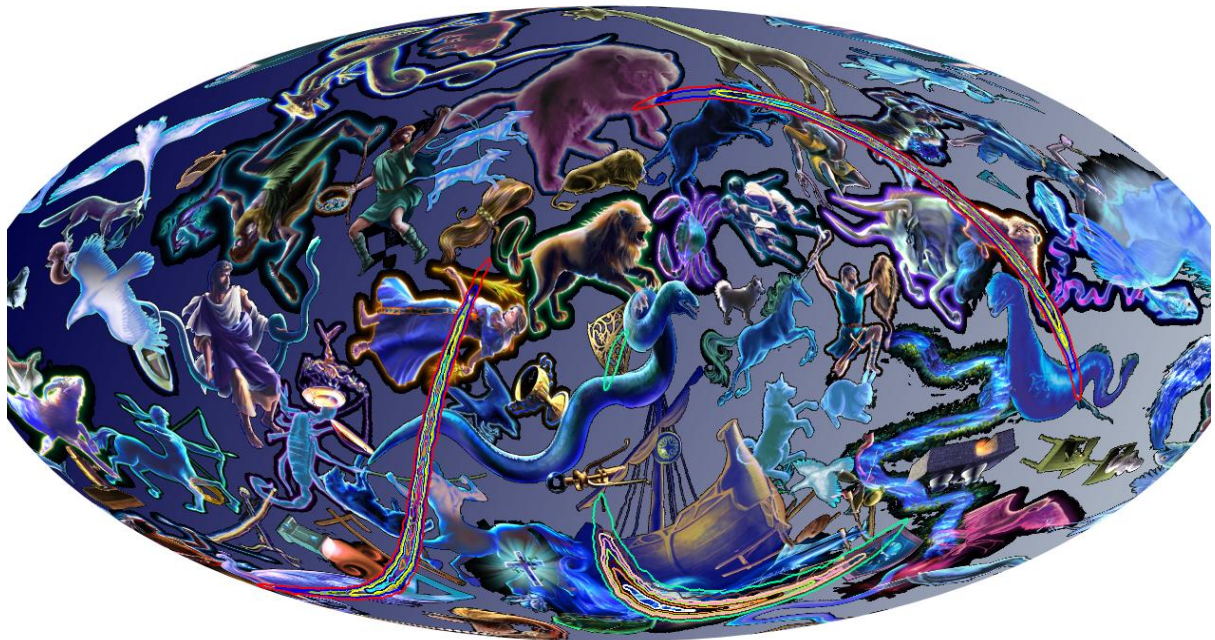


# Handling gravitational-wave sky maps for EM-followUP observations

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Second ASTERICS Virtual Observatory School

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**Cover image:** the sky locations of the two gravitational-wave events detected so far: **GW 150914** and **GW 151226**. The colored lines represent the enclosed probabilities from a 90% confidence level to a 10% confidence level in step of 10%. Background: Artistic constellation map. Image credit: LIGO/Virgo/Aladin.

## Summary

The Birth of Gravitational-Wave Astronomy.....	3
 Sky Maps and Skymap Viewer .....	5
 Load a probability sky map .....	5
 MOC representation of sky areas enclosed into iso-contour lines .....	7
 MOC contour plot generation .....	8
 Query Catalogs from MOC contour plots .....	9
 SAMP .....	10
 Send Aladin planes to TOPCAT via SAMP .....	10
 3D sky maps .....	11
 The Marginal Distance Distribution Integrated over the Sky .....	11
 Planning for follow-up observations .....	13
Appendix I: load instrument FoV .....	14
Appendix II: GWsky.....	15

## The Birth of Gravitational-Wave Astronomy

On September 14, 2015 at 09:50:45 UTC, the LIGO/Virgo Collaboration (LVC; [Abbott et al. 2016](#)) made the first direct detection of an astrophysical gravitational-wave (GW) signal that turned out to be from a binary black hole (BBH) merger. Twenty-five participating teams of observers responded to the GW alert to mobilize satellites and ground-based telescopes spanning 19 orders of magnitude in EM wavelength. Fig. 1 shows the footprints of all reported observations in comparison with the 50% and 90% credible levels of the initially distributed GW localization maps. The radio fields are shaded in red, optical/infrared fields are in green, and the XRT fields are indicated by the blue circles. The all-sky *Fermi* GBM, LAT, *INTEGRAL* SPI-ACS, and MAXI observations are not shown. Where fields overlap, the shading is darker. The initial [cWB](#) localization is shown as thin black contour lines and the [LIB](#) localization as thick black lines. The inset highlights the *Swift* observations consisting of a hexagonal grid and a selection of the *a posteriori* most highly ranked galaxies.

