data quality issues that may affect the significance estimates or the GW parameter inferences. Unresolved data quality issues could mean that sky localization estimates may shift after they have been mitigated, but does not mean that they will. This is to be considered as advisory information.

### 4.4.2 Sky Localization Ellipse

Generally, GW sky localizations are irregularly shaped. However, for particularly accurately localized events, the sky localization region can be well described by an ellipse. When the area of the 90% ellipse is less than 1.35 times the area of the *smallest possible 90% credible region*, the GCN Circular will provide a 90% containment ellipse. For details of the ellipse fitting algorithm, see [ligo.skymap.postprocess.ellipse](#).

The ellipse is described in the format of a [DS9 region string](#). Many tools can read DS9 region strings, including [DS9](#), [Aladin](#), [astropy-regions](#), and [pyregion](#). The region string contains the right ascension, declination, semi-major axis, semi-minor axis, position angle of the semi-minor axis). Here is an example:

```
icrs; ellipse(03h08m25s, -45d08m14s, 9d, 3d, 112d)
```

## 4.5 Not Included in Alerts

The alerts will not contain quantitative estimates of intrinsic properties such as masses and spins, nor contain information on the GW strain or reconstructed waveforms. After final analysis, those data products are released through the [Gravitational Wave Open Science Center](#).

## 4.6 Notice Examples

### 4.6.1 Kafka

Below are examples of GCN notices to illustrate the formatting of the Notices. The `skymap` field has been truncated for display purposes, though links to the full files for both formats can be found in the [SCiMMA](#) and [GCN](#) sample code sections. Recall that SCiMMA notices follow the same schema as GCN notices, however the `skymap` field in SCiMMA notices contain raw bytes while the `skymap` field in GCN notices is [base64 encoded](#).

*Coming Soon:* Example of a notice with an external coincident event.

EarlyWarning

Preliminary

Initial

Update

Retraction

```
{
  "alert_type": "EARLY_WARNING",
  "time_created": "2018-11-01T22:34:20Z",
  "superevent_id": "MS181101ab",
  "urls": {
    "gracedb": "https://example.org/superevents/MS181101ab/view/"
  },
  "event": {
    "time": "2018-11-01T22:22:46.654Z",
    "far": 9.11069936486e-14,
    "instruments": [
      "H1",
      "L1",
      "V1"
    ],
    "group": "CBC",
    "pipeline": "gstlal",
    "search": "MDC",
    "properties": {
      "HasNS": 0.95,
      "HasRemnant": 0.91,
      "HasMassGap": 0.01
    },
    "classification": {
      "BNS": 0.95,
      "NSBH": 0.01,
      "BBH": 0.03,
      "Terrestrial": 0.01
    },
    "skymap": "U01NUExFICA9ICAgICAgICAgICAgICAgICBUIC8gY29uZm..."
  },
  "external_coinc": null
}
```

```
{
  "alert_type": "PRELIMINARY",
  "time_created": "2018-11-01T22:34:49Z",
  "superevent_id": "MS181101ab",
  "urls": {
    "gracedb": "https://example.org/superevents/MS181101ab/view/"
  },
  "event": {
    "time": "2018-11-01T22:22:46.654Z",
    "far": 9.11069936486e-14,
    "instruments": [
```

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```

        "H1",
        "L1",
        "V1"
    ],
    "group": "CBC",
    "pipeline": "gstlal",
    "search": "MDC",
    "properties": {
        "HasNS": 0.95,
        "HasRemnant": 0.91,
        "HasMassGap": 0.01
    },
    "classification": {
        "BNS": 0.95,
        "NSBH": 0.01,
        "BBH": 0.03,
        "Terrestrial": 0.01
    },
    "skymap": "U01NUExFICA9ICAgICAgICAgICAgICAgICBUIC8gY29uZm..."
},
"external_coinc": null
}

```

```

{
  "alert_type": "INITIAL",
  "time_created": "2018-11-01T22:36:25Z",
  "superevent_id": "MS181101ab",
  "urls": {
    "gracedb": "https://example.org/superevents/MS181101ab/view/"
  },
  "event": {
    "time": "2018-11-01T22:22:46.654Z",
    "far": 9.11069936486e-14,
    "instruments": [
      "H1",
      "L1",
      "V1"
    ],
    "group": "CBC",
    "pipeline": "gstlal",
    "search": "MDC",
    "properties": {
        "HasNS": 0.95,
        "HasRemnant": 0.91,
        "HasMassGap": 0.01
    },
    "classification": {
        "BNS": 0.95,
        "NSBH": 0.01,
        "BBH": 0.03,
        "Terrestrial": 0.01
    }
  },
}

```

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```

    "skymap": "U01NUExFICA9ICAgICAgICAgICAgICAgICBUIC8gY29uZm..."
  },
  "external_coinc": null
}

```

```

{
  "alert_type": "UPDATE",
  "time_created": "2018-11-01T22:36:25Z",
  "superevent_id": "MS181101ab",
  "urls": {
    "gracedb": "https://example.org/superevents/MS181101ab/view/"
  },
  "event": {
    "time": "2018-11-01T22:22:46.654Z",
    "far": 9.11069936486e-14,
    "instruments": [
      "H1",
      "L1",
      "V1"
    ],
    "group": "CBC",
    "pipeline": "gstlal",
    "search": "MDC",
    "properties": {
      "HasNS": 0.95,
      "HasRemnant": 0.91,
      "HasMassGap": 0.01
    },
    "classification": {
      "BNS": 0.95,
      "NSBH": 0.01,
      "BBH": 0.03,
      "Terrestrial": 0.01
    },
    "skymap": "U01NUExFICA9ICAgICAgICAgICAgICAgICBUIC8gY29uZm..."
  },
  "external_coinc": null
}

```

```

{
  "alert_type": "RETRACTION",
  "time_created": "2018-11-01T23:36:23Z",
  "superevent_id": "MS181101ab",
  "urls": {
    "gracedb": "https://example.org/superevents/MS181101ab/view/"
  },
  "event": null,
  "external_coinc": null
}

```

## 4.6.2 GCN Classic

Below are examples of VOEvent notices.

EarlyWarning

Preliminary

Initial

Update

Retraction

External Coincidence

```
<?xml version='1.0' encoding='UTF-8'?>
<voe:VOEvent xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:voe="http://www.
↳ivoa.net/xml/VOEvent/v2.0" xsi:schemaLocation="http://www.ivoa.net/xml/VOEvent/v2.0
↳http://www.ivoa.net/xml/VOEvent/VOEvent-v2.0.xsd" version="2.0" role="test" ivorn=
↳"ivo://gwnet/LVC#MS181101ab-1-EarlyWarning">
  <Who>
    <Date>2018-11-01T22:34:20Z</Date>
    <Author>
      <contactName>LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA
↳Collaboration</contactName>
    </Author>
  </Who>
  <What>
    <Param dataType="int" name="Packet_Type" value="163">
      <Description>The Notice Type number is assigned/used within GCN, eg type=163 is an
↳LVC_EARLY_WARNING notice</Description>
    </Param>
    <Param dataType="int" name="internal" value="0">
      <Description>Indicates whether this event should be distributed to LSC/Virgo/KAGRA
↳members only</Description>
    </Param>
    <Param dataType="int" name="Pkt_Ser_Num" value="1">
      <Description>A number that increments by 1 each time a new revision is issued for
↳this event</Description>
    </Param>
    <Param dataType="string" name="GraceID" ucd="meta.id" value="MS181101ab">
      <Description>Identifier in GraceDB</Description>
    </Param>
    <Param dataType="string" name="AlertType" ucd="meta.version" value="EarlyWarning">
      <Description>VOEvent alert type</Description>
    </Param>
    <Param dataType="int" name="HardwareInj" ucd="meta.number" value="0">
      <Description>Indicates that this event is a hardware injection if 1, no if 0</
↳Description>
    </Param>
    <Param dataType="int" name="OpenAlert" ucd="meta.number" value="1">
      <Description>Indicates that this event is an open alert if 1, no if 0</Description>
    </Param>
    <Param dataType="string" name="EventPage" ucd="meta.ref.url" value="https://example.
↳org/superevents/MS181101ab/view/">
```

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```

    <Description>Web page for evolving status of this GW candidate</Description>
  </Param>
  <Param dataType="string" name="Instruments" ucd="meta.code" value="H1,L1,V1">
    <Description>List of instruments used in analysis to identify this event</
  <Description>
  </Param>
  <Param dataType="float" name="FAR" ucd="arith.rate;stat.falsealarm" unit="Hz" value=
  <Description>False alarm rate for GW candidates with this strength or greater</
  <Description>
  </Param>
  <Param dataType="string" name="Group" ucd="meta.code" value="CBC">
    <Description>Data analysis working group</Description>
  </Param>
  <Param dataType="string" name="Pipeline" ucd="meta.code" value="gstlal">
    <Description>Low-latency data analysis pipeline</Description>
  </Param>
  <Param dataType="string" name="Search" ucd="meta.code" value="MDC">
    <Description>Specific low-latency search</Description>
  </Param>
  <Group name="GW_SKYMAP" type="GW_SKYMAP">
    <Param dataType="string" name="skymap_fits" ucd="meta.ref.url" value="https://
    <Description>Sky Map FITS</Description>
  </Param>
  </Group>
  <Group name="Classification" type="Classification">
    <Param dataType="float" name="BNS" ucd="stat.probability" value="0.95">
    <Description>Probability that the source is a binary neutron star merger (both
    <Description>
    </Param>
    <Param dataType="float" name="NSBH" ucd="stat.probability" value="0.01">
    <Description>Probability that the source is a neutron star-black hole merger
    <Description>
    </Param>
    <Param dataType="float" name="BBH" ucd="stat.probability" value="0.03">
    <Description>Probability that the source is a binary black hole merger (both
    <Description>
    </Param>
    <Param dataType="float" name="Terrestrial" ucd="stat.probability" value="0.01">
    <Description>Probability that the source is terrestrial (i.e., a background
    <Description>
    </Param>
    <Description>Source classification: binary neutron star (BNS), neutron star-black
    <Description>
  </Group>
  <Group name="Properties" type="Properties">
    <Param dataType="float" name="HasNS" ucd="stat.probability" value="0.95">
    <Description>Probability that at least one object in the binary has a mass that
    <Description>
    </Param>
    <Param dataType="float" name="HasRemnant" ucd="stat.probability" value="0.91">

```

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```

    <Description>Probability that a nonzero mass was ejected outside the central_
    ↪ remnant object</Description>
    </Param>
    <Param dataType="float" name="HasMassGap" ucd="stat.probability" value="0.01">
    <Description>Probability that at least one object in the binary has a mass_
    ↪ between 3 and 5 solar masses</Description>
    </Param>
    <Description>Qualitative properties of the source, conditioned on the assumption_
    ↪ that the signal is an astrophysical compact binary merger</Description>
    </Group>
  </What>
  <WhereWhen>
    <ObsDataLocation>
      <ObservatoryLocation id="LIGO Virgo KAGRA"/>
      <ObservationLocation>
        <AstroCoordSystem id="UTC-FK5-GEO"/>
        <AstroCoords coord_system_id="UTC-FK5-GEO">
          <Time unit="s">
            <TimeInstant>
              <ISOTime>2018-11-01T22:22:46.654437Z</ISOTime>
            </TimeInstant>
          </Time>
        </AstroCoords>
      </ObservationLocation>
    </ObsDataLocation>
  </WhereWhen>
  <Description>Early warning report of a candidate gravitational wave event</Description>
  <How>
    <Description>Candidate gravitational wave event identified by low-latency analysis</
    ↪ Description>
    <Description>H1: LIGO Hanford 4 km gravitational wave detector</Description>
    <Description>L1: LIGO Livingston 4 km gravitational wave detector</Description>
    <Description>V1: Virgo 3 km gravitational wave detector</Description>
    <Description>K1: KAGRA 3 km gravitational wave detector</Description>
  </How>
</voe:VOEvent>

```

```

<?xml version='1.0' encoding='UTF-8'?>
<voe:VOEvent xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:voe="http://www.
    ↪ ivoa.net/xml/VOEvent/v2.0" xsi:schemaLocation="http://www.ivoa.net/xml/VOEvent/v2.0_
    ↪ http://www.ivoa.net/xml/VOEvent/VOEvent-v2.0.xsd" version="2.0" role="test" ivorn=
    ↪ "ivo://gwnet/LVC#MS181101ab-2-Preliminary">
  <Who>
    <Date>2018-11-01T22:34:49Z</Date>
    <Author>
      <contactName>LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA_
    ↪ Collaboration</contactName>
    </Author>
  </Who>
  <What>
    <Param dataType="int" name="Packet_Type" value="150">
      <Description>The Notice Type number is assigned/used within GCN, eg type=150 is an_

```

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```

↪LVC_PRELIMINARY notice</Description>
  </Param>
  <Param dataType="int" name="internal" value="0">
    <Description>Indicates whether this event should be distributed to LSC/Virgo/KAGRA_
↪members only</Description>
  </Param>
  <Param dataType="int" name="Pkt_Ser_Num" value="2">
    <Description>A number that increments by 1 each time a new revision is issued for_
↪this event</Description>
  </Param>
  <Param dataType="string" name="GraceID" ucd="meta.id" value="MS181101ab">
    <Description>Identifier in GraceDB</Description>
  </Param>
  <Param dataType="string" name="AlertType" ucd="meta.version" value="Preliminary">
    <Description>VOEvent alert type</Description>
  </Param>
  <Param dataType="int" name="HardwareInj" ucd="meta.number" value="0">
    <Description>Indicates that this event is a hardware injection if 1, no if 0</
↪Description>
  </Param>
  <Param dataType="int" name="OpenAlert" ucd="meta.number" value="1">
    <Description>Indicates that this event is an open alert if 1, no if 0</Description>
  </Param>
  <Param dataType="string" name="EventPage" ucd="meta.ref.url" value="https://example.
↪org/superevents/MS181101ab/view/">
    <Description>Web page for evolving status of this GW candidate</Description>
  </Param>
  <Param dataType="string" name="Instruments" ucd="meta.code" value="H1,L1,V1">
    <Description>List of instruments used in analysis to identify this event</
↪Description>
  </Param>
  <Param dataType="float" name="FAR" ucd="arith.rate;stat.falsealarm" unit="Hz" value=
↪"9.11069936486e-14">
    <Description>False alarm rate for GW candidates with this strength or greater</
↪Description>
  </Param>
  <Param dataType="string" name="Group" ucd="meta.code" value="CBC">
    <Description>Data analysis working group</Description>
  </Param>
  <Param dataType="string" name="Pipeline" ucd="meta.code" value="gstlal">
    <Description>Low-latency data analysis pipeline</Description>
  </Param>
  <Param dataType="string" name="Search" ucd="meta.code" value="MDC">
    <Description>Specific low-latency search</Description>
  </Param>
  <Group name="GW_SKYMAP" type="GW_SKYMAP">
    <Param dataType="string" name="skymap_fits" ucd="meta.ref.url" value="https://
↪emfollow.docs.ligo.org/userguide/_static/bayestar.muliorder.fits,0">
    <Description>Sky Map FITS</Description>
  </Param>
  </Group>
  <Group name="Classification" type="Classification">

```

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```

    <Param dataType="float" name="BNS" ucd="stat.probability" value="0.95">
      <Description>Probability that the source is a binary neutron star merger (both
↳ objects lighter than 3 solar masses)</Description>
    </Param>
    <Param dataType="float" name="NSBH" ucd="stat.probability" value="0.01">
      <Description>Probability that the source is a neutron star-black hole merger
↳ (secondary lighter than 3 solar masses)</Description>
    </Param>
    <Param dataType="float" name="BBH" ucd="stat.probability" value="0.03">
      <Description>Probability that the source is a binary black hole merger (both
↳ objects heavier than 3 solar masses)</Description>
    </Param>
    <Param dataType="float" name="Terrestrial" ucd="stat.probability" value="0.01">
      <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), or terrestrial (noise)</Description>
  </Group>
  <Group name="Properties" type="Properties">
    <Param dataType="float" name="HasNS" ucd="stat.probability" value="0.95">
      <Description>Probability that at least one object in the binary has a mass that
↳ is less than 3 solar masses</Description>
    </Param>
    <Param dataType="float" name="HasRemnant" ucd="stat.probability" value="0.91">
      <Description>Probability that a nonzero mass was ejected outside the central
↳ remnant object</Description>
    </Param>
    <Param dataType="float" name="HasMassGap" ucd="stat.probability" value="0.01">
      <Description>Probability that at least one object in the binary has a mass
↳ between 3 and 5 solar masses</Description>
    </Param>
    <Description>Qualitative properties of the source, conditioned on the assumption
↳ that the signal is an astrophysical compact binary merger</Description>
  </Group>
</What>
<WhereWhen>
  <ObsDataLocation>
    <ObservatoryLocation id="LIGO Virgo KAGRA"/>
    <ObservationLocation>
      <AstroCoordSystem id="UTC-FK5-GEO"/>
      <AstroCoords coord_system_id="UTC-FK5-GEO">
        <Time unit="s">
          <TimeInstant>
            <ISOTime>2018-11-01T22:22:46.654437Z</ISOTime>
          </TimeInstant>
        </Time>
      </AstroCoords>
    </ObservationLocation>
  </ObsDataLocation>
</WhereWhen>
<Description>Report of a candidate gravitational wave event</Description>

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<How>
  <Description>Candidate gravitational wave event identified by low-latency analysis</
→Description>
  <Description>H1: LIGO Hanford 4 km gravitational wave detector</Description>
  <Description>L1: LIGO Livingston 4 km gravitational wave detector</Description>
  <Description>V1: Virgo 3 km gravitational wave detector</Description>
  <Description>K1: KAGRA 3 km gravitational wave detector</Description>
</How>
<Citations>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-1-EarlyWarning</EventIVORN>
  <Description>Initial localization is now available (preliminary)</Description>
</Citations>
</voe:VOEvent>

```

```

<?xml version='1.0' encoding='UTF-8'?>
<voe:VOEvent xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:voe="http://www.
→ivoa.net/xml/VOEvent/v2.0" xsi:schemaLocation="http://www.ivoa.net/xml/VOEvent/v2.0
→http://www.ivoa.net/xml/VOEvent/VOEvent-v2.0.xsd" version="2.0" role="test" ivorn=
→"ivo://gwnet/LVC#MS181101ab-3-Initial">
  <Who>
    <Date>2018-11-01T22:36:25Z</Date>
    <Author>
      <contactName>LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA
→Collaboration</contactName>
    </Author>
  </Who>
  <What>
    <Param dataType="int" name="Packet_Type" value="151">
      <Description>The Notice Type number is assigned/used within GCN, eg type=151 is an
→LVC_INITIAL notice</Description>
    </Param>
    <Param dataType="int" name="internal" value="0">
      <Description>Indicates whether this event should be distributed to LSC/Virgo/KAGRA
→members only</Description>
    </Param>
    <Param dataType="int" name="Pkt_Ser_Num" value="3">
      <Description>A number that increments by 1 each time a new revision is issued for
→this event</Description>
    </Param>
    <Param dataType="string" name="GraceID" ucd="meta.id" value="MS181101ab">
      <Description>Identifier in GraceDB</Description>
    </Param>
    <Param dataType="string" name="AlertType" ucd="meta.version" value="Initial">
      <Description>VOEvent alert type</Description>
    </Param>
    <Param dataType="int" name="HardwareInj" ucd="meta.number" value="0">
      <Description>Indicates that this event is a hardware injection if 1, no if 0</
→Description>
    </Param>
    <Param dataType="int" name="OpenAlert" ucd="meta.number" value="1">
      <Description>Indicates that this event is an open alert if 1, no if 0</Description>
    </Param>

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<Param dataType="string" name="EventPage" ucd="meta.ref.url" value="https://example.
↳org/superevents/MS181101ab/view/">
  <Description>Web page for evolving status of this GW candidate</Description>
</Param>
<Param dataType="string" name="Instruments" ucd="meta.code" value="H1,L1,V1">
  <Description>List of instruments used in analysis to identify this event</
↳Description>
</Param>
<Param dataType="float" name="FAR" ucd="arith.rate;stat.falsealarm" unit="Hz" value=
↳"9.11069936486e-14">
  <Description>False alarm rate for GW candidates with this strength or greater</
↳Description>
</Param>
<Param dataType="string" name="Group" ucd="meta.code" value="CBC">
  <Description>Data analysis working group</Description>
</Param>
<Param dataType="string" name="Pipeline" ucd="meta.code" value="gstlal">
  <Description>Low-latency data analysis pipeline</Description>
</Param>
<Param dataType="string" name="Search" ucd="meta.code" value="MDC">
  <Description>Specific low-latency search</Description>
</Param>
<Group name="GW_SKYMAP" type="GW_SKYMAP">
  <Param dataType="string" name="skymap_fits" ucd="meta.ref.url" value="https://
↳emfollow.docs.ligo.org/userguide/_static/bayestar.muliorder.fits,0">
    <Description>Sky Map FITS</Description>
  </Param>
</Group>
<Group name="Classification" type="Classification">
  <Param dataType="float" name="BNS" ucd="stat.probability" value="0.95">
    <Description>Probability that the source is a binary neutron star merger (both
↳objects lighter than 3 solar masses)</Description>
  </Param>
  <Param dataType="float" name="NSBH" ucd="stat.probability" value="0.01">
    <Description>Probability that the source is a neutron star-black hole merger
↳(secondary lighter than 3 solar masses)</Description>
  </Param>
  <Param dataType="float" name="BBH" ucd="stat.probability" value="0.03">
    <Description>Probability that the source is a binary black hole merger (both
↳objects heavier than 3 solar masses)</Description>
  </Param>
  <Param dataType="float" name="Terrestrial" ucd="stat.probability" value="0.01">
    <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), or terrestrial (noise)</Description>
</Group>
<Group name="Properties" type="Properties">
  <Param dataType="float" name="HasNS" ucd="stat.probability" value="0.95">
    <Description>Probability that at least one object in the binary has a mass that
↳is less than 3 solar masses</Description>

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    </Param>
    <Param dataType="float" name="HasRemnant" ucd="stat.probability" value="0.91">
      <Description>Probability that a nonzero mass was ejected outside the central
    ↪ remnant object</Description>
    </Param>
    <Param dataType="float" name="HasMassGap" ucd="stat.probability" value="0.01">
      <Description>Probability that at least one object in the binary has a mass
    ↪ between 3 and 5 solar masses</Description>
    </Param>
    <Description>Qualitative properties of the source, conditioned on the assumption
    ↪ that the signal is an astrophysical compact binary merger</Description>
  </Group>
</What>
<WhereWhen>
  <ObsDataLocation>
    <ObservatoryLocation id="LIGO Virgo KAGRA"/>
    <ObservationLocation>
      <AstroCoordSystem id="UTC-FK5-GEO"/>
      <AstroCoords coord_system_id="UTC-FK5-GEO">
        <Time unit="s">
          <TimeInstant>
            <ISOTime>2018-11-01T22:22:46.654437Z</ISOTime>
          </TimeInstant>
        </Time>
      </AstroCoords>
    </ObservationLocation>
  </ObsDataLocation>
</WhereWhen>
<Description>Report of a candidate gravitational wave event</Description>
<How>
  <Description>Candidate gravitational wave event identified by low-latency analysis</
    ↪ Description>
  <Description>H1: LIGO Hanford 4 km gravitational wave detector</Description>
  <Description>L1: LIGO Livingston 4 km gravitational wave detector</Description>
  <Description>V1: Virgo 3 km gravitational wave detector</Description>
  <Description>K1: KAGRA 3 km gravitational wave detector</Description>
</How>
<Citations>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-2-Preliminary</EventIVORN>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-1-EarlyWarning</EventIVORN>
  <Description>Initial localization is now available</Description>
</Citations>
</voe:VOEvent>

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```

<?xml version='1.0' encoding='UTF-8'?>
<voe:VOEvent xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:voe="http://www.
    ↪ ivoa.net/xml/VOEvent/v2.0" xsi:schemaLocation="http://www.ivoa.net/xml/VOEvent/v2.0
    ↪ http://www.ivoa.net/xml/VOEvent/VOEvent-v2.0.xsd" version="2.0" role="test" ivorn=
    ↪ "ivo://gwnet/LVC#MS181101ab-4-Update">
  <Who>
    <Date>2018-11-01T22:36:25Z</Date>
    <Author>

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    <contactName>LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA
↪ Collaboration</contactName>
    </Author>
  </Who>
  <What>
    <Param dataType="int" name="Packet_Type" value="152">
      <Description>The Notice Type number is assigned/used within GCN, eg type=152 is an
↪ LVC_UPDATE notice</Description>
    </Param>
    <Param dataType="int" name="internal" value="0">
      <Description>Indicates whether this event should be distributed to LSC/Virgo/KAGRA
↪ members only</Description>
    </Param>
    <Param dataType="int" name="Pkt_Ser_Num" value="4">
      <Description>A number that increments by 1 each time a new revision is issued for
↪ this event</Description>
    </Param>
    <Param dataType="string" name="GraceID" ucd="meta.id" value="MS181101ab">
      <Description>Identifier in GraceDB</Description>
    </Param>
    <Param dataType="string" name="AlertType" ucd="meta.version" value="Update">
      <Description>V0Event alert type</Description>
    </Param>
    <Param dataType="int" name="HardwareInj" ucd="meta.number" value="0">
      <Description>Indicates that this event is a hardware injection if 1, no if 0</
↪ Description>
    </Param>
    <Param dataType="int" name="OpenAlert" ucd="meta.number" value="1">
      <Description>Indicates that this event is an open alert if 1, no if 0</Description>
    </Param>
    <Param dataType="string" name="EventPage" ucd="meta.ref.url" value="https://example.
↪ org/superevents/MS181101ab/view/">
      <Description>Web page for evolving status of this GW candidate</Description>
    </Param>
    <Param dataType="string" name="Instruments" ucd="meta.code" value="H1,L1,V1">
      <Description>List of instruments used in analysis to identify this event</
↪ Description>
    </Param>
    <Param dataType="float" name="FAR" ucd="arith.rate;stat.falsealarm" unit="Hz" value=
↪ "9.11069936486e-14">
      <Description>False alarm rate for GW candidates with this strength or greater</
↪ Description>
    </Param>
    <Param dataType="string" name="Group" ucd="meta.code" value="CBC">
      <Description>Data analysis working group</Description>
    </Param>
    <Param dataType="string" name="Pipeline" ucd="meta.code" value="gstlal">
      <Description>Low-latency data analysis pipeline</Description>
    </Param>
    <Param dataType="string" name="Search" ucd="meta.code" value="MDC">
      <Description>Specific low-latency search</Description>
    </Param>

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<Group name="GW_SKYMAP" type="GW_SKYMAP">
  <Param dataType="string" name="skymap_fits" ucd="meta.ref.url" value="https://
→emfollow.docs.ligo.org/userguide/_static/bayestar.mutiorder.fits,0">
    <Description>Sky Map FITS</Description>
  </Param>
</Group>
<Group name="Classification" type="Classification">
  <Param dataType="float" name="BNS" ucd="stat.probability" value="0.95">
    <Description>Probability that the source is a binary neutron star merger (both
→objects lighter than 3 solar masses)</Description>
  </Param>
  <Param dataType="float" name="NSBH" ucd="stat.probability" value="0.01">
    <Description>Probability that the source is a neutron star-black hole merger
→(secondary lighter than 3 solar masses)</Description>
  </Param>
  <Param dataType="float" name="BBH" ucd="stat.probability" value="0.03">
    <Description>Probability that the source is a binary black hole merger (both
→objects heavier than 3 solar masses)</Description>
  </Param>
  <Param dataType="float" name="Terrestrial" ucd="stat.probability" value="0.01">
    <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), or terrestrial (noise)</Description>
</Group>
<Group name="Properties" type="Properties">
  <Param dataType="float" name="HasNS" ucd="stat.probability" value="0.95">
    <Description>Probability that at least one object in the binary has a mass that
→is less than 3 solar masses</Description>
  </Param>
  <Param dataType="float" name="HasRemnant" ucd="stat.probability" value="0.91">
    <Description>Probability that a nonzero mass was ejected outside the central
→remnant object</Description>
  </Param>
  <Param dataType="float" name="HasMassGap" ucd="stat.probability" value="0.01">
    <Description>Probability that at least one object in the binary has a mass
→between 3 and 5 solar masses</Description>
  </Param>
  <Description>Qualitative properties of the source, conditioned on the assumption
→that the signal is an astrophysical compact binary merger</Description>
</Group>
</What>
<WhereWhen>
  <ObsDataLocation>
    <ObservatoryLocation id="LIGO Virgo KAGRA"/>
    <ObservationLocation>
      <AstroCoordSystem id="UTC-FK5-GEO"/>
      <AstroCoords coord_system_id="UTC-FK5-GEO">
        <Time unit="s">
          <TimeInstant>
            <ISOTime>2018-11-01T22:22:46.654437Z</ISOTime>

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        </TimeInstant>
      </Time>
    </AstroCoords>
  </ObservationLocation>
</ObsDataLocation>
</WhereWhen>
<Description>Report of a candidate gravitational wave event</Description>
<How>
  <Description>Candidate gravitational wave event identified by low-latency analysis</
  Description>
  <Description>H1: LIGO Hanford 4 km gravitational wave detector</Description>
  <Description>L1: LIGO Livingston 4 km gravitational wave detector</Description>
  <Description>V1: Virgo 3 km gravitational wave detector</Description>
  <Description>K1: KAGRA 3 km gravitational wave detector</Description>
</How>
<Citations>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-3-Initial</EventIVORN>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-2-Preliminary</EventIVORN>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-1-EarlyWarning</EventIVORN>
  <Description>Updated localization is now available</Description>
</Citations>
</voe:VOEvent>

```

```

<?xml version='1.0' encoding='UTF-8'?>
<voe:VOEvent xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:voe="http://www.
  ivoa.net/xml/VOEvent/v2.0" xsi:schemaLocation="http://www.ivoa.net/xml/VOEvent/v2.0
  http://www.ivoa.net/xml/VOEvent/VOEvent-v2.0.xsd" version="2.0" role="test" ivorn=
  "ivo://gwnet/LVC#MS181101ab-5-Retraction">
  <Who>
    <Date>2018-11-01T23:36:23Z</Date>
    <Author>
      <contactName>LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA
      Collaboration</contactName>
    </Author>
  </Who>
  <What>
    <Param dataType="int" name="Packet_Type" value="164">
      <Description>The Notice Type number is assigned/used within GCN, eg type=164 is an
      LVC_RETRACTION notice</Description>
    </Param>
    <Param dataType="int" name="internal" value="0">
      <Description>Indicates whether this event should be distributed to LSC/Virgo/KAGRA
      members only</Description>
    </Param>
    <Param dataType="int" name="Pkt_Ser_Num" value="5">
      <Description>A number that increments by 1 each time a new revision is issued for
      this event</Description>
    </Param>
    <Param dataType="string" name="GraceID" ucd="meta.id" value="MS181101ab">
      <Description>Identifier in GraceDB</Description>
    </Param>
    <Param dataType="string" name="AlertType" ucd="meta.version" value="Retraction">

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    <Description>VOEvent alert type</Description>
  </Param>
  <Param dataType="int" name="HardwareInj" ucd="meta.number" value="0">
    <Description>Indicates that this event is a hardware injection if 1, no if 0</
  <Description>
  </Param>
  <Param dataType="int" name="OpenAlert" ucd="meta.number" value="1">
    <Description>Indicates that this event is an open alert if 1, no if 0</Description>
  </Param>
  <Param dataType="string" name="EventPage" ucd="meta.ref.url" value="https://example.
  <org/superevents/MS181101ab/view/">
    <Description>Web page for evolving status of this GW candidate</Description>
  </Param>
</What>
<WhereWhen>
  <ObsDataLocation>
    <ObservatoryLocation id="LIGO Virgo KAGRA"/>
    <ObservationLocation>
      <AstroCoordSystem id="UTC-FK5-GEO"/>
      <AstroCoords coord_system_id="UTC-FK5-GEO">
        <Time unit="s">
          <TimeInstant>
            <ISOTime>2018-11-01T22:22:46.654437Z</ISOTime>
          </TimeInstant>
        </Time>
      </AstroCoords>
    </ObservationLocation>
  </ObsDataLocation>
</WhereWhen>
<Citations>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-4-Update</EventIVORN>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-3-Initial</EventIVORN>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-2-Preliminary</EventIVORN>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-1-EarlyWarning</EventIVORN>
  <Description>Determined to not be a viable GW event candidate</Description>
</Citations>
</voe:VOEvent>

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```

<?xml version='1.0' encoding='UTF-8'?>
<voe:VOEvent xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:voe="http://www.
  <ivoa.net/xml/VOEvent/v2.0" xsi:schemaLocation="http://www.ivoa.net/xml/VOEvent/v2.0
  <http://www.ivoa.net/xml/VOEvent/VOEvent-v2.0.xsd" version="2.0" role="test" ivorn=
  <"ivo://gwnet/LVC#MS181101ab-6-Update">
  <Who>
    <Date>2018-11-01T22:39:25Z</Date>
    <Author>
      <contactName>LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA
  <Collaboration</contactName>
    </Author>
  </Who>
  <What>
    <Param dataType="int" name="Packet_Type" value="152">

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    <Description>The Notice Type number is assigned/used within GCN, eg type=152 is an LVC_UPDATE notice</Description>
  </Param>
  <Param dataType="int" name="internal" value="0">
    <Description>Indicates whether this event should be distributed to LSC/Virgo/KAGRA members only</Description>
  </Param>
  <Param dataType="int" name="Pkt_Ser_Num" value="6">
    <Description>A number that increments by 1 each time a new revision is issued for this event</Description>
  </Param>
  <Param dataType="string" name="GraceID" ucd="meta.id" value="MS181101ab">
    <Description>Identifier in GraceDB</Description>
  </Param>
  <Param dataType="string" name="AlertType" ucd="meta.version" value="Update">
    <Description>VOEvent alert type</Description>
  </Param>
  <Param dataType="int" name="HardwareInj" ucd="meta.number" value="0">
    <Description>Indicates that this event is a hardware injection if 1, no if 0</Description>
  </Param>
  <Param dataType="int" name="OpenAlert" ucd="meta.number" value="1">
    <Description>Indicates that this event is an open alert if 1, no if 0</Description>
  </Param>
  <Param dataType="string" name="EventPage" ucd="meta.ref.url" value="https://example.org/superevents/MS181101ab/view/">
    <Description>Web page for evolving status of this GW candidate</Description>
  </Param>
  <Param dataType="string" name="Instruments" ucd="meta.code" value="H1,L1,V1">
    <Description>List of instruments used in analysis to identify this event</Description>
  </Param>
  <Param dataType="float" name="FAR" ucd="arith.rate;stat.falsealarm" unit="Hz" value="9.11069936486e-14">
    <Description>False alarm rate for GW candidates with this strength or greater</Description>
  </Param>
  <Param dataType="string" name="Group" ucd="meta.code" value="CBC">
    <Description>Data analysis working group</Description>
  </Param>
  <Param dataType="string" name="Pipeline" ucd="meta.code" value="gstlal">
    <Description>Low-latency data analysis pipeline</Description>
  </Param>
  <Param dataType="string" name="Search" ucd="meta.code" value="MDC">
    <Description>Specific low-latency search</Description>
  </Param>
  <Group name="External Coincidence" type="External Coincidence">
    <Param dataType="string" name="External_GCN_Notice_Id" ucd="meta.id" value="1234567">
      <Description>GCN trigger ID of external event</Description>
    </Param>
    <Param dataType="string" name="External_Ivorn" ucd="meta.id" value="ivo://nasa.

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↪gsfc.gcn/Fermi#GBM_Gnd_Pos_2018-11-01T22:36:25.31_1234567_58-278">
  <Description>IVORN of external event</Description>
</Param>
<Param dataType="string" name="External_Observatory" ucd="meta.code" value="Fermi">
  <Description>External Observatory</Description>
</Param>
<Param dataType="string" name="External_Search" ucd="meta.code" value="GRB">
  <Description>External astrophysical search</Description>
</Param>
<Param dataType="float" name="Time_Difference" ucd="meta.code" value="1.54">
  <Description>Time difference between GW candidate and external event, centered
↪on the GW candidate</Description>
</Param>
<Param dataType="float" name="Time_Coincidence_FAR" ucd="arith.rate;stat.falsealarm
↪" unit="Hz" value="1e-16">
  <Description>Estimated coincidence false alarm rate in Hz using timing</
↪Description>
</Param>
<Param dataType="float" name="Time_Sky_Position_Coincidence_FAR" ucd="arith.rate;
↪stat.falsealarm" unit="Hz" value="1e-17">
  <Description>Estimated coincidence false alarm rate in Hz using timing and sky
↪position</Description>
</Param>
<Description>Properties of joint coincidence found by RAVEN</Description>
</Group>
<Group name="GW_SKYMAP" type="GW_SKYMAP">
  <Param dataType="string" name="skymap_fits" ucd="meta.ref.url" value="https://
↪emfollow.docs.ligo.org/userguide/_static/bayestar.multiorder.fits,0">
  <Description>Sky Map FITS</Description>
</Param>
</Group>
<Group name="Classification" type="Classification">
  <Param dataType="float" name="BNS" ucd="stat.probability" value="0.95">
  <Description>Probability that the source is a binary neutron star merger (both
↪objects lighter than 3 solar masses)</Description>
</Param>
  <Param dataType="float" name="NSBH" ucd="stat.probability" value="0.01">
  <Description>Probability that the source is a neutron star-black hole merger
↪(secondary lighter than 3 solar masses)</Description>
</Param>
  <Param dataType="float" name="BBH" ucd="stat.probability" value="0.03">
  <Description>Probability that the source is a binary black hole merger (both
↪objects heavier than 3 solar masses)</Description>
</Param>
  <Param dataType="float" name="Terrestrial" ucd="stat.probability" value="0.01">
  <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), or terrestrial (noise)</Description>
</Group>
<Group name="Properties" type="Properties">

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    <Param dataType="float" name="HasNS" ucd="stat.probability" value="0.95">
      <Description>Probability that at least one object in the binary has a mass that
↳ is less than 3 solar masses</Description>
    </Param>
    <Param dataType="float" name="HasRemnant" ucd="stat.probability" value="0.91">
      <Description>Probability that a nonzero mass was ejected outside the central
↳ remnant object</Description>
    </Param>
    <Param dataType="float" name="HasMassGap" ucd="stat.probability" value="0.01">
      <Description>Probability that at least one object in the binary has a mass
↳ between 3 and 5 solar masses</Description>
    </Param>
    <Description>Qualitative properties of the source, conditioned on the assumption
↳ that the signal is an astrophysical compact binary merger</Description>
  </Group>
</What>
<WhereWhen>
  <ObsDataLocation>
    <ObservatoryLocation id="LIGO Virgo KAGRA"/>
    <ObservationLocation>
      <AstroCoordSystem id="UTC-FK5-GEO"/>
      <AstroCoords coord_system_id="UTC-FK5-GEO">
        <Time unit="s">
          <TimeInstant>
            <ISOTime>2018-11-01T22:22:46.654437Z</ISOTime>
          </TimeInstant>
        </Time>
      </AstroCoords>
    </ObservationLocation>
  </ObsDataLocation>
</WhereWhen>
<Description>Report of a candidate gravitational wave event</Description>
<How>
  <Description>Candidate gravitational wave event identified by low-latency analysis</
↳ Description>
  <Description>H1: LIGO Hanford 4 km gravitational wave detector</Description>
  <Description>L1: LIGO Livingston 4 km gravitational wave detector</Description>
  <Description>V1: Virgo 3 km gravitational wave detector</Description>
  <Description>K1: KAGRA 3 km gravitational wave detector</Description>
</How>
<Citations>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-5-Retractio</EventIVORN>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-4-Update</EventIVORN>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-3-Initial</EventIVORN>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-2-Preliminary</EventIVORN>
  <EventIVORN cite="supersedes">ivo://gwnet/LVC#MS181101ab-1-EarlyWarning</EventIVORN>
  <Description>Updated localization is now available</Description>
</Citations>
</voe:VOEvent>

```



## SAMPLE CODE

This section provides Python sample code for receiving and interacting with *Notices*. Notices are available over several different protocols and in several different formats. LIGO/Virgo/KAGRA recommends using the VOEvent Transport Protocol (*VTP*) to receive notices in *VOEvent* XML format because it is anonymous, configuration-free, and easy to parse.

---

### Warning

The VOEvent XML alerts are official data products of LIGO/Virgo/KAGRA. GCN produces *several other legacy formats* from them, in particular a text-based “full format” and binary format. LIGO/Virgo/KAGRA performs only limited quality control of the legacy formats.

---

This tutorial will walk you through writing a Python script to receive and process the example LIGO/Virgo/KAGRA notices that are sent every hour. The tutorial is broken into the following subsections:

## 5.1 Prerequisites

In order to run this sample code, you will need Python  $\geq 3.8$  on a Unix-like operating system (Linux or macOS) and a few third-party Python packages.

### 5.1.1 Python Packages

If you want to consume notices over Kafka (recommended), you will need one of either:

- *gcn-kafka* for connecting to *GCN Kafka* to receive JSON-serialized notices over Kafka
- *hop-client* for connecting to *HOPSKOTCH* to receive Avro-serialized notices over Kafka

---

### Note

The Kafka servers hosted by *GCN Kafka* and *HOPSKOTCH* should be accessible using any Kafka client, however we will only provide directions in this guide that use *gcn-kafka* for the former and *hop-client* for the latter.

---

If you want to consume notices from *GCN Classic*, you will need:

- *PyGCN* for connecting to legacy GCN (alternatives: *comet*)
- *lxml* for parsing *VOEvent* XML packets (see also the *voevent-parse* and *VOEventLib* helper libraries, both of which are based on *lxml*)

The following libraries are needed for working with the sky maps associated with notices:

- [Healpy](#) for decoding [HEALPix](#) coordinates (alternatives: [astropy-healpix](#), the official C/C++/Fortran/Java/IDL HEALPix bindings for [HEALPix](#), [DS9](#), [Aladin](#))
- [astropy](#) for astronomical coordinate transformations, observability, etc.
- [numpy](#) and [matplotlib](#), popular math and plotting packages for Python

### 5.1.2 Installation

The fastest way to install the dependencies is with [pip](#), a package manager that comes with most Python distributions. Another option is the [Anaconda](#) Python distribution.

#### Pip

Run the following command to install [gcn-kafka](#) and the packages needed to work with sky maps:

```
$ pip install gcn-kafka healpy
```

Run the following command to install [hop-client](#) and the packages needed to work with sky maps:

```
$ pip install hop-client healpy
```

Run the following command to install [PyGCN](#), [lxml](#), and the packages needed to work with sky maps:

```
$ pip install pygcn healpy
```

#### Anaconda

To install these packages using Anaconda, first [install conda](#).

Run the following command to install [gcn-kafka](#) and the packages needed to work with sky maps:

```
$ conda install -c conda-forge gcn-kafka healpy
```

Run the following command to install [hop-client](#) and the packages needed to work with sky maps:

```
$ conda install -c conda-forge hop-client healpy
```

Run the following command to install [PyGCN](#), [lxml](#), and the packages needed to work with sky maps:

```
$ conda install -c conda-forge pygcn healpy
```

## 5.2 Receiving Notices

There are three supported methods of receiving notices. The two recommended methods both involve receiving serialized messages over Kafka; receiving VOEvents over Classic GCN is also supported. All three methods communicate the same information, and involve writing code to both listen for and parse the notices.

Events come in two very general flavors: ‘CBC’ for compact binary coalescence candidates detected by matched filtering, and ‘Burst’ for candidates detected by model-independent methods. Your code can take different actions based on this. The examples in the following sections will handle only ‘CBC’ events.



### 5.2.1 VOEvent Notices via GCN Classic

In this section, we'll write a GCN handler function, write a script to receive and parse VOEvent notices using PyGCN, and finally download and parse an example notice. You do not need to create an account or set up credentials to receive GCN classic notices.

#### Receiving and Parsing Notices

The following basic handler function will parse out the URL of the FITS file, download it, and extract the probability sky map. We `decorate` the handler with `@gcn.handlers.include_notice_types` to specify that we only want to process certain GCN notice types (LVC\_PRELIMINARY, LVC\_INITIAL, and LVC\_UPDATE).

---

#### Important

Note that mock or 'test' observations are denoted by the `role="test"` VOEvent attribute. Alerts resulting from real LIGO/Virgo/KAGRA science data will always have `role="observation"`. The sample code below will respond **only** to 'test' events. When preparing for actual observations, you **must remember to switch to 'observation' events**.

---

#### Note

Observe in the example below that we do not have to explicitly download the FITS file because the `hp.read_map()` function works with either URLs or filenames. However, you could download and save the FITS file in order to save it locally using `astropy.utils.data.download_file()`, `requests.get()`, `urllib.request.urlopen()`, or even `curl`.

---

```
import gcn
import healpy as hp
import ligo.skymap
import ligo.skymap.io

# Function to call every time a GCN is received.
# Run only for notices of type
# LVC_PRELIMINARY, LVC_INITIAL, LVC_UPDATE, or LVC_RETRACTION.
@gcn.handlers.include_notice_types(
    gcn.notice_types.LVC_PRELIMINARY,
    gcn.notice_types.LVC_INITIAL,
    gcn.notice_types.LVC_UPDATE,
    gcn.notice_types.LVC_RETRACTION)
def process_gcn(payload, root):
    # Respond only to 'test' events.
    # VERY IMPORTANT! Replace with the following code
    # to respond to only real 'observation' events.
    # if root.attrib['role'] != 'observation':
    #     return
    if root.attrib['role'] != 'test':
        return

    # Read all of the VOEvent parameters from the "What" section.
    params = {elem.attrib['name']:
               elem.attrib['value']
               for elem in root.iterfind('./Param')}
```

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```

if params['AlertType'] == 'Retraction':
    print(params['GraceID'], 'was retracted')
    return

# Respond only to 'CBC' events. Change 'CBC' to 'Burst'
# to respond to only unmodeled burst events.
if params['Group'] != 'CBC':
    return

# Print all parameters.
for key, value in params.items():
    print(key, '=', value)

if 'skymap_fits' in params:
    # Read the HEALPix sky map and the FITS header.
    skymap, header = ligo.skymap.io.read_sky_map(params['skymap_fits'])
    header = dict(header)

    # Print some values from the FITS header.
    print('Distance =', header['distmean'], '+/-', header['diststd'])

```

## Listen for GCNs

Now, we will start the VOEvent client to listen for GCNs using the `gcn.listen` function. By default, this will connect to the anonymous, public GCN server. You just need to tell `gcn.listen` what function to call whenever it receives an GCN; in this example, that is the `process_gcn` handler that we defined above.

```

# Listen for GCNs until the program is interrupted
# (killed or interrupted with control-C).
gcn.listen(handler=process_gcn)

```

When you run this script you should receive a sample LIGO/Virgo/KAGRA GCN Notice every hour. For each event received it will print output that looks like what is shown in the [Offline Testing](#) example below.

---

### Note

`gcn.listen` will try to automatically reconnect if the network connection is ever broken.

---

## Offline Testing

Sometimes it is convenient to be able to explicitly call the GCN handler with a sample input, rather than waiting for the next broadcast of a sample alert. You can download the [example GCN notices](#) from this documentation and pass it into your GCN handler at any time. First, download the sample GCN notice:

```
$ curl -O https://emfollow.docs.ligo.org/userguide/_static/MS181101ab-2-Preliminary.xml
```

Then you can manually invoke your GCN handler using this Python code:

```
import lxml.etree
payload = open('MS181101ab-2-Preliminary.xml', 'rb').read()
root = lxml.etree.fromstring(payload)
process_gcn(payload, root)
```

Upon running this, you should see:

```
Packet_Type = 150
internal = 0
Pkt_Ser_Num = 2
GraceID = MS181101ab
AlertType = Preliminary
HardwareInj = 0
OpenAlert = 1
EventPage = https://example.org/superevents/MS181101ab/view/
Instruments = H1,L1,V1
FAR = 9.11069936486e-14
Group = CBC
Pipeline = gstlal
Search = MDC
skymap_fits = https://emfollow.docs.ligo.org/userguide/_static/bayestar.multiorder.fits,0
BNS = 0.95
NSBH = 0.01
BBH = 0.03
Terrestrial = 0.01
HasNS = 0.95
HasRemnant = 0.91
HasMassGap = 0.01
Distance = 39.76999609489013 +/- 8.308435058808886
```

## 5.2.2 Kafka Notices via GCN

In this section, we'll show you how to register for a GCN account and then set up credentials to receive JSON-serialized notices over Kafka. We will then write a script to receive and parse these notices. Finally, we'll download and parse an example notice.

### Account Creation and Credential Generation

1. Sign up for an account at <https://gcn.nasa.gov/quickstart>.
2. Create new credentials by following the guide from the previous step. Select `gcn.nasa.gov/kafka-public-consumer` from the Scope down-down menu (this should already be selected by default).
3. Do not click on any of the check boxes in the Customize Alerts section.
4. Record the `client_id` and `client_secret` values in the generated code on the next section.

---

#### Note

You can retrieve your `client_id` and `client_secret` at a later time by signing in at <https://gcn.nasa.gov> and navigating to the credentials page. This page can be found in the drop-down menu underneath your sign-in name in the top menu-bar.

---

## Receiving and Parsing Notices

Once you are authenticated to receive JSON-serialized LIGO/Virgo/KAGRA notices from GCN, we can write a function to parse them.

---

### Important

Note that mock or ‘test’ observations have superevent IDs that begin with ‘M’, while real observations have superevent IDs that begin with ‘S’. Mock events also list the search that found them as ‘MDC’, however this field is not present in retraction alerts so it is best to check the first character of the superevent ID to distinguish between the two.

---

```
from base64 import b64decode
from io import BytesIO
import json
from pprint import pprint

from astropy.table import Table
import astropy_healpix as ah
from gcn_kafka import Consumer
import numpy as np

def parse_notice(record):
    record = json.loads(record)

    # Only respond to mock events. Real events have GraceDB IDs like
    # S1234567, mock events have GraceDB IDs like M1234567.
    # NOTE NOTE NOTE replace the conditional below with this commented out
    # conditional to only parse real events.
    # if record['superevent_id'][0] != 'S':
    #     return
    if record['superevent_id'][0] != 'M':
        return

    if record['alert_type'] == 'RETRACTION':
        print(record['superevent_id'], 'was retracted')
        return

    # Respond only to 'CBC' events. Change 'CBC' to 'Burst' to respond to
    # only unmodeled burst events.
    if record['event']['group'] != 'CBC':
        return

    # Parse sky map
    skymap_str = record.get('event', {}).pop('skymap')
    if skymap_str:
        # Decode, parse skymap, and print most probable sky location
        skymap_bytes = b64decode(skymap_str)
        skymap = Table.read(BytesIO(skymap_bytes))

        level, ipix = ah.uniq_to_level_ipix(
            skymap[np.argmax(skymap['PROBDENSITY'])]['UNIQ']
        )
```

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```

ra, dec = ah.healpix_to_lonlat(ipix, ah.level_to_nside(level),
                              order='nested')
print(f'Most probable sky location (RA, Dec) = ({ra.deg}, {dec.deg})')

# Print some information from FITS header
print(f'Distance = {skymap.meta["DISTMEAN"]} +/- {skymap.meta["DISTSTD"]}')

# Print remaining fields
print('Record:')
pprint(record)

```

The final step is to set up a Kafka consumer that calls our function whenever a notice is received.

```

consumer = Consumer(client_id='fill me in', client_secret='fill me in')
consumer.subscribe(['igwn.gwalert'])

while True:
    for message in consumer.consume():
        parse_notice(message.value())

```

When you run this script you should receive a sample LIGO/Virgo/KAGRA notice every hour. The output will be the same as the output in the *Offline Testing* section below.

## Offline Testing

Sample files are available to download at any time for testing responses to notices without needing to wait for the one-per-hour example.

```
$ curl -O https://emfollow.docs.ligo.org/userguide/_static/MS181101ab-preliminary.json
```

This file can be parsed as follows:

```

# Read the file and then parse it
with open('MS181101ab-preliminary.json', 'r') as f:
    record = f.read()

parse_notice(record)

```

Running this should produce the following output:

```

Most probable sky location (RA, Dec) = (194.30419921874997, -17.856895095545468)
Distance = 39.76999609489013 +/- 8.308435058808886
Record:
{'alert_type': 'PRELIMINARY',
 'event': {'classification': {'BBH': 0.03,
                             'BNS': 0.95,
                             'NSBH': 0.01,
                             'Terrestrial': 0.01},
           'far': 9.11069936486e-14,
           'group': 'CBC',
           'instruments': ['H1', 'L1', 'V1'],
           'pipeline': 'gstlal',

```

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```
'properties': {'HasMassGap': 0.01,
               'HasNS': 0.95,
               'HasRemnant': 0.91},
'search': 'MDC',
'time': '2018-11-01T22:22:46.654Z'},
'external_coinc': None,
'superevent_id': 'MS181101ab',
'time_created': '2018-11-01T22:34:49Z',
'urls': {'gracedb': 'https://example.org/superevents/MS181101ab/view/'}}
```

## Examples

Below are some sample JSON alerts that can be used for testing purposes.

- MS181101ab-earlywarning.json
- MS181101ab-preliminary.json
- MS181101ab-initial.json
- MS181101ab-update.json
- MS181101ab-retraction.json

## 5.2.3 Kafka Notices via SCiMMA

In this section, we'll show you how to register for a SCiMMA account and then set up credentials to receive Avro-serialized notices over Kafka. We will then write a script to receive and parse these notices. Finally, we'll download and parse an example notice.

### Account Creation and Credential Generation

1. Sign up for an account at <https://hop.scimma.org>. Note that if you are not affiliated with any options in the identity provider list, you can use a [GitHub](#) or Google account.
2. Create credentials at <https://my.hop.scimma.org/>. Take care to save your credential password when you do so.

---

#### Important

You will not be able to access the password for your newly created credentials again after this step. If you lose it you will need to create new credentials.

---

3. Subscribe to the `igwn.gwalert` topic. You will find the list of topics available for subscribing by clicking the "Manage" button next to the credential you created at <https://my.hop.scimma.org/>

---

#### Note

It can take up to approximately an hour for a newly added subscription to register and become usable.

---

4. Finally, add your credentials to your environment with

```
hop auth add
```

This will prompt you for your [HOPSKOTCH](#) credentials username and password.

## Receiving and Parsing Notices

Once you're authenticated to receive LIGO/Virgo/KAGRA notices, we can write a function to parse them.

### Important

Note that mock or 'test' observations have superevent IDs that begin with 'M', while real observations have superevent IDs that begin with 'S'. Mock events also list the search that found them as 'MDC', however this field is not present in retraction alerts so it is best to check the first character of the superevent ID to distinguish between the two.

```
from io import BytesIO
from pprint import pprint

from astropy.table import Table
import astropy_healpix as ah
from hop import stream
import numpy as np

def parse_notice(record):
    # Only respond to mock events. Real events have GraceDB IDs like
    # S1234567, mock events have GraceDB IDs like M1234567.
    # NOTE NOTE NOTE replace the conditional below with this commented out
    # conditional to only parse real events.
    # if record['superevent_id'][0] != 'S':
    #     return
    if record['superevent_id'][0] != 'M':
        return

    if record['alert_type'] == 'RETRACTION':
        print(record['superevent_id'], 'was retracted')
        return

    # Respond only to 'CBC' events. Change 'CBC' to 'Burst' to respond to
    # only unmodeled burst events.
    if record['event']['group'] != 'CBC':
        return

    # Parse sky map
    skymap_bytes = record.get('event', {}).pop('skymap')
    if skymap_bytes:
        # Parse skymap directly and print most probable sky location
        skymap = Table.read(BytesIO(skymap_bytes))

        level, ipix = ah.uniq_to_level_ipix(
            skymap[np.argmax(skymap['PROBDENSITY'])]['UNIQ']
        )
        ra, dec = ah.healpix_to_lonlat(ipix, ah.level_to_nside(level),
```

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```

                                order='nested')
    print(f'Most probable sky location (RA, Dec) = ({ra.deg}, {dec.deg})')

    # Print some information from FITS header
    print(f'Distance = {skymap.meta["DISTMEAN"]} +/- {skymap.meta["DISTSTD"]}')

    # Print remaining fields
    print('Record:')
    pprint(record)

```

The final step is to set up a Kafka consumer that calls our function whenever a notice is received.

```

with stream.open('kafka://kafka.scimma.org/igwn.gwalert', 'r') as s:
    for message in s:
        parse_notice(message.content[0])

```

When you run this script you should receive a sample LIGO/Virgo/KAGRA notice every hour. The output will be the same as the output in the *Offline Testing* section below.

## Offline Testing

Sample files are available to download at any time for testing responses to notices without needing to wait for the one-per-hour example.

```
$ curl -O https://emfollow.docs.ligo.org/userguide/_static/MS181101ab-preliminary.avro
```

Now you can parse the Avro packet using the code we wrote above.

```

import fastavro

# Read the file in bytes mode and then parse it
with open('MS181101ab-preliminary.avro', 'rb') as fo:
    reader = fastavro.reader(fo)
    # LIGO/Virgo/KAGRA notices will only ever contain one record
    record = next(reader)

parse_notice(record)

```

Running this should produce the following output:

```

Most probable sky location (RA, Dec) = (194.30419921874997, -17.856895095545468)
Distance = 39.76999609489013 +/- 8.308435058808886
Record:
{'alert_type': 'PRELIMINARY',
 'event': {'classification': {'BBH': 0.03,
                             'BNS': 0.95,
                             'NSBH': 0.01,
                             'Terrestrial': 0.01},
           'far': 9.11069936486e-14,
           'group': 'CBC',
           'instruments': ['H1', 'L1', 'V1'],
           'pipeline': 'gstlal',

```

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```

    'properties': {'HasMassGap': 0.01,
                  'HasNS': 0.95,
                  'HasRemnant': 0.91},
    'search': 'MDC',
    'time': '2018-11-01T22:22:46.654Z'},
'external_coinc': None,
'superevent_id': 'MS181101ab',
'time_created': '2018-11-01T22:34:49Z',
'urls': {'gracedb': 'https://example.org/superevents/MS181101ab/view/'}}

```

## Examples

Below are some sample Avro alerts that can be used for testing purposes.

- MS181101ab-earlywarning.avro
- MS181101ab-preliminary.avro
- MS181101ab-initial.avro
- MS181101ab-update.avro
- MS181101ab-retraction.avro

## 5.3 Working with Multi-Order Sky Maps

For all events, LIGO/Virgo/KAGRA distributes both the standard *HEALPix* format with the file extension `.fits.gz`, as well as the new multi-resolution HEALPix format, distinguished by the file extension `.multiorder.fits`. The multi-resolution HEALPix format is the primary and preferred format, and the only format that is explicitly listed in the GCN Notices and Circulars.

### 5.3.1 What Problem Do Multi-Resolution Sky Maps Solve?

The multi-resolution format has been introduced as a forward-looking solution to deal with computational challenges related to highly accurate localizations. We are getting better at pinpointing gravitational-wave sources as more detectors come online and existing detectors become more sensitive. Unfortunately, as position accuracy improves, the size of the standard HEALPix sky maps will blow up. This started being a minor inconvenience in O2 with GW170817. It will get slowly worse as we approach design sensitivity. It's already a major pain if you are studying future detector networks with simulations.

It is worth reviewing why LIGO/Virgo/KAGRA has adopted HEALPix rather than a more commonplace image format for sky maps in the first place. Gravitational-wave localizations are distinguished from many other kinds of astronomical image data by the following features:

- The probability regions can subtend large angles.
- They can wrap around the whole sky.
- They can have multiple widely separated modes.
- They can have irregular shapes or interference-like fringes.

As a consequence of these features, it is difficult to pick a good partial-sky projection (e.g. gnomonic, orthographic) in the general case. Traditional all-sky projections have wild variations in pixel size (e.g. plate carée) or shape (e.g.

Mollweide, Aitoff) and as well as seams at the projection boundaries. HEALPix was already well-established for specialized uses in astronomy that cannot tolerate such projection artifacts (e.g. cosmic microwave background data sets and full-sky mosaics from optical surveys).

The natural sky resolution varies from one gravitational-wave event to another depending on its *SNR* and the number of detectors. During early Advanced LIGO and Virgo, HEALPix resolutions of  $n_{\text{side}}=512$  (6.9' per pixel) to  $n_{\text{side}}=2048$  (1.7'' per pixel) were adequate. However, as existing gravitational-wave detectors improve in sensitivity and additional detectors come online, finer resolutions will be required.

Fortunately, the increased resolution will come at little to no computational cost for actually producing localizations because most LIGO/Virgo/KAGRA parameter estimation analyses use a simple multi-resolution adaptive mesh refinement scheme that limits them to sampling the sky at only about 20k points.

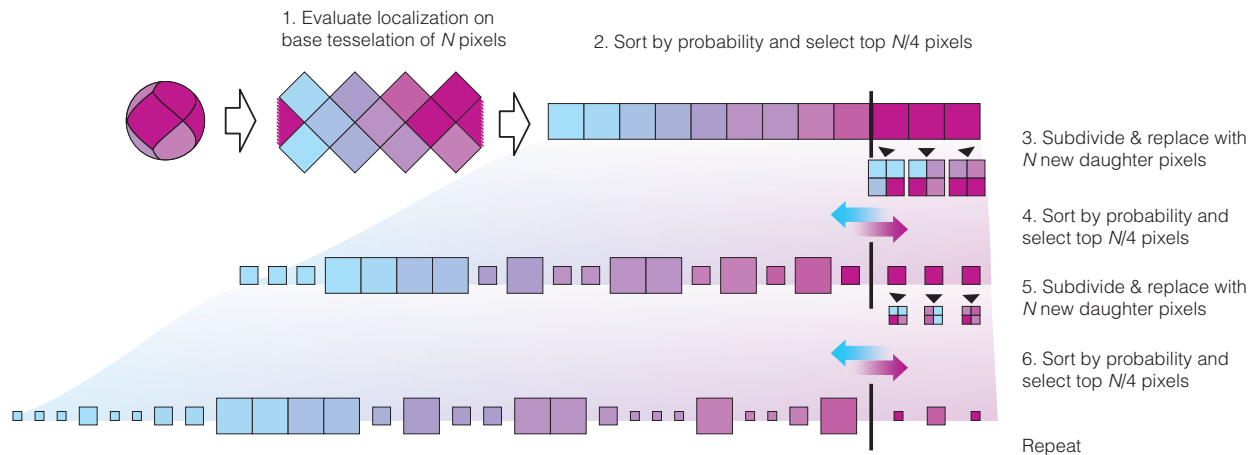


Fig. 1: An illustration of the adaptive mesh refinement scheme, reproduced from [Page 62, 1](#).

When these multi-resolution meshes are flattened to a single HEALPix resolution, all but the finest nodes in the mesh become long sequences of repeated pixel values. High resolution also does not cost much in terms of disk space because gzip compression can store the long runs of repeated pixel values efficiently. The diagram below illustrates a multi-resolution structure that is fairly typical of gravitational-wave localizations from O1 and O2.

However, the resolution does come at a significant cost in the time it takes to decompress and read the FITS files (already up to tens of seconds for GW170817) and in terms of memory (up to several gigabytes). The time and memory will worsen as localization accuracy improves.

The multi-resolution format is immune to these issues because it is a direct representation of the adaptive mesh produced by the LIGO/Virgo/KAGRA localization algorithms.

### 5.3.2 The UNIQ Indexing Scheme

Recall from before that three pieces of information are required to specify a HEALPix tile: *nside* to specify the resolution, *ipix* to identify a sky position at that resolution, and the indexing scheme.

HEALPix has a couple different indexing schemes. In the **RING** scheme, indices advance west to east and then north to south. In the **NESTED** scheme, indices encode the hierarchy of parent pixels in successively lower resolutions. The image below illustrates these two indexing schemes.

There is a third HEALPix indexing scheme called **UNIQ**. The **UNIQ** indexing scheme is special because it encodes both the resolution *and* the sky position in a single integer. It assigns a single unique integer to every HEALPix tile at

<sup>1</sup> Singer, L. P., & Price, L. R. 2016, *Phys. Rev. D*, 93, 024013. doi:10.1103/PhysRevD.93.024013

<sup>2</sup> Górski, K. M., Wandelt, B. D., et al. 1999. arXiv:astro-ph/9905275

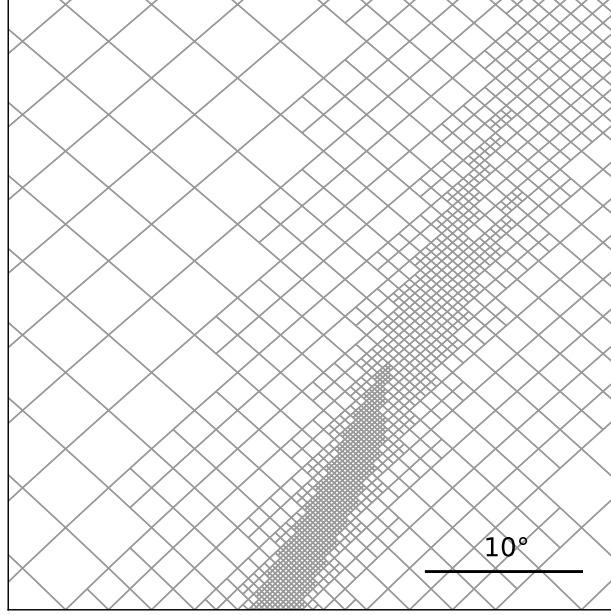


Fig. 2: An example multi-resolution mesh from a typical two-detector (*LHO* and *LLO*) localization produced with BAYESTAR. Reproduced from<sup>1</sup>. The scale bar at bottom right has a length of  $10^\circ$ .

every resolution. If *ipix* is the pixel index in the NESTED ordering, then the unique pixel index *uniq* is:

$$uniq = ipix + 4 \, nside^2.$$

The inverse is:

$$nside = 2^{\lfloor \log_2(uniq/4)/2 \rfloor}$$

$$ipix = uniq - 4 \, nside^2.$$

### 5.3.3 FITS Format for Multi-Order Sky Maps

The FITS format for LIGO/Virgo/KAGRA multi-resolution sky maps uses the **UNIQ** indexing scheme and is a superset of the FITS serialization for Multi-Order Coverage (MOC) maps specified by IVOA<sup>4</sup> as part of the Hierarchical Progressive Survey (HiPS) capability<sup>3</sup>, notably used by Aladin for storing and display all-sky image mosaics.

Let's download an example multi-order FITS file with curl:

```
$ curl -O https://emfollow.docs.ligo.org/userguide/_static/bayestar.multiorder.fits
```

Let's look at the FITS header:

```
$ fitsheader bayestar.multiorder.fits
# HDU 0 in bayestar.multiorder.fits:
SIMPLE = T / conforms to FITS standard
BITPIX = 8 / array data type
NAXIS = 0 / number of array dimensions
EXTEND = T
```

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<sup>4</sup> Fernique, P., Boch, T., et al. 2014, IVOA Recommendation. [arXiv:1505.02937](https://arxiv.org/abs/1505.02937)

<sup>3</sup> Fernique, P., Allen, et al. 2015, *Astron. Astrophys.*, 578, A114. [doi:10.1051/0004-6361/201526075](https://doi.org/10.1051/0004-6361/201526075)

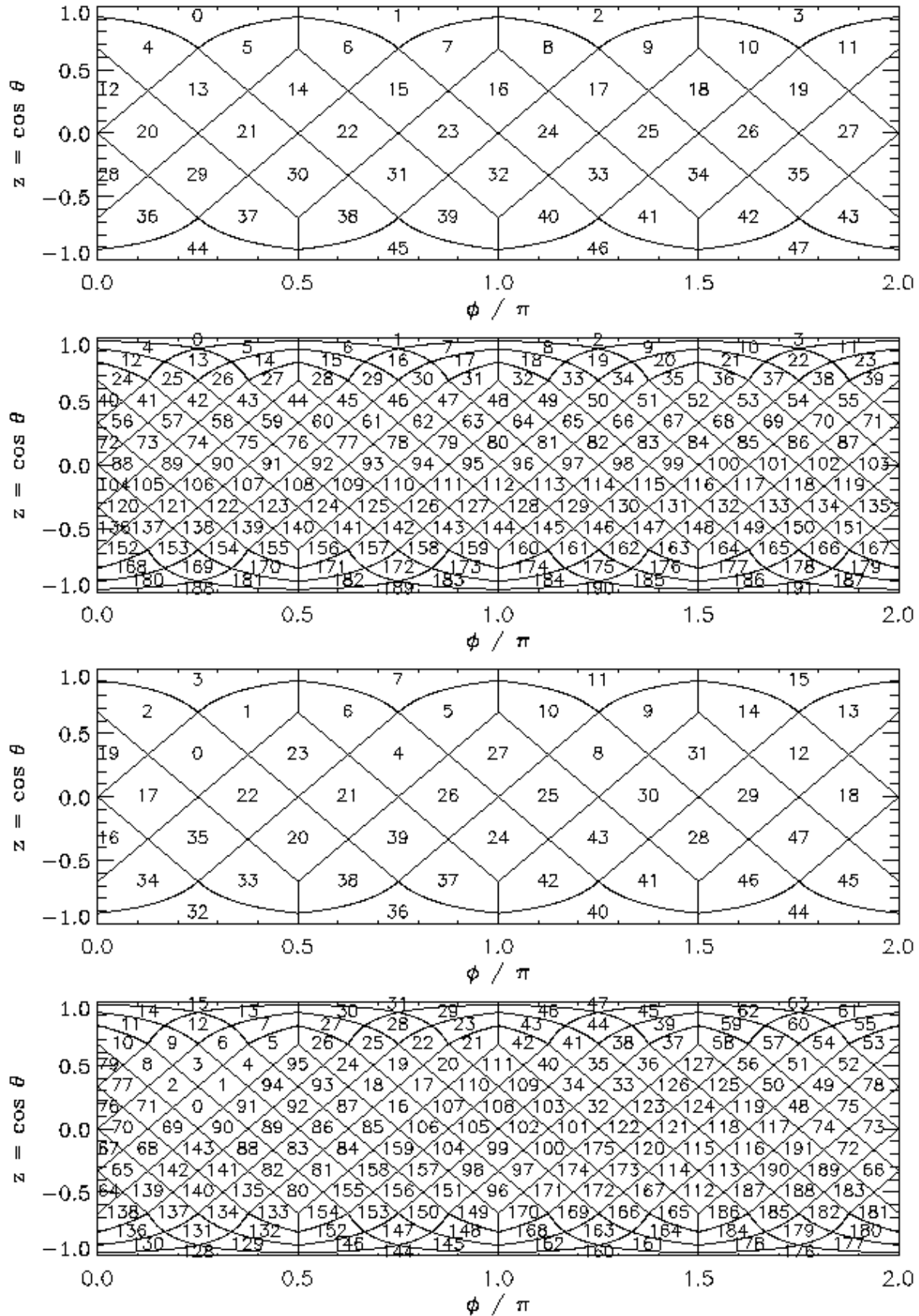


Fig. 3: The **RING** and **NESTED** indexing schemes of HEALPix. Reproduced from The image below, reproduced from<sup>2</sup>.

(continued from previous page)

```

# HDU 1 in bayestar.multiorder.fits:
XTENSION= 'BINTABLE'           / binary table extension
BITPIX   =                      8 / array data type
NAXIS    =                      2 / number of array dimensions
NAXIS1   =                     40 / length of dimension 1
NAXIS2   =                   19200 / length of dimension 2
PCOUNT   =                      0 / number of group parameters
GCOUNT   =                      1 / number of groups
TFIELDS  =                      5 / number of table fields
TTYPE1   = 'UNIQ'              '
TFORM1   = 'K'                  '
TTYPE2   = 'PROBDENSITY'       '
TFORM2   = 'D'                  '
TUNIT2   = 'sr-1'               '
TTYPE3   = 'DISTMU'            '
TFORM3   = 'D'                  '
TUNIT3   = 'Mpc'                '
TTYPE4   = 'DISTSIGMA'         '
TFORM4   = 'D'                  '
TUNIT4   = 'Mpc'                '
TTYPE5   = 'DISTNORM'          '
TFORM5   = 'D'                  '
TUNIT5   = 'Mpc-2'             '
PIXTYPE  = 'HEALPIX'           / HEALPIX pixelisation
ORDERING= 'NUNIQ'              / Pixel ordering scheme: RING, NESTED, or NUNIQ
COORDSYS= 'C'                  / Eclicptic, Galactic or Celestial (equatorial)
MOCORDER=                     11 / MOC resolution (best order)
INDXSCHM= 'EXPLICIT'           / Indexing: IMPLICIT or EXPLICIT
OBJECT   = 'MS181101ab'        / Unique identifier for this event
REFERENC= 'https://example.org/superevents/MS181101ab/view/' / URL of this event
INSTRUME= 'H1,L1,V1'           / Instruments that triggered this event
DATE-OBS= '2018-11-01T22:22:46.654437' / UTC date of the observation
MJD-OBS  = 58423.93248442635 / modified Julian date of the observation
DATE     = '2018-11-01T22:34:49.000000' / UTC date of file creation
CREATOR  = 'BAYESTAR'          / Program that created this file
ORIGIN   = 'LIGO/Virgo/KAGRA'  / Organization responsible for this FITS file
RUNTIME  = 3.24746292643249 / Runtime in seconds of the CREATOR program
DISTMEAN= 39.76999609489013 / Posterior mean distance (Mpc)
DISTSTD  = 8.308435058808886 / Posterior standard deviation of distance (Mpc)
LOGBCI   = 13.64819688928804 / Log Bayes factor: coherent vs. incoherent
LOGBSN   = 261.0250944470225 / Log Bayes factor: signal vs. noise
VCSVERS  = 'ligo.skymap 0.1.8' / Software version
VCSREV   = 'becb07110491d799b753858845b5c24c82705404' / Software revision (Git)
DATE-BLD= '2019-07-25T22:36:58' / Software build date
HISTORY
HISTORY Generated by calling the following Python function:
HISTORY ligo.skymap.bayestar.localize(event=..., waveform='o2-uberbank', f_low=3
HISTORY 0, min_inclination=0.0, max_inclination=1.5707963267948966, min_distance
HISTORY =None, max_distance=None, prior_distance_power=2, cosmology=False, mcmc=
HISTORY False, chain_dump=None, enable_snr_series=True, f_high_truncate=0.95)
HISTORY

```

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```
HISTORY This was the command line that started the program:
HISTORY bayestar-localize-lvalert -N G298107 -o bayestar.muliorder.fits
```

This should look very similar to the FITS header for the standard HEALPix file from the [previous section](#). The key differences are:

1. The ORDERING key has changed from NESTED to NUNIQ.
2. The INDXSCHM key has changed from IMPLICIT to EXPLICIT.
3. There is an extra column, UNIQ, that explicitly identifies each pixel in the **UNIQ** indexing scheme.
4. The PROB column has been renamed to PROBDENSITY, and the units have change from probability to probability per steradian.

### 5.3.4 Reading Multi-Resolution Sky Maps

Now let's go through some of the same common HEALPix operations from the previous section, but using the multi-resolution format. Instead of Healpy, we will use `astropy-healpix` because it has basic support for the **UNIQ** indexing scheme.

First, we need the following imports:

```
>>> from astropy.table import Table
>>> from astropy import units as u
>>> import astropy_healpix as ah
>>> import numpy as np
```

Next, let's read the sky map. Instead of a special-purpose HEALPix method, we just read the FITS file into an `Astropy` table using `Astropy's unified file read/write interface`:

```
>>> skymap = Table.read('bayestar.muliorder.fits')
```

### 5.3.5 Most Probable Sky Location

Next, let's find the highest probability density sky position. This is a three-step process.

1. Find the **UNIQ** pixel index of the highest probability density tile:

```
>>> i = np.argmax(skymap['PROBDENSITY'])
>>> uniq = skymap[i]['UNIQ']
```

What is the probability density per square degree in that tile?

```
>>> skymap[i]['PROBDENSITY'] * (np.pi / 180)**2
0.0782516470191411
```

2. Unpack the **UNIQ** pixel index into the resolution, `nside`, and the **NESTED** pixel index, `ipix`, using the method `astropy_healpix.uniq_to_level_ipix()`. (Note that this method returns `level`, which is the logarithm base 2 of `nside`, so we must also convert from `level` to `nside` using `astropy_healpix.level_to_nside()`.)

```
>>> level, ipix = ah.uniq_to_level_ipix(uniq)
>>> nside = ah.level_to_nside(level)
```

3. Convert from `nside` and `ipix` to right ascension and declination using `astropy_healpix.healpix_to_lonlat()` (which is equivalent to `hp.pix2ang`):

```
>>> ra, dec = ah.healpix_to_lonlat(ipix, nside, order='nested')
>>> ra.deg
194.30419921874997
>>> dec.deg
-17.856895095545468
```

### 5.3.6 Probability Density at a Known Position

Now let's look up the probability density at a known sky position. In this case, let's use the position of `NGC 4993`:

```
>>> ra = 197.4133 * u.deg
>>> dec = -23.3996 * u.deg
```

#### Brute Force Linear Search

The following brute force method of looking up a pixel by sky position has a complexity of  $O(N)$ , where  $N$  is the number of multi-resolution pixels.

1. Unpack the **UNIQ** pixel indices into their resolution and their **NESTED** pixel index.

```
>>> level, ipix = ah.uniq_to_level_ipix(skymap['UNIQ'])
>>> nside = ah.level_to_nside(level)
```

2. Determine the **NESTED** pixel index of the target sky position at the resolution of each multi-resolution tile.

```
>>> match_ipix = ah.lonlat_to_healpix(ra, dec, nside, order='nested')
```

3. Find the multi-resolution tile whose **NESTED** pixel index equals the target pixel index.

```
>>> i = np.flatnonzero(ipix == match_ipix)[0]
>>> i
13484
```

That pixel contains the target sky position.

```
>>> skymap[i]['PROBDENSITY'] * (np.pi / 180)**2
0.03467919098907807
```

#### Fast Binary Search

The following binary search method of looking up a pixel by sky position exploits the algebraic properties of HEALPix. It has a complexity of  $O(\log N)$  where  $N$  is the number of multi-resolution pixels. It assumes that every sky position is mapped on to exactly one multi-resolution tile, which is true for LIGO/Virgo/KAGRA multi-resolution sky maps.

1. First, find the **NESTED** pixel index of every multi-resolution tile, at an arbitrarily high resolution. (`nside = 2**29` works nicely because it is the highest possible HEALPix resolution that can be represented in a 64-bit signed integer.)



```
>>> max_level = 29
>>> max_nside = ah.level_to_nside(max_level)
>>> level, ipix = ah.uniq_to_level_ipix(skymap['UNIQ'])
>>> index = ipix * (2**(max_level - level))**2
```

Sort the pixels by this value.

```
>>> sorter = np.argsort(index)
```

2. Determine the **NESTED** pixel index of the target sky location at that resolution.

```
>>> match_ipix = ah.lonlat_to_healpix(ra, dec, max_nside, order='nested')
```

Do a binary search for that value.

```
>>> i = sorter[np.searchsorted(index, match_ipix, side='right', sorter=sorter) - 1]
>>> i
13484
```

That pixel contains the target sky position.

```
>>> skymap[i]['PROBDENSITY'] * (np.pi / 180)**2
0.03467919098907807
```

## 5.4 Working with Flat Resolution Sky Maps

For all events, LIGO/Virgo/KAGRA also distribute the standard *HEALPix* format with the file extension `.fits.gz`, that was the default format during the **O3** run. They are FITS image files and can be manipulated and viewed with many commonplace FITS tools. However, they are a little unusual in two regards. First, since they are all-sky images, they are stored in the *HEALPix*<sup>1</sup> projection, a format that is used for *Planck* all-sky CMB maps and by Aladin for hierarchical, progressively refined, all-sky survey images (*HiPS*). Second, the value stored at each pixel is the probability that the gravitational-wave source is within that pixel.

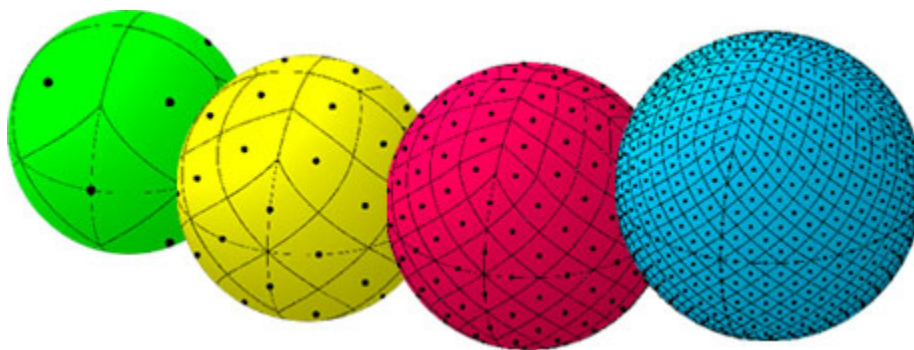


Fig. 4: An illustration of the first four HEALPix tessellations (`nside=1`, `nside=2`, `nside=4`, and `nside=8`). Reproduced from <https://healpix.jpl.nasa.gov>.

Let's download an example FITS file with `curl`:

<sup>1</sup> Górski, K.M., Hivon, E., Banday, A.J., et al. 2005, *Astrophys. J.*, 622, 759. doi:10.1086/427976



```
$ curl -O https://emfollow.docs.ligo.org/userguide/_static/bayestar.fits.gz,0
```

We can look at the metadata inside the FITS file by printing its header with tools like `funhead` from `Funtools`, `imhead` from `WCSTools`, or `fitsheader` from `Astropy`:

```
$ fitsheader bayestar.fits.gz,0
# HDU 0 in bayestar.fits.gz,0:
SIMPLE  =                               T / conforms to FITS standard
BITPIX  =                               8 / array data type
NAXIS   =                               0 / number of array dimensions
EXTEND  =                               T

# HDU 1 in bayestar.fits.gz,0:
XTENSION= 'BINTABLE'                    / binary table extension
BITPIX  =                               8 / array data type
NAXIS   =                               2 / number of array dimensions
NAXIS1  =                               32 / length of dimension 1
NAXIS2  =          50331648 / length of dimension 2
PCOUNT  =                               0 / number of group parameters
GCOUNT  =                               1 / number of groups
TFIELDS =                               4 / number of table fields
TTYPE1  = 'PROB'                        '
TFORM1  = 'D'                          '
TUNIT1  = 'pix-1'                       '
TTYPE2  = 'DISTMU'                      '
TFORM2  = 'D'                          '
TUNIT2  = 'Mpc'                         '
TTYPE3  = 'DISTSIGMA'                  '
TFORM3  = 'D'                          '
TUNIT3  = 'Mpc'                         '
TTYPE4  = 'DISTNORM'                   '
TFORM4  = 'D'                          '
TUNIT4  = 'Mpc-2'                      '
PIXTYPE = 'HEALPIX'                    / HEALPIX pixelisation
ORDERING= 'NESTED'                     / Pixel ordering scheme: RING, NESTED, or NUNIQ
COORDSYS= 'C'                          / Ecliptic, Galactic or Celestial (equatorial)
NSIDE   =          2048 / Resolution parameter of HEALPIX
INDXSCHM= 'IMPLICIT'                   / Indexing: IMPLICIT or EXPLICIT
OBJECT  = 'MS181101ab'                  / Unique identifier for this event
REFERENC= 'https://example.org/superevents/MS181101ab/view/' / URL of this event
INSTRUME= 'H1,L1,V1'                   / Instruments that triggered this event
DATE-OBS= '2018-11-01T22:22:46.654437' / UTC date of the observation
MJD-OBS  =    58423.93248442613 / modified Julian date of the observation
DATE     = '2018-11-01T22:34:49.000000' / UTC date of file creation
CREATOR  = 'BAYESTAR'                   / Program that created this file
ORIGIN   = 'LIGO/Virgo/KAGRA'           / Organization responsible for this FITS file
RUNTIME  =    3.24746292643249 / Runtime in seconds of the CREATOR program
DISTMEAN=    39.76999609489013 / Posterior mean distance (Mpc)
DISTSTD  =    8.308435058808886 / Posterior standard deviation of distance (Mpc)
LOGBCI   =    13.64819688928804 / Log Bayes factor: coherent vs. incoherent
LOGBSN   =    261.0250944470225 / Log Bayes factor: signal vs. noise
VCSVERS  = 'ligo.skymap 0.1.8' / Software version
VCSREV   = 'becb07110491d799b753858845b5c24c82705404' / Software revision (Git)
```

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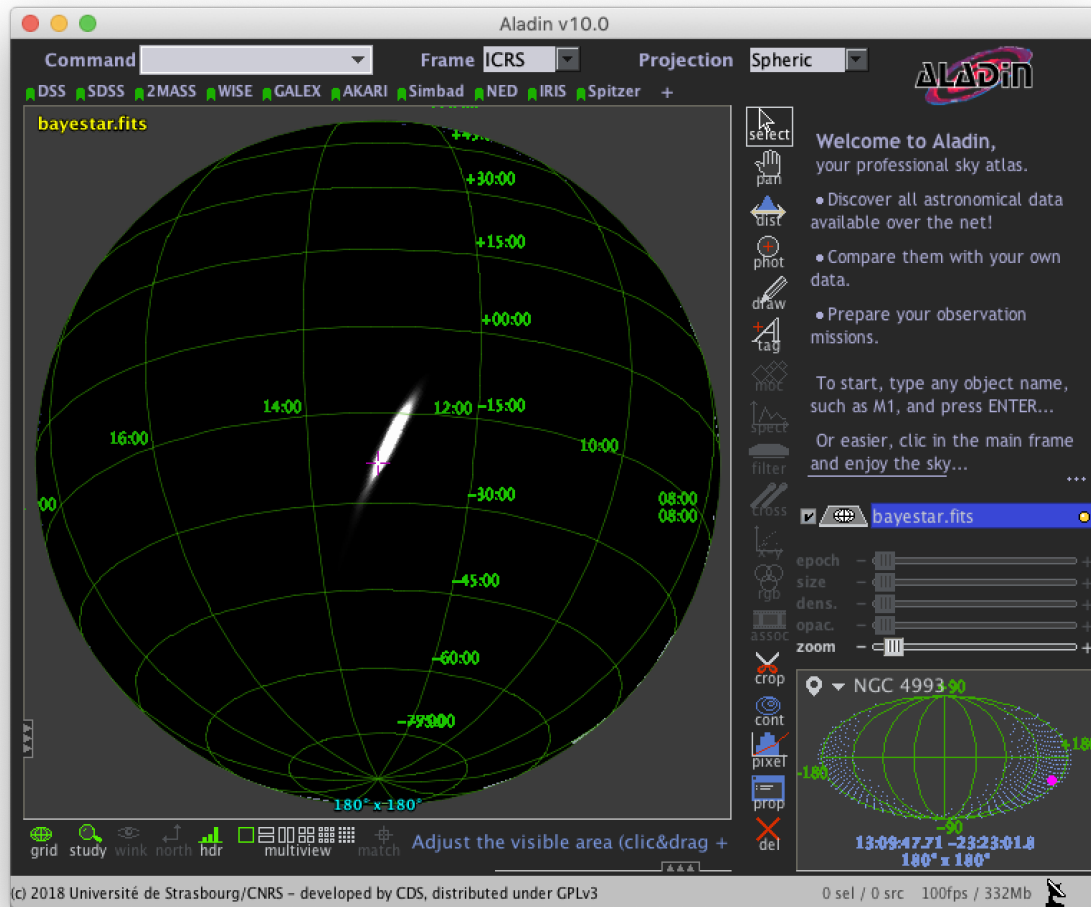
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```
DATE-BLD= '2019-07-25T22:36:58' / Software build date
HISTORY
HISTORY Generated by calling the following Python function:
HISTORY ligo.skymap.bayestar.localize(event=..., waveform='o2-uberbank', f_low=3
HISTORY 0, min_inclination=0.0, max_inclination=1.5707963267948966, min_distance
HISTORY =None, max_distance=None, prior_distance_power=2, cosmology=False, mcmc=
HISTORY False, chain_dump=None, enable_snr_series=True, f_high_truncate=0.95)
HISTORY
HISTORY This was the command line that started the program:
HISTORY bayestar-localize-lvalert -N G298107 -o bayestar.multiorder.fits
```

There are several useful pieces of information here:

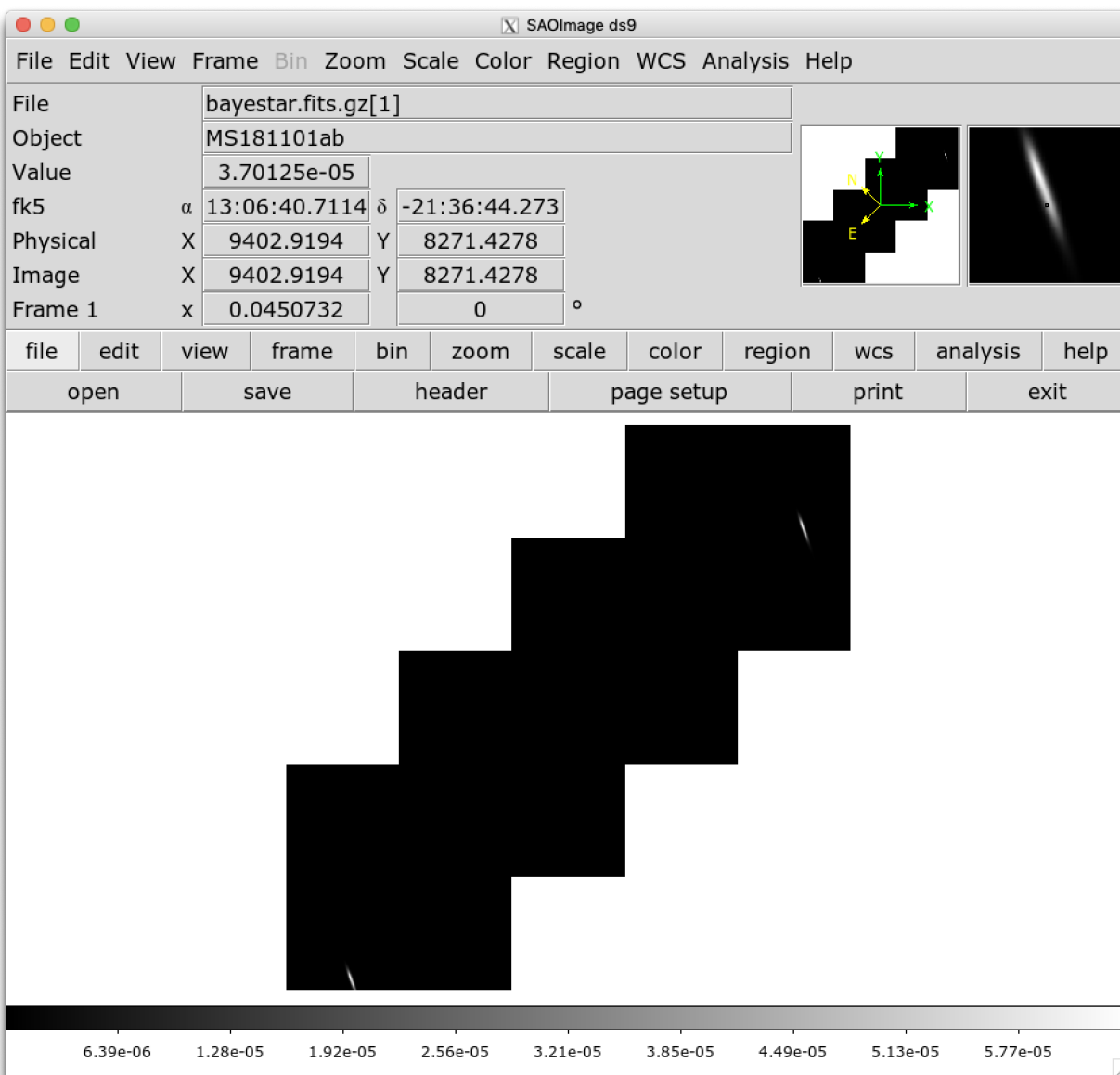
- COORDSYS=C, telling you that the [HEALPix](#) projection is in the Celestial (equatorial, ICRS) frame, as all LIGO/Virgo/KAGRA probability sky maps will be.
- OBJECT, the unique LIGO/Virgo/KAGRA identifier for the event.
- REFERENC, a link to the candidate page in [GraceDB](#).
- INSTRUME, a list of gravitational-wave sites that triggered on the event: *HI* for LIGO Hanford, *LI* for LIGO Livingston, *VI* for Virgo, and *KI* for KAGRA.
- DATE-OBS, the UTC time of the event. In the case of a compact binary coalescence candidate, this is the time that the signal from the merger passed through the geocenter.
- MJD-OBS, same as *DATE-OBS*, but given as a modified Julian day.

You can view the sky map in many common FITS image viewers such as [Aladin](#):



or [DS9](#) (although DS9 shows HEALPix sky maps in an unusual orientation; see Figure 4 of<sup>2</sup> for more information).

<sup>2</sup> Calabretta, M. R., & Roukema, B. F. 2007, *Mon. Notices Royal Astron. Soc.*, 381, 865. doi:10.1111/j.1365-2966.2007.12297.x



Now, let's go through some examples of manipulating HEALPix sky maps programmatically. The [HEALPix](#) project provides official libraries for many languages, including C, C++, Fortran, IDL, and Java. However, since this is a Python tutorial, we are going to demonstrate how to manipulate HEALPix maps with the official Python library, [Healpy](#).

### 5.4.1 Reading Sky Maps

First, if you have not already downloaded an example sky map, you can do so now by having Python call *curl* on the command line:

```
$ curl -O https://emfollow.docs.ligo.org/userguide/_static/bayestar.fits.gz,0
```

Next, we need to read in the file in Python with Healpy:

```
>>> import healpy as hp
>>> import numpy as np
```

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```
>>> hpx = hp.read_map('bayestar.fits.gz', 0')
```

You can read both the HEALPix image data and the FITS header by passing the `h=True` keyword argument:

```
>>> hpx, header = hp.read_map('bayestar.fits.gz', h=True)
```

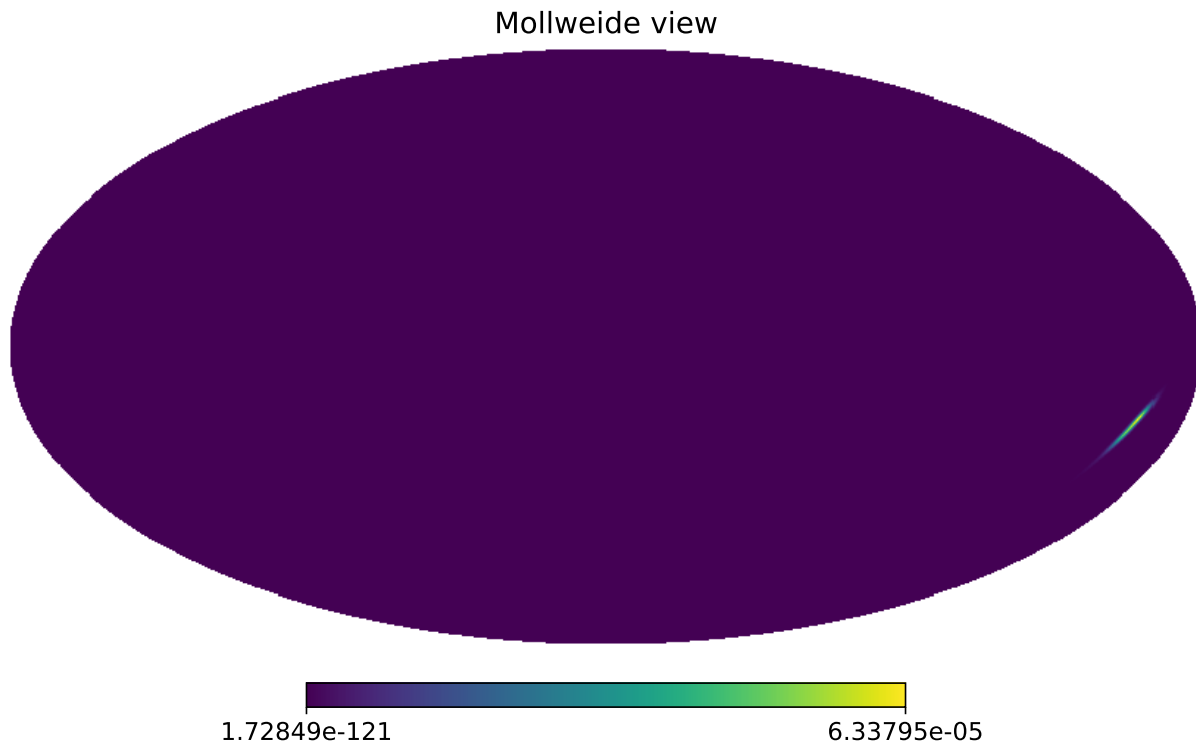
## 5.4.2 Manipulating HEALPix Coordinates

The image data is a 1D array of values:

```
>>> hpx
array([2.70726059e-66, 1.27374324e-66, 2.62611513e-67, ...,
       2.04700874e-40, 1.05781210e-35, 4.44174764e-31])
```

Healpy has several useful plotting routines including `hp.mollview` for plotting a Mollweide-projection all-sky map:

```
>>> hp.mollview(hpx)
```



Each entry in the array represents the probability contained within a quadrilateral pixel whose position on the sky is uniquely specified by the index in the array and the array's length. Because HEALPix pixels are equal area, we can find the number of pixels per square degree just from the length of the HEALPix array:

```
>>> npix = len(hpx)
>>> sky_area = 4 * 180**2 / np.pi
>>> sky_area / npix
0.0008196227004015301
```

The function `hp.pix2ang` converts from pixel index to spherical polar coordinates; the function `hp.ang2pix` does the reverse.

Both `hp.pix2ang` and `hp.ang2pix` take, as their first argument, `nside`, the lateral resolution of the HEALPix map. You can find `nside` from the length of the image array by calling `hp.npix2nside`:

```
>>> nside = hp.npix2nside(npix)
>>> nside
2048
```

Let's look up the right ascension and declination of pixel number 123. We'll call `hp.pix2ang` to get the spherical polar coordinates ( $\theta, \phi$ ) in radians, and then use `np.rad2deg` to convert these to right ascension and declination in degrees.

```
>>> ipix = 123
>>> theta, phi = hp.pix2ang(nside, ipix)
>>> ra = np.rad2deg(phi)
>>> dec = np.rad2deg(0.5 * np.pi - theta)
>>> ra, dec
(129.375, 89.81725848475484)
```

Let's find which pixel contains the point RA=194.95, Dec=27.98.

```
>>> ra = 194.95
>>> dec = 27.98
>>> theta = 0.5 * np.pi - np.deg2rad(dec)
>>> phi = np.deg2rad(ra)
>>> ipix = hp.ang2pix(nside, theta, phi)
>>> ipix
13361492
```

### 5.4.3 Test if a Sky Location is in the 90% Credible Region

You can easily test if a given sky position is in the 90% credible region. Let's continue using the sky position from the previous example, for which we have already determined the pixel index.

Use the following simple algorithm to construct a map that gives the *credible level of each pixel*:

1. Sort the pixels by descending probability density.
2. Cumulatively sum the pixels' probability.
3. Return the pixels to their original order.

In Python, you can use this simple recipe:

```
>>> i = np.flipud(np.argsort(hpx))
>>> sorted_credible_levels = np.cumsum(hpx[i])
>>> credible_levels = np.empty_like(sorted_credible_levels)
>>> credible_levels[i] = sorted_credible_levels
>>> credible_levels
array([1., 1., 1., ..., 1., 1., 1.]
```

---

#### Note

Observe that the values in the resulting *credible level map* vary inversely with probability density: the most probable pixel is assigned to the credible level 0.0, and the least likely pixel is assigned the credible level 1.0.

### Tip

This recipe is implemented in the package `ligo.skymap` as the function `find_greedy_credible_levels()`:

```
>>> from ligo.skymap.postprocess import find_greedy_credible_levels
>>> credible_levels = find_greedy_credible_levels(hpx)
>>> credible_levels
array([1., 1., 1., ..., 1., 1., 1.]
```

To check if the pixel that we identified in the previous section is within the 90% credible level, simply test if the value of the credible level map is less than or equal to 0.9 at that pixel:

```
>>> credible_levels[ipix]
0.99999999999947833
>>> credible_levels[ipix] <= 0.9
False
```

The credible level map has a value greater than 0.9 at that sky location, therefore the sky location is outside the 90% credible region.

## 5.4.4 Find the Area of the 90% Credible Region

Since we just found the credible level map, it's easy to compute the 90% credible area by counting the number of pixels inside the 90% credible region and multiplying by the area per pixel.

In the Python expression below, note that `(credible_levels <= 0.9)` evaluates to a binary array; when it is summed over, true values are treated as 1 and false values are treated as 0.

```
>>> np.sum(credible_levels <= 0.9) * hp.nside2pixarea(nside, degrees=True)
30.979279207076633
```

## 5.4.5 Most Probable Sky Location

Let's find the highest probability pixel.

```
>>> ipix_max = np.argmax(hpx)
```

What is the probability density per square degree at that position?

```
>>> hpx[ipix_max] / hp.nside2pixarea(nside, degrees=True)
0.0782516470191411
```

Where is the highest probability pixel on the sky? Use `hp.pix2ang`.

```
>>> theta, phi = hp.pix2ang(nside, ipix_max)
>>> ra = np.rad2deg(phi)
>>> dec = np.rad2deg(0.5 * np.pi - theta)
```

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```
>>> ra, dec
(194.30419921875, -17.856895095545475)
```

## 5.4.6 Integrated Probability in a Circle

How do we find the probability that the source is contained within a circle on the sky? First we find the pixels that are contained within the circle using `hp.query_disc`. Note that this function takes as its arguments the Cartesian coordinates of the center of the circle, and its radius in radians. Then, we sum the values of the HEALPix image array contained at those pixels.

First, we define the RA, Dec, and radius of circle in degrees:

```
>>> ra = 213.22
>>> dec = -37.45
>>> radius = 3.1
```

Then we convert to spherical polar coordinates and radius of circle in radians:

```
>>> theta = 0.5 * np.pi - np.deg2rad(dec)
>>> phi = np.deg2rad(ra)
>>> radius = np.deg2rad(radius)
```

Then we calculate the Cartesian coordinates of the center of circle:

```
>>> xyz = hp.ang2vec(theta, phi)
```

We call `hp.query_disc`, which returns an array of the indices of the pixels that are inside the circle:

```
>>> ipix_disc = hp.query_disc(nside, xyz, radius)
```

Finally, we sum the probability in all of the matching pixels:

```
>>> hpx[ipix_disc].sum()
3.655661941088471e-10
```

## 5.4.7 Integrated Probability in a Polygon

Similarly, we can use the `hp.query_polygon` function to look up the indices of the pixels within a polygon (defined by the Cartesian coordinates of its vertices), and then compute the probability that the source is inside that polygon by summing the values of the pixels.

```
>>> xyz = [[-0.69601758, -0.41315628, -0.58724902],
...        [-0.68590811, -0.40679797, -0.60336181],
...        [-0.69106913, -0.39820114, -0.60320752],
...        [-0.7011786 , -0.40455945, -0.58709473]]
>>> ipix_poly = hp.query_polygon(nside, xyz)
>>> hpx[ipix_poly].sum()
1.128695302404769e-12
```

These are all of the HEALPix functions from Healpy that we will need for the remainder of this tutorial.



Other useful Healpy functions include `hp.ud_grade` for upsampling or downsampling a sky map and `hp.get_interp_val` for performing bilinear interpolation between pixels. See the [Healpy tutorial](#) for other useful operations.

## 5.5 Basic Observability Calculations

Now we are going to teach our GCN handler how to determine whether a gravitational-wave event is observable. We are going to use the `astropy.coordinates` module. (See also the Astropy example on [observation planning in Python](#).) First, we will need to import a few extra Python modules:

```
import astropy.coordinates
import astropy.time
import astropy.units as u
```

The LIGO/Virgo/KAGRA probability sky maps are always in equatorial coordinates. Once we have looked up the coordinates of the *HEALPix* pixels, we will use Astropy to transform those coordinates to a horizontal (altitude–azimuth) frame for a particular site on the Earth at a particular time. Then we can quickly determine which pixels are visible from that site at that time, and integrate (sum) the probability contained in those pixels.

### Note

You may want to do something more sophisticated like determine how much of the probability is visible for at least a certain length of time. This example will illustrate one key function of *HEALPix* (looking up coordinates of the grid with `hp.pix2ang`) and some of the key positional astronomy functions with Astropy. For more advanced functionality, we recommend the *astroplan* package.

```
def prob_observable(m, header):
    """
    Determine the integrated probability contained in a gravitational-wave
    sky map that is observable from a particular ground-based site at a
    particular time.

    Bonus: make a plot of probability versus UTC time!
    """

    # Determine resolution of sky map
    npix = len(m)
    nside = hp.npix2nside(npix)

    # Get time now
    time = astropy.time.Time.now()
    # Or at the time of the gravitational-wave event...
    # time = astropy.time.Time(header['MJD-OBS'], format='mjd')
    # Or at a particular time...
    # time = astropy.time.Time('2015-03-01 13:55:27')

    # Geodetic coordinates of observatory (example here: Mount Wilson)
    observatory = astropy.coordinates.EarthLocation(
        lat=34.2247*u.deg, lon=-118.0572*u.deg, height=1742*u.m)

    # Alt/az reference frame at observatory, now
```

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```

frame = astropy.coordinates.AltAz(obstime=time, location=observatory)

# Look up (celestial) spherical polar coordinates of HEALPix grid.
theta, phi = hp.pix2ang(nside, np.arange(npix))
# Convert to RA, Dec.
radecs = astropy.coordinates.SkyCoord(
    ra=phi*u.rad, dec=(0.5*np.pi - theta)*u.rad)

# Transform grid to alt/az coordinates at observatory, now
altaz = radecs.transform_to(frame)

# Where is the sun, now?
sun_altaz = astropy.coordinates.get_sun(time).transform_to(altaz)

# How likely is it that the (true, unknown) location of the source
# is within the area that is visible, now? Demand that sun is at
# least 18 degrees below the horizon and that the airmass
# (secant of zenith angle approximation) is at most 2.5.
prob = m[(sun_altaz.alt <= -18*u.deg) & (altaz.secz <= 2.5)].sum()

# Done!
return prob

```

Finally, we need to update our GCN handler to call this function:

```

@gcn.handlers.include_notice_types(
    gcn.notice_types.LVC_PRELIMINARY,
    gcn.notice_types.LVC_INITIAL,
    gcn.notice_types.LVC_UPDATE)
def process_gcn(payload, root):
    # Respond only to 'test' events.
    # VERY IMPORTANT! Replce with the following line of code
    # to respond to only real 'observation' events.
    # if root.attrib['role'] != 'observation':
    #     return
    if root.attrib['role'] != 'test':
        return

    # Respond only to 'CBC' events. Change 'CBC' to "Burst"
    # to respond to only unmodeled burst events.
    if root.find("./Param[@name='Group']").attrib['value'] != 'CBC':
        return

    skymap_url = root.find("./Param[@name='skymap_fits']").attrib['value']

    skymap, header = hp.read_map(skymap_url, h=True)
    prob = prob_observable(skymap, header)
    print('Source has a {:.d}% chance of being observable now'.format(
        int(round(100 * prob))))
    if prob > 0.5:
        pass # FIXME: perform some action

```

Let's run the new GCN handler now...

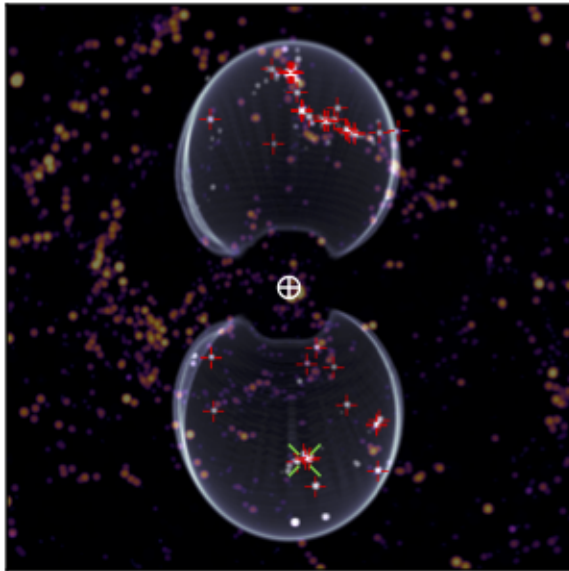
```
# Listen for GCNs until the program is interrupted
# (killed or interrupted with control-C).
gcn.listen(handler=process_gcn)
```

When you run this script, each time you receive a sample LIGO/Virgo/KAGRA GCN Notice, it will print something like the following (note that probability will change as a function of time):

Source has a 76% chance of being observable now

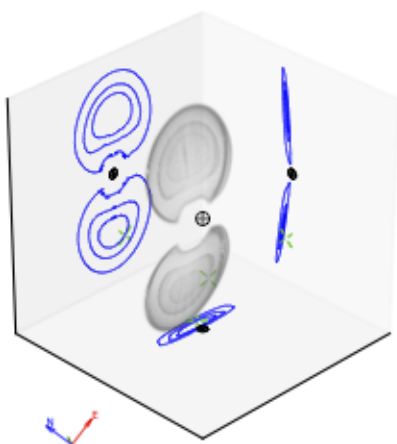
## 5.6 Distance and 3D Sky Maps

All sky localization FITS files for CBC events are three dimensional: they include both the sky probability map and a directionally dependent distance estimate. This can be useful for identifying possible host galaxies using a galaxy redshift catalog. For further details see<sup>1</sup> and for sample code see<sup>2</sup>.



<sup>1</sup> Singer, L. P., Chen, H.-Y., Holz, D. E., et al. 2016, *Astropys. J. Lett.*, 829, L15. doi:10.3847/2041-8205/829/1/L15

<sup>2</sup> Singer, L. P., Chen, H.-Y., Holz, D. E., et al. 2016, *Astropys. J. Supp.*, 226, 10. doi:10.3847/0067-0049/226/1/10



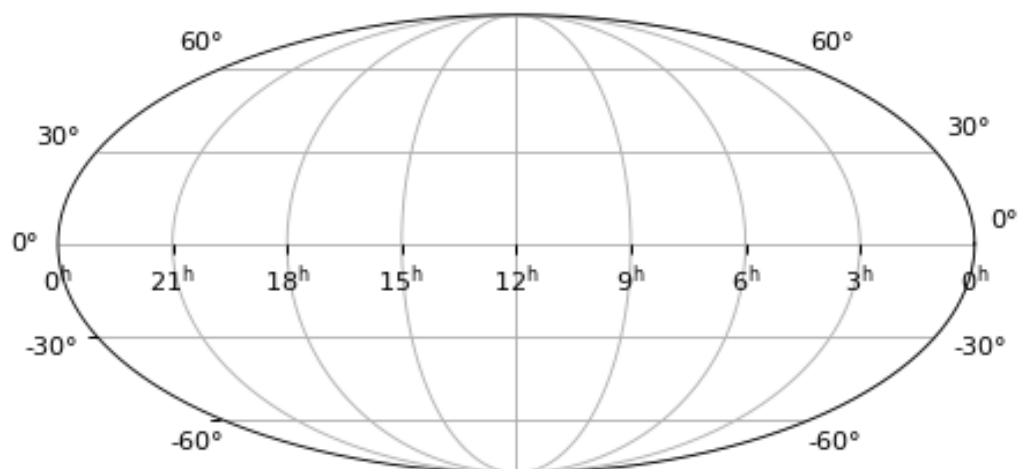
## ADDITIONAL RESOURCES

Here are a few additional resources for working with LIGO/Virgo/KAGRA alerts.

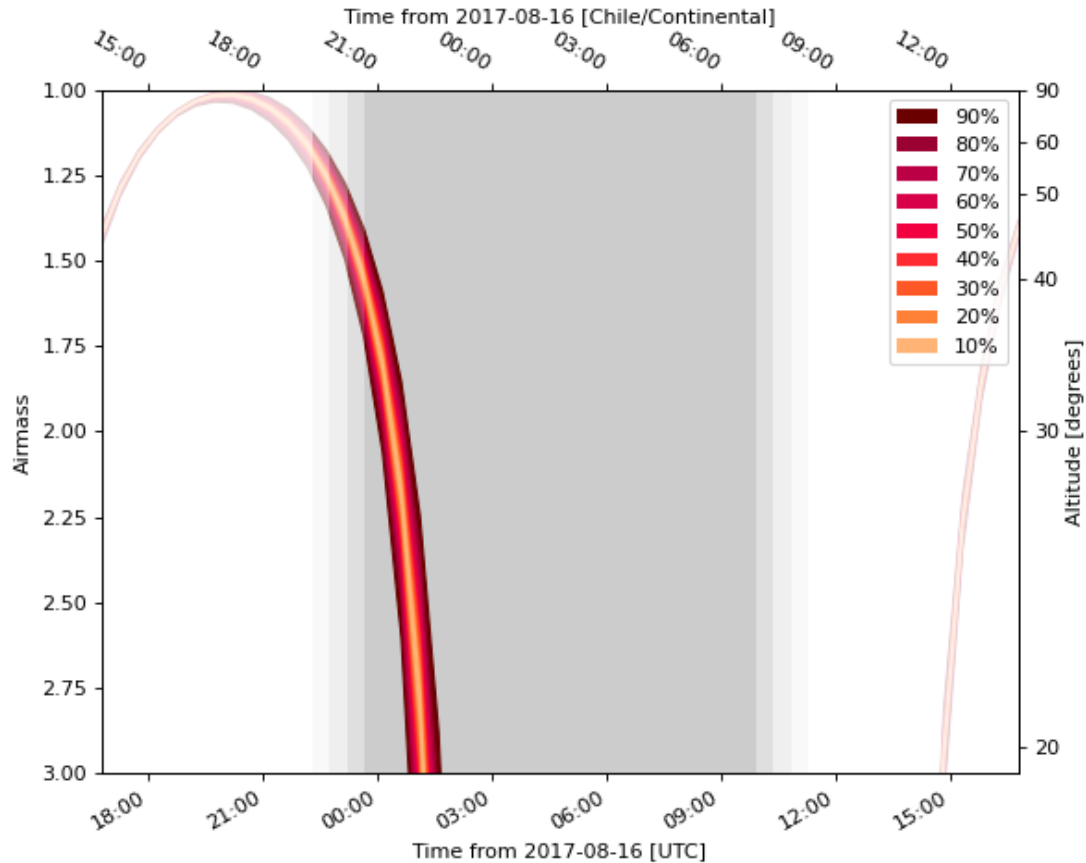
### 6.1 `ligo.skymap`: Advanced Python Tools for Probability Sky Maps

The `ligo.skymap` Python package includes a number of advanced tools for working with GW probability sky maps.

- Publication-quality astronomical mapmaking built on Astropy (`ligo.skymap.plot.allsky`)



- Functions for manipulating distance posteriors (`ligo.skymap.distance`)
- Probabilistic airmass plots (`ligo-skymap-plot-airmass`)



- The rapid sky localization code [BAYESTAR](#), which is used to produce the initial sky maps for CBC events but can also be used to create [simulated sky localizations](#).
- The postprocessing tool that creates updated sky maps from [MCMC](#) samples ([ligo-skymap-from-samples](#))

## 6.2 Sky Map Visualizations and Credible Regions in Aladin

In this section, we demonstrate working with gravitational-wave sky localizations in [Aladin Desktop](#). The following main topics are addressed.

- *MOC and GW Sky Localizations*
- *Running Aladin Desktop*
- *Loading a GW Sky Localization*
- *Building a Credible Region*
- *Area Within a Credible Region*
- *Querying and Filtering a Galaxy Catalog*
- *Thumbnail View Generator*
- *Building a Spatial and Temporal Credible Region*
- *Spatial and Temporal Coverage Intersections*

### 6.2.1 MOC and GW Sky Localizations

The enclosed area within a given probability level contour of a GW sky map can be effectively described with a Multi-Order Coverage (*MOC*) map<sup>1</sup>. MOC is a standard of the Virtual Observatory which provides a representation of arbitrary regions on the unit sphere using the *HEALPix* sky tessellation.

The MOC data structure encodes irregular sky regions as a hierarchy of HEALPix pixels. Each MOC cell is defined by two numbers: the hierarchy level (HEALPix *order*) and the pixel index (HEALPix *ipix*). MOCs are serialized as FITS or JSON files. The finest level of refinement within the MOC hierarchy is determined by the HEALPix *order* parameter or the equivalent *nside* parameter, related by  $nside = 2^{order}$ . For example, *order*=9 corresponds to *nside*=512, and a resolution of 6.9' per pixel.

The MOC maps make database queries for retrieving objects and logical operation (such as union, intersection, subtraction, difference) extremely fast even for very complex sky regions.

MOC maps and *multi-order sky maps* are closely related. They use similar multi-resolution HEALPix data structures. The main distinction is that MOC maps encode *regions on the sphere*, whereas multi-order sky maps encode *sampled images or functions on the sphere*. The multi-order sky map FITS format is a superset of the MOC FITS format, the only difference being that a multi-order sky map has values attached to each cell (probability density, distance estimates) whereas a MOC map does not. Aladin version v12 supports the LIGO/Virgo/KAGRA multi-resolution sky maps.

### 6.2.2 Running Aladin Desktop

Aladin Desktop is a Java application. To run it, you must first have the [Java Virtual Machine](#) (JVM) installed. More details are in Aladin's [download page](#).

---

#### Note

Aladin may fail to load some LIGO/Virgo/KAGRA sky maps and display a `java.lang.OutOfMemoryError` error message. This is because the highest resolution LIGO/Virgo/KAGRA sky maps do not fit inside Aladin's default memory size.

You can increase the maximum memory size used by your Java runtime environment by following the instructions below.

Download the Aladin.jar from the Aladin [download page](#). Execute it from a terminal by typing:

```
$ java -Xmx2g -jar Aladin.jar
```

The flag `-Xmx<ammount of memory>` specifies the maximum memory allocation pool for a JVM. Here 2GB of memory is allocated. For GW sky localizations with *nside*=2048, increase the memory allocated up to 3GB, `-Xmx3g`.

---

### 6.2.3 Loading a GW Sky Localization

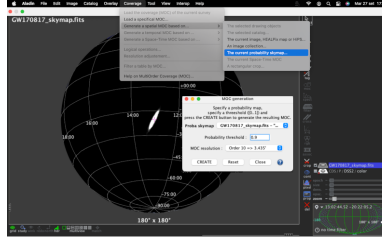
You can copy and paste the sky map URL from the [GraceDB](#) or drag and drop a HEALPix FITS file from your operating system's file browser in the main Aladin window. Aladin v12 recognizes both the standard HEALPix format with the file extension `.fits.gz` and the multi-resolution HEALPix format, distinguished by the file extension `.multiorder.fits`. Better performances are achieved with the multi-resolution format. Here we will work with the [LALInference sky map of GW170817](#).

---

<sup>1</sup> Fernique, P., et al. 2015, *Astron. Astrophys.*, 578, A114. doi:10.1051/0004-6361/201526075

## 6.2.4 Building a Credible Region

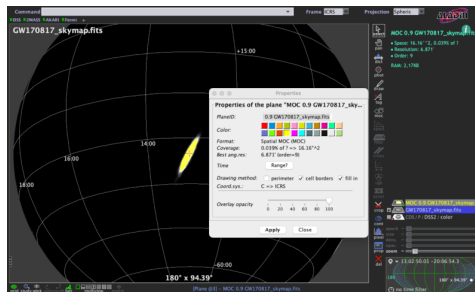
The sequence of the Aladin Desktop commands to create a credible region at a defined confidence level is described below. From the menu bar, select *Coverage* → *Generate a MOC based on* → *The current probability skymap*.



The *MOC generation* window has three options: the probability sky map, the threshold, and the MOC resolution. Make sure that the GW sky map that we loaded in the previous step is selected in the *Proba skymap* dropdown menu. Then enter a number between 0 and 1 for the credible level in the *Probability threshold* box. Finally, press the *CREATE* button. The MOC for the credible region is created and loaded in the Aladin Stack. If you repeat this process multiple times for different credible levels, then you can select each MOC independently from the Aladin stack.

## 6.2.5 Area Within a Credible Region

There are two ways to get the area within a MOC credible region. If you hover over the cursor over the MOC name in the Aladin stack, then the area in square degrees and the percentage of the sky are shown in the top-right corner of the Aladin window. Alternatively, you can right-click the MOC in the Aladin stack and select *Properties* from the contextual menu. The area and percentage of the sky are shown in the *Properties* dialog box. From this dialog box, you can also control the appearance and color of the MOC, which is useful for distinguishing multiple MOCs for different credible levels.



## 6.2.6 Querying and Filtering a Galaxy Catalog

Each gravitational-wave sky map for a *CBC* event provides a three-dimensional probability distribution as a function of sky position and distance<sup>2</sup>. Cross-matching that distribution with positions and redshifts of a galaxy catalog provides a filtered list of possible host galaxies (see *Distance and 3D Sky Maps*). Aladin does not yet implement a galaxy catalog query by the three-dimensional posterior probability distribution. However, it is currently possible in Aladin to search for galaxies within the 2D credible region on the sky and, afterwards, apply a distance cut that is independent of sky position.

Here we query the galaxies collected in the *GLADE* catalog inside the 90% credible region of GW170817. Then we filter those galaxies according to the marginal distance posterior distribution integrated over the whole sky.

<sup>2</sup> Singer, L. P., Chen, H.-Y., Holz, D. E., et al. 2016, *Astrophys. J. Lett.*, 829, L15. doi:10.3847/2041-8205/829/1/L15



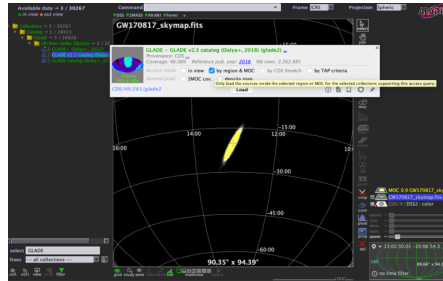
### 1. Pick out the galaxy catalog from the data collections tree.

Any of the 20,000 catalogs published in the Virtual Observatory can be retrieved from the data collections tree in the left panel of the main Aladin window.

To find the GLADE catalog, make sure that – *all collections* – is selected in the *from* dropdown menu in the bottom of the left panel, then type GLADE in the *select* text field. In the data collections tree, click on *GLADE v2.3 catalog (Dalya+, 2018)*.

### 2. Load the galaxy catalog filtered by the 2D credible region.

In the popup window, click the *by region & MOC* checkbox in order to filter it by the 2D credible region that we created earlier. Then press the *Load* button.



### 3. Filter the galaxy catalog by distance.

The posterior mean distance and the posterior standard deviation of luminosity distance in Mpc are reported in the FITS file header with the keywords DISTMEAN and DISTSTD, respectively. In the case of GW170817, they have the values DISTMEAN = 38.0 and DISTSTD = 7.5.

Select *Catalog* → *Create a filter* from the menu bar. This opens the *Properties* dialog box contains two tabs. Select the *Advanced mode* tab and copy the following text into the filter definition box:

```
${Dist} > 30.5 && ${Dist} < 45.5 {draw}
```

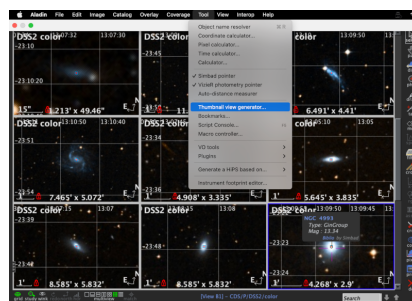
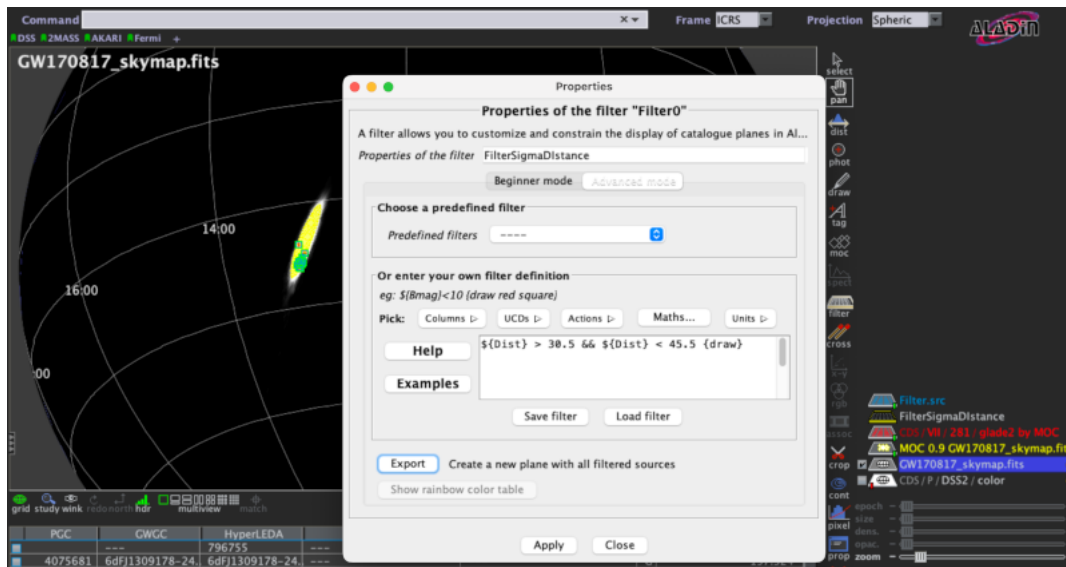
This is an expression for a 1-sigma cut on distance in the [Aladin filter syntax](#). Dist is the column in the GLADE catalog corresponding to the distance in Mpc.

Click on *Apply* and then on *Export* to create a new level in the Aladin stack consisting only of sources selected by the filter.

## 6.2.7 Thumbnail View Generator

Finally, we make a mosaic of the filtered galaxies. Here the thumbnails are color composition images of the Digitized Sky Surveys (DSS).

To get this, we load the DSS colored survey from the data collections tree. Then select *Tool* → *Thumbnail view generator* from the menu bar, and click the *Ok* button in the dialog box. Aladin will generate thumbnail views from the current image in the main window. To change it, check the corresponding plan in the Aladin stack.

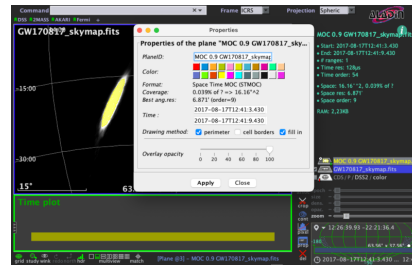


## 6.2.8 Building a Spatial and Temporal Credible Region

Aladin v12 offers the functionality to add temporal information in any spatial coverage described by the MOC data structure. The resulting new data structure is indicated with STMOC (Space and Time MOC)<sup>3</sup>.

Click on the name of the plan corresponding to the credible region. `MOC 0.9 GW170817_skymap.fits` will appear highlighted. From the menu bar, press *Coverage* → *Generate a Space-Time MOC based on* → *The selected space MOC*. The *Properties* is equipped with the *Time* section with two boxes in which you can select a time interval. The merge time of GW170817 occurs at 2017-08-17T12:41:04.43 UTC. Searching for coincident with external triggers, we apply a time window from -1 s to 5 s around the GW time i.e., from 2017-08-17T12:41:03.43 UTC to 2017-08-17T12:41:09.43 UTC.

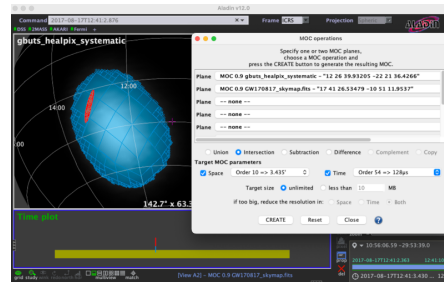
Click on *Apply* to create a credible region with this time range. The main Aladin window shows a bottom box *Time plot* displaying the associated time line.



## 6.2.9 Spatial and Temporal Coverage Intersections

The STMOC data structure allows you to perform operations in space and time simultaneously. We build a new STMOC with the [error box of GRB 170817](#) provided by the GBM instrument on board the Fermi satellite. GRB170817 occurred at 2017-08-17T12:41:06 UTC<sup>4</sup>.

The intersection is performed by opening the window *Logical operations* from *Coverage*. An additional MOC layer is loaded into the Aladin stack with information on the spatial and temporal coincident of the two astrophysical events.



<sup>3</sup> Fernique, P., et al. 2022, IVOA Recommendation 27 July 2022. <https://ivoa.net/documents/MOC/>

<sup>4</sup> Goldstein, A., et al. 2017, *Astrophys. J. Lett.*, 848 L14 doi:<https://doi.org/10.3847/2041-8213/aa8f41>

## 6.3 Mobile Apps

There are two unofficial apps for mobile devices. Install one of these apps to view GW alerts on your smart phone or tablet.

- [Gravitational Wave Events](#) for iOS by Peter Kramer
- [Chirp](#) for Android by Laser Labs

## 6.4 Gravitational Wave Treasure Map

This webpage is helpful for astronomers in coordinating electromagnetic follow-up of gravitational-wave events.

- [Treasure Map](#)

## NEW: EARLY-WARNING ALERTS

*BNS* mergers spend several minutes in band of the Advanced ground-based gravitational-wave detectors. For some loud and nearby *BNS* mergers, it is possible to accumulate enough *SNR* and detect them several tens of seconds before merger. During O3, automated public alerts for *CBC* events have been sent within as little as 2 minutes after merger. In O4, we will be deploying search pipelines that can in principle detect BNS events before merger.

Since it is generally assumed that detectable electromagnetic (or neutrino) emission starts shortly *after* merger, a pre-merger gravitational-wave detection would provide *early warning* of an impending electromagnetic transient and might make it possible for automated follow-up facilities to capture any prompt emission from the merger environment, the jet, and other unknown activity.

We had previously conducted a trial early warning public alert infrastructure in June 2020 replaying an 8-day period of archival LIGO data from O3. Results from this study were published in<sup>1</sup>. This study demonstrated that in principle it is possible to sent out GCN Notices in advance of a BNS merger. Based on the current expect BNS merger rate, we expect O(1) event per year to be detected before merger in O4.

**We have commissioned capability to produce and distribute early warning gravitational-wave alerts up to tens of seconds before merger. We have also reduced the latency of ordinary post-merger alerts to within tens of seconds after merger.**

### 7.1 Subscribe to Early-Warning Alerts

Early warning alerts are publicly distributed as *Notices* just like ordinary gravitational-wave alerts (see the *Alert Contents* section). **They have exactly the same format and content** as a *Preliminary Notice*. In particular, early warning GCN Notices have significance estimates, sky localizations, and source classifications. Also, like Preliminary GCN Notices, **Early Warning Notices are sent prior to vetting by humans, and are not accompanied by a GCN Circular.**

Early warning GCN Notices are differentiated from ordinary GCN Notices by the new LVC\_EARLY\_WARNING GCN Notice type. If you are receiving GCN Notices via an anonymous VOEvent connection and you are using the Python sample code from the *VOEvent Notices via GCN Classic* section, then all you have to do is add the notice type to your GCN handler:

```
import gcn

@gcn.handlers.include_notice_types(
    gcgn.notice_types.LVC_EARLY_WARNING,  # <-- new notice type here
    gcgn.notice_types.LVC_PRELIMINARY,
    gcgn.notice_types.LVC_INITIAL,
    gcgn.notice_types.LVC_UPDATE,
    gcgn.notice_types.LVC_RETRACTION)
```

(continues on next page)

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<sup>1</sup> Magee, R., Chatterjee, D., Singer, L. P., Sachdev, S., et al. 2022. doi:10.3847/2041-8213/abed54

(continued from previous page)

```
def process_gcn(payload, root):  
    ... # <-- put your code here  
  
gcn.listen(handler=process_gcn)
```

(If you are using a non-anonymous GCN connection or one of the many other notice formats provided by GCN, then you will also need to [submit a change to your GCN Notice subscription settings](#).)

---

### Important

Since these early-warning events will arise from time-shifted and replayed data and not live observations, the GCN notices will be flagged as test events by setting the VOEvent `role="test"` attribute.

---

## 7.2 Detection Method

All of our *CBC* search pipelines (GstLAL<sup>2</sup>, MBTA, PyCBC, and SPIIR) are participating in early-warning alerts. See the *Online Pipelines* section for details on these analyses. Localizations will be produced with BAYESTAR; see the *Sky Localization and Parameter Estimation* section for details.

*BNS* signals sweep up smoothly in frequency for a few minutes across the Advanced LIGO band. In that time, they may accumulate enough SNR to be detected before merger. A GW170817-like system with a total network SNR of 32 will already accumulate an SNR of 11 by the time the signal sweeps up to 30 Hz, about a minute before merger.

The early warning search is a matched-filter search that uses templates that have been truncated at a selection of end frequencies—or equivalently, cut off at a selection of times before merger.

## 7.3 Source Classification

The automated *source classification and properties* have not been trained or tested extensively for early warning alerts. However, the early warning analysis is **only sensitive to BNS-mass mergers**. As a result, the favored source class in early warning GCN Notices will always be either BNS or Terrestrial, with a 0% chance of NSBH or BBH. The HasNS and HasRemnant fields will always show 100%.

## 7.4 Localization

Sky localizations for early warning alerts are typically very coarse because the early warning analysis inherently does not make use of the full duration and bandwidth of the gravitational-wave signal. The localization improves slowly up until the last second before merger, and then converges rapidly in the last second.

The animations below taken from the data release<sup>3</sup> show the evolution of early-warning sky maps for three representative events with different *SNR* values. Note that this study assumed the detectors to be operating at their final design sensitivity.

In this PDF version of the User Guide, the images below are hyperlinks to the animations. Clicking on one of them will open the animation in your Web browser.

---

<sup>2</sup> Sachdev, S., Magee, R., Hanna, C., et al. 2020. doi:10.3847/2041-8213/abc753

<sup>3</sup> <https://gstlal.docs.ligo.org/ewgw-data-release/>

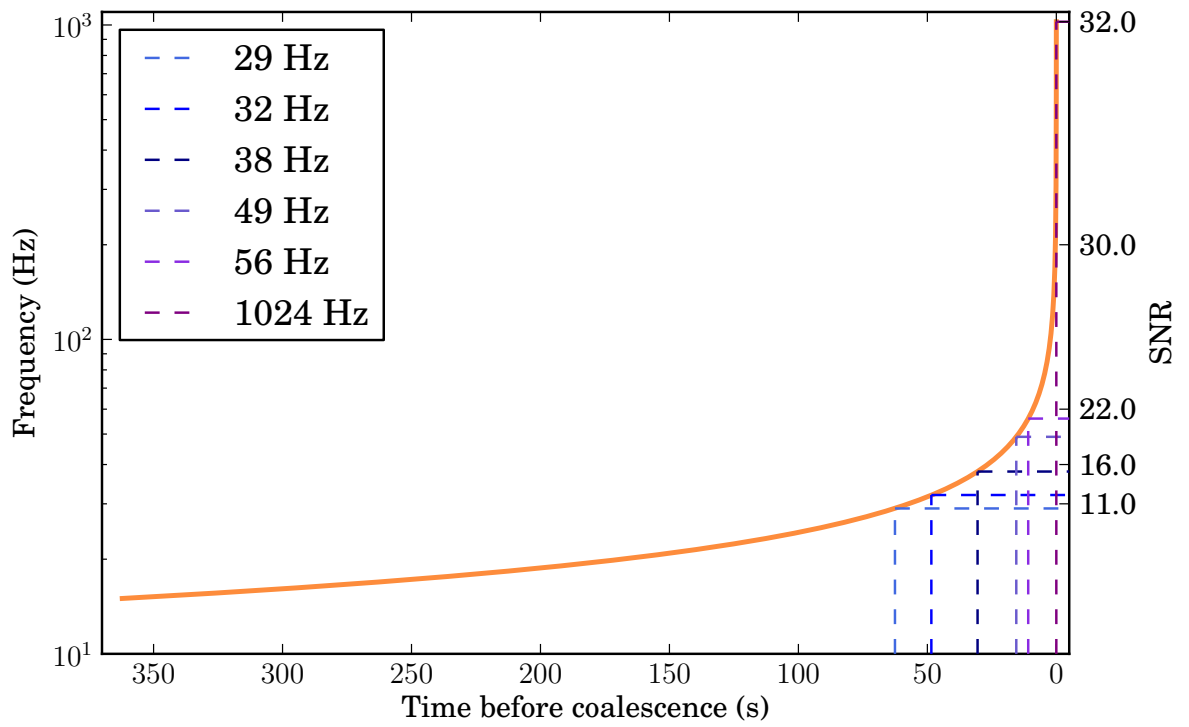
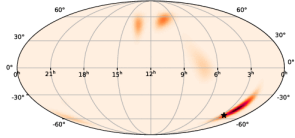
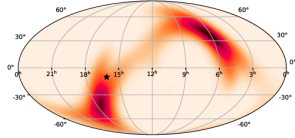
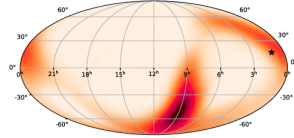


Fig. 1: The time evolution of the gravitational-wave frequency and the cumulative *SNR* for a GW170817-like *BNS* system.

Final SNR	11	18	25
Distance	250 Mpc	210 Mpc	160 Mpc
Sky map (animated GIF)			
Frequency	Localization accuracy (90% credible area)		
29 Hz	Not detected	Not detected	12000 deg <sup>2</sup>
32 Hz			10000 deg <sup>2</sup>
38 Hz			8200 deg <sup>2</sup>
49 Hz	2300 deg <sup>2</sup>	1000 deg <sup>2</sup>	730 deg <sup>2</sup>
56 Hz	1000 deg <sup>2</sup>	700 deg <sup>2</sup>	250 deg <sup>2</sup>
1024 Hz	10 deg <sup>2</sup>	31 deg <sup>2</sup>	5.4 deg <sup>2</sup>



## CHANGE LOG

### A.1 Version 17.1 (2022-12-14)

#### Sample Code

- Fix a copy-paste error in the GCN sample code.

### A.2 Version 17 (2022-12-14)

#### General

- Change the name of this document from “LIGO/Virgo Public Alerts User Guide” to “LIGO/Virgo/KAGRA Public Alerts User Guide”.
- Use the new `sphinx-immaterial-igwn` theme which is common to many LIGO/Virgo/KAGRA documents.
- Multi-resolution FITS files are now the preferred format for sky maps.
- Add tutorial on receiving and parsing notices distributed over Kafka via GCN and SCiMMA. This change is reflected in multiple sections: **Alert Contents** and **Sample Code**.
- Remove `MassGap` from source classification and add `HasMassGap` to source properties. This change is reflected in multiple sections: **Data Analysis**, **Alert Contents**, and **Sample Code**.

#### Observing Capabilities

- Update the observing timeline, detection and localization estimates, and sample sky maps data release for O4 and O5.

#### Data Analysis

- Several changes to source properties:
  - Add a reference to the source properties methods paper.
  - Add details on equation of state marginalization.

## Alert Contents

- Add RAVEN space-time coincidence FAR to alert example.
- Add INTEGRAL to notice types considered by RAVEN.
- Add a terminal Z to all time strings in the VOEvents to that they are in the UTC time zone and to conform to the ISO 8601 date-time format. See [RFC 3339](#).

## Sample Code

- Update information on working on multi-resolution sky maps. Changed the presentation order to reflect that multi-resolution is now the default.

## Additional Resources

- Update information about early warning, pre-merger for compact binary events.
- Add a link to the Gravitational Wave Treasure Map.

# A.3 Version 16 (2020-05-28)

## General

- Add the new *New: Early-Warning Alerts* section to introduce early warning alerts as a public post-O3 technology demonstration. Early warning alerts are detections of binary neutron star merger candidates up to tens of seconds before merger. **Starting on 2020-06-09 and lasting for one week, simulated early-warning alerts from replayed O3 LIGO/Virgo data will be publicly distributed at a rate of approximately once per day.**

## Observing Capabilities

- Note suspension of Observing Run 3 (O3) on March 27, 2020, due to the COVID-19 pandemic. When it becomes safe to resume normal activities, there may be a short period of additional O3 observations before an extended shutdown to prepare for the next observing run (O4). Updates will be posted in this document as they become available.

## Alert Contents

- Add an example EarlyWarning GCN notice.

# A.4 Version 15 (2020-01-15)

## Observing Capabilities

- Add sensitivity, detection rate, and localization accuracy statistics for O3 and O4 from the most recent arXiv submission of the LIGO/Virgo/KAGRA observing scenarios paper, [arXiv:1304.0670](#). Add ranges for BBH and NSBH sources. Update O3 timeline and range schedule figures. Expect another update in the next few weeks incorporating O3a.

## A.5 Version 14 (2020-01-06)

### Data Analysis

- Change FAR threshold due to the additional trials from the GRB coincidence search.

### Alert Contents

- Add VOEvent documentation and examples for gravitational-wave events that are coincident with GRBs.

## A.6 Version 13 (2019-12-16)

### Data Analysis

- Add a note that the oLIB search is not currently in operation.

### Alert Contents

- Add a warning that *VOEvent* over anonymous *VTP* is the only GCN format and distribution method that is fully supported by LIGO/Virgo/KAGRA. In particular, LIGO/Virgo/KAGRA performs only limited quality control checks for the textual “full format” and the binary format.
- In the VOEvent alert schema, add a `name` attribute to each `<Group>` tag so that parameter groups are recognized by the `get_grouped_params()` function from the `voevent-parse` package. For backwards compatibility, both the `name` attribute and the `type` attribute will be set to the same value.

The groups are now denoted as follows:

- `<Group name="GW_SKYMAP" type="GW_SKYMAP">` for localization parameters
- `<Group name="Classification" type="Classification">` for compact binary source classification parameters
- `<Group name="Properties" type="Properties">` for compact binary source properties parameters

### Additional Resources

- Add the [Chirp](#) mobile app for iOS and Android by Laser Labs.

## A.7 Version 12 (2019-10-24)

### Observing Capabilities

- Update ranges and rates based on up-to-date O3 analysis. Add BBH and NSBH ranges. Update range and observing schedule figures.
- Generalize the definition of the range so that it is unambiguous at high redshift. It is now defined as in [arXiv:1709.08079](#).
- Add the end date of Observing Run 3 (O3) on 2020-04-30.

## Data Analysis

- Document the false alarm rate threshold for public alerts.

## Alert Contents

- Remove the documentation for the Fluence parameter from burst alerts because it is not currently present in the VOEvents.
- Update the list of pipeline names that can appear in GCN Notices.

## Additional Resources

- Created a new section for additional and contributed tools. The *ligo.skymap* and *Aladin* pages have been moved into this section.
- Add instructions for cross-matching sky localizations with galaxy catalogs in Aladin Desktop.
- Add the unofficial iOS Gravitational Wave Events app.

# A.8 Version 11 (2019-09-15)

## Data Analysis

- Update the documentation about superevents describing the criteria by which the preferred event is selected. For CBC events, events with three detectors are preferred over two detectors, and events with two detectors are preferred over events with one detector.

## Alert Contents

- Add references to the HEALPix paper (Górski et al. 2005, [doi:10.1086/427976](https://doi.org/10.1086/427976)).
- Add version number suffixes to sky map FITS filenames in GCN notices to distinguish between different sky maps with the same filename. For example, the first file with the name `bayestar.fits.gz` will be referred to as `bayestar.fits.gz,0`, then the next will be `bayestar.fits.gz,1`, and so on. The filename with no version suffix always points to the most recent version.

## Sample Code

- Add attribution for a HEALPix illustration that was reproduced from <https://healpix.jpl.nasa.gov>.
- Fix the example image for `hp.mollview()`, which was distorted due to a file conversion issue.
- Add section on sky map visualization and credible regions in Aladin.

## A.9 Version 10 (2019-07-31)

### Data Analysis

- Add a more detailed description of the RAVEN pipeline. Previously just mentioned types of searches but now has information on external experiments, coincident searches, and coincident false alarm rates.
- Fixed PyCBC Live reference.

### Alert Contents

- Changed the data type of the UNIQ column of the multi-order sky map format from an unsigned integer to a signed integer as specified by the [MOC-in-FITS standard](#).

This will improve interoperability with the `mrdfits` function from the [IDL Astronomy User's Library](#) and the `fvFITS Viewer` from [FTOOLS](#), both of which were reported to have problems with the old unsigned integer column. It will also make it simpler to work with Numpy indexing operations, since Numpy uses a signed integer type for indexing.

This change will go into effect in the LIGO/Virgo/KAGRA low-latency alert system on 2019-08-06.

Users of `ligo.skymap` should update to version 0.1.8 or newer because older versions will be unable to read old files with unsigned UNIQ columns. The new version of `ligo.skymap` can read files with either signed or unsigned UNIQ columns.

## A.10 Version 9 (2019-06-13)

### General

- There is now a shorter URL for the Public Alerts User Guide, which can now be found at either <https://emfollow.docs.ligo.org> or <https://emfollow.docs.ligo.org/userguide>.

### Data Analysis

- Renamed this section from “Procedures” to “Data Analysis” and reordered its subsections to better reflect the chronological order of the steps of the analysis.

### Sample Code

- Remove MacPorts installation instructions.
- Add tutorial on working with multi-resolution sky maps.
- Add sample code to test whether a sky position is in the 90% credible region.
- Add sample code to find the area of the 90% credible region.

## A.11 Version 8 (2019-05-22)

### Alert Contents

- Describe the two localization formats, the official `*.fits.gz` HEALPix-in-FITS format and the experimental multi-resolution HEALPix `*.multiorder.fits` format.

Effective 2019-05-28, the multi-resolution file suffix will be renamed from `*.fits` to `*.multiorder.fits`. The old `*.fits` suffix had caused confusion because the multi-resolution format is *not* the same as the `*.fits.gz` files without gzip compression.

**The multi-resolution format is currently recommended only for advanced users.** Tutorials and sample code will soon be included in an upcoming version of the User Guide.

- Update the description of the HasNS property in the sample GCN Notices. Previously, it was defined as the probability that at least one object in the binary has a mass that is less than 2.83 solar masses. Now, for consistency with the source classification definitions, it is defined as the probability that at least one object in the binary has a mass that is less than 3 solar masses.
- Add some shading to the source classification diagram to make it clear that the definitions of the source classes are symmetric under exchange of the component masses, but that by convention the component masses are defined such that  $m_1 \geq m_2$ .

## A.12 Version 7.1 (2019-03-02)

- Remove the warning on the front page about significant changes to this document occurring before the start of O3.

## A.13 Version 7 (2019-03-02)

### Observing Capabilities

- Record the official start of O3.

### Procedures

- Add Gravitational Wave/High Energy Neutrino search to the list of multi-messenger search pipelines.

### Sample Code

- Add instructions for installing required packages using the Anaconda Python distribution.

## A.14 Version 6 (2019-03-08)

### Alert Contents

- Switch to the GW170817 Hanford-Livingston-Virgo localization for the example sky map.

## A.15 Version 5 (2019-03-01)

### Alert Contents

- Add a human-readable description to the Pkt\_Ser\_Num parameter.
- Add `<EventIVORN cite="supersedes">` elements to the sample Initial and Update notices in order to cite all prior VOEvents. GraceDB already includes this metadata, but it was missing from the examples.
- Add MassGap classification for compact binary mergers.

## A.16 Version 4 (2019-02-15)

### General

- Changed the contact email to `<emfollow-userguide@support.ligo.org>` because some mail clients had trouble with the slash in the old contact email address, `<contact+emfollow/userguide@support.ligo.org>`. (The old address will also still work.)

### Getting Started Checklist

- Update links for OpenLVEM enrollment instructions.

### Observing Capabilities

- Update planned dates for Engineering Run 14 (ER14; starts 2019-03-04) and Observing Run 3 (O3; starts 2019-04-01).
- Add Live Status section, listing some public web pages that provide real-time detector status.

### Sample Code

- Update the example GCN notice handler so that it does not fail if the notice is missing a sky map, because as we have specified them, LVC\_RETRACTION notices never contain sky maps and LVC\_PRELIMINARY notices may or may not contain sky maps.
- When building the documentation, test all of the sample code automatically.

## A.17 Version 3 (2019-02-13)

### Alert Contents

- Remove the `skymap_png` parameter from the `VOEvents`. The sky map plots take longer to generate than the FITS files themselves, so they would have needlessly delayed the preliminary alerts.
- Change the IVORN prefix from `ivo://gwnet/gcn_sender` to `ivo://gwnet/LVC`, because GCN traditionally uses the text after the `/` to indicate the name of the mission, which most closely corresponds to “LVC,” short for “LIGO/Virgo/KAGRA Collaboration.” Note that this IVORN is used for historical purposes and continuity with the GCN notice format used in O1 and O2, and is likely to change in the future with the commissioning of additional gravitational-wave facilities.
- Retraction notices now get a separate GCN notice packet type, `LVC_RETRACTION=164`. The `Retraction` parameter has been removed from the `<What>` section.

## A.18 Version 2 (2018-12-13)

### Alert Contents

- Removed the `Vetted` parameter from GCN Notices. It was intended to indicate whether the event had passed human vetting. However, it was redundant because by definition Preliminary events have not been vetted and all Initial and Update alerts have been vetted.
- The type of the `Retraction` parameter in the GCN Notices was changed from a string (`false` or `true`) to an integer (`0` or `1`) for consistency with other flag-like parameters.
- Remove the `units` attribute from parameters that are not numbers.

### Sample Code

- GCN has now begun publicly broadcasting sample LIGO/Virgo/KAGRA GCN Notices. Updated the sample code accordingly with instructions for receiving live sample notices.

## A.19 Version 1 (2018-11-27)

### Getting Started Checklist

- Updated instructions for joining the OpenLVEM Community.

### Observing Capabilities

- Changed the expected number of BNS events in O3 from 1-50, as stated in the latest version of the Living Review, to 1-10 events, as stated in the more recent rates presentation.



## Alert Contents

- In the example VOEvents, moved the Classification and Inference quantities from the <Why> section to the <What> section so that they validate against the VOEvent 2.0 schema.



## GLOSSARY

**Avro**

Apache Avro is an open, binary data serialization format. See <https://avro.apache.org> for more information.

**Base64**

A common binary encoding scheme supported by many open-source libraries, e.g. the [python standard library](#).

**BBH**

Binary black hole, a binary system composed of two black holes. See [BH](#).

**BH**

Black hole.

**BNS**

Binary neutron star, a binary system composed of two neutron stars. See [NS](#).

**burst**

In the context of gravitational waves, a signal candidate that is detected without a template and without prior knowledge of the waveform. Examples of potential sources of gravitational-wave bursts include high mass [BBH](#) mergers, core-collapse supernovae, and cosmic string cusps.

**chirp mass**

In a binary system, the chirp mass is a symmetric combination of the [primary](#) and [secondary](#) component masses  $m_1$  and  $m_2$  that parameterizes the leading-order time or frequency evolution of the gravitational-wave signal. It is usually denoted by a script “M” symbol,  $\mathcal{M}$ , and is defined as  $\mathcal{M} = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$ .

**CBC**

Compact binary coalescence.

**EOS**

Equation of state. The equation of state determines the relation between mass and radius, or mass and compactness, or pressure and (mass, energy, or number) density, of neutron stars.

**FAR**

False alarm rate, a statistic that is used to describe the significance of a gravitational-wave event. See section [false alarm rate \(FAR\)](#) for details. FAR has units of frequency (one over time).

**FITS**

Flexible Image Transport System, a format for astronomical tables, images, and multidimensional data sets. See NASA’s FITS Support Office (<https://fits.gsfc.nasa.gov>) for specifications, software, and documentation.

**GCN**

The General Coordinates Network (<https://gcn.nasa.gov>), a NASA-hosted public portal for discoveries and observations of astronomical transients. GCN hosts one of the [Kafka](#) brokers used to distribute LIGO/Virgo/KAGRA alerts. See <https://gcn.nasa.gov>.

**GCN Circular**

A human-readable astronomical bulletin distributed through [GCN](#).

**GraceDB**

Gravitational Wave Candidate Event Database (<https://gracedb.ligo.org>), the official public marshal portal for LIGO/Virgo/KAGRA candidates.

**GRB**

Gamma-ray burst.

**HEALPix**

Hierarchical Equal Area isoLatitude Pixelation, a scheme for indexing positions on the unit sphere. See <https://healpix.sourceforge.io>.

**HEN**

High Energy Neutrino, particularly in the context of multi-messenger GW+HEN follow-up.

**JSON**

JavaScript Object Notation is an open data serialization format. JSON-serialized data look like JavaScript literals. See <https://json.org> for more information.

**Kafka**

Apache Kafka is an open-source distributed event streaming platform. See <https://kafka.apache.org> for more information.

**KAGRA**

Kamioka Gravitational Wave Detector (see [KAGRA home page](#)), an underground gravitational-wave detector in the Kamioka mine in Japan.

**LHO**

LIGO Hanford Observatory (see [LHO observatory home page](#)), site of a 4 km gravitational-wave detector in Hanford, Washington, USA.

**LLO**

LIGO Livingston Observatory (see [LLO observatory home page](#)), site of a 4 km gravitational-wave detector in Livingston, Louisiana, USA.

**MassGap**

Compact binary systems with at least one compact object whose mass is in the hypothetical “mass gap” between neutron stars and black holes, defined here as 3-5 solar masses.

**MCMC**

Markov chain Monte Carlo. A numerical algorithm for sampling complex, multidimensional probability distributions, or for integrating functions of many variables. Used extensively in gravitational-wave parameter estimation.

**MOC**

Multi-Order Coverage map, a format to describe the coverage of an arbitrary region on the unit sphere. A MOC consists of a list of [HEALPix](#) cells at different depths. For the specification, see the [HiPS IVOA Recommendation](#).

**Notice**

A machine-readable alert distributed through [GCN](#) or [SCiMMA](#).

**NS**

Neutron star.

**NSBH**

Neutron star black hole, a binary system composed of one neutron star and one black hole. See [NS](#), [BH](#).

**O1**

Advanced LIGO and Advanced Virgo’s first observing run.

**O2**

Advanced LIGO and Advanced Virgo’s second observing run.

**O3**

Advanced LIGO and Advanced Virgo's third observing run.

**primary**

When referring to the two component compact objects or the masses of the two component compact objects in a binary, the *primary* is the more massive one, i.e.,  $m_1 \geq m_2$ . See *secondary*.

**range**

A figure of merit to describe the sensitivity of a gravitational-wave detector to a given source population at cosmologically significant distances. It is defined as the radius  $R$  of a Euclidean sphere with the volume equal to the *sensitive volume*  $V_z$ . It may be written as:

$$R = \left( \frac{3V_z}{4\pi} \right)^{1/3}.$$

**secondary**

When referring to the two component compact objects or the masses of the two component compact objects in a binary, the *secondary* is the less massive one, i.e.,  $m_2 \leq m_1$ . See *primary*.

**sensitive volume**

A figure of merit for the sensitivity of a gravitational-wave detector or a network of detectors. It is defined as the space-time volume surveyed per unit detector time, and may be expressed as (cf.<sup>1</sup>):

$$V_z = \frac{\int_{z < z^*(\Theta)} p(\Theta) \frac{dV_C}{dz} \frac{dz}{1+z}}{\int p(\Theta) d\Theta}.$$

Here,  $\Theta$  is the set of parameters that describe the gravitational-wave signal (merger time, sky location, orbital elements, masses, and spins) and  $p(\Theta)$  is the redshift-independent population model for those parameters. The term  $\frac{dV_C}{dz}$  is differential comoving volume per unit redshift. The function  $z^*(\Theta)$  is the *threshold redshift*, or the redshift at which a binary with parameters  $\Theta$  is just at the limit of detection. The factor of  $1 + z$  in the denominator accounts for time dilation from the source frame to the detector frame.

If a population of sources occurs at a fixed rate per unit comoving volume per unit proper time  $\dot{n}$ , then the rate of observed events in the detector frame is  $\dot{n}V_z$ .

**SN**

Supernova.

**SNR**

Signal-to-noise ratio, here applied to gravitational-wave signals. It is defined as the square root of the integral over frequency of the power spectral density of the gravitational-wave signal divided by the integral over frequency of the average power spectral density of the noise.

**source-frame mass**

Since observed frequencies of distant sources are subject to redshift by  $f_{\text{obs}} = (1+z)^{-1} f_{\text{source}}$ , and gravitational-wave frequency scales inversely with mass, the observer- and source-frame masses are related by  $m_{\text{obs}} = (1+z)m_{\text{source}}$ .

**Terrestrial**

Classification for signals in gravitational-wave detectors that are of instrumental or environmental origin. Terrestrial signals are not astrophysical and not due to gravitational waves. Some examples of sources of terrestrial signals are statistical noise fluctuations, detector glitches, and ground motion.

**SCiMMA**

Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics. SCiMMA hosts one of the *Kafka* brokers used to distribute LIGO/Virgo/KAGRA alerts. See <https://scimma.org>.

<sup>1</sup> Chen, H.-Y., Holz, D. E., et al. 2017, *Distance measures in gravitational-wave astrophysics and cosmology*. arXiv:1709.08079

**Virgo**

Virgo Observatory (see [Virgo observatory home page](#)), site of a 3 km gravitational-wave detector in Cascina, Italy.

**VOEvent**

An XML format for describing astronomical transients. For the specification, see the official [VOEvent IVOA Recommendation](#).

**VTP**

VOEvent Transport Protocol, a simple TCP-based protocol for sending and receiving VOEvents, used by [GCN](#). For the specification, see the official [VTP IVOA recommendation](#).

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