This first broadband campaign to search for a counterpart of an Advanced LIGO and Virgo source represents a milestone and highlights the broad capabilities of the transient astronomy community. The localization and broadband follow-up of this GW event constitutes an important first step in a new era of gravitational wave multi-messenger astronomy.

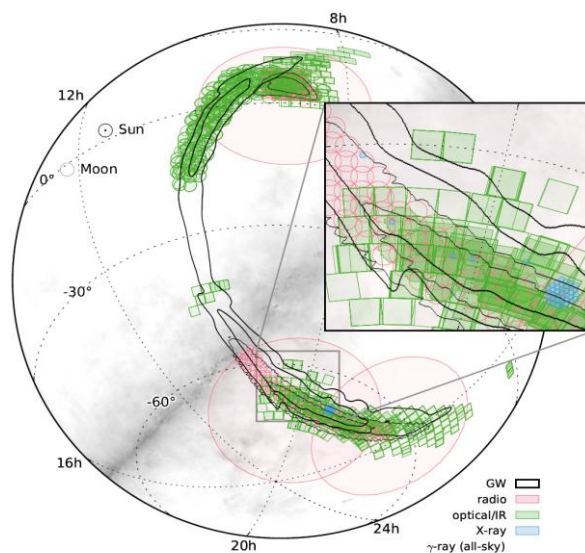


Figure 1. EM followUP campaign of GW 150914 from [Localization and broad follow-up of the gravitational-wave transient GW150914](#), Abbott et al. 2016.

The tutorial focuses on some basic strategies for working with gravitational-wave sky maps in the context of the EM-followUP activity. Here we propose the use of [Aladin](#), [TOPCAT](#), [Skymap Viewer](#) and [GWsky](#).

The following main topics are addressed.

- 1) Probability sky map visualization
- 2) Access to existing catalogs using the Multi-Order Coverage map (MOC)
- 3) Planning for follow-up observations

Here the simulated sky maps for compact binary Coalescence (CBC) sources from [The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo](#) (F2Y; Singer *et al.* 2014) and from [Going the distance: Mapping Host Galaxies of LIGO and Virgo Sources in Three Dimensions Using Local Cosmography and Targeted Follow-up](#) (3D; Singer *et al.* 2016) are used. The sky maps for burst events are simulated in the paper [Localization of short duration gravitational-wave transients with the early advanced LIGO and Virgo detectors](#) (Essick *et al.* 2015).



You are the operation manager at the ESO Paranal Observatory. The LIGO-Virgo alert number G211117 was received few minutes ago. Your task is to review and evaluate the follow-up strategy for the VLT Survey Telescope proposed by your team.

Before you can do this, you first need to learn how to visualize and process GW sky maps. This tutorial will take you gradually through the various steps.

The tutorial is organized as follows.



are short focus sections in which the main concepts are reported.



are work sections in which the students are invited to explore the proposed steps.



are short exercises assigned at the end of a section.

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## Sky Maps and Skymap Viewer

LIGO/Virgo probability sky maps are all-sky images stored in the [HEALPix](#) projection, a format that is used for [Planck](#) all-sky CMB maps and by Aladin for [archival all-sky survey images](#). The sphere is hierarchically tessellated into curvilinear quadrilaterals; the resolution of the tessellation increases by the division of each pixel into four new ones. The lowest resolution partition is comprised of twelve base pixels. The value stored at each pixel is the probability that the gravitational-wave source is within that pixel. The pixel position on the sky is uniquely specified by the index in the array and the array's length.

[Skymap Viewer](#) is an interactive, web-based tool to display a sky map in an astronomical context along with a host of relevant information for follow-up observers. The sky map is shown as a contour plot, each color-coded line enclosing a given percentage of the total probability (see Fig. 2).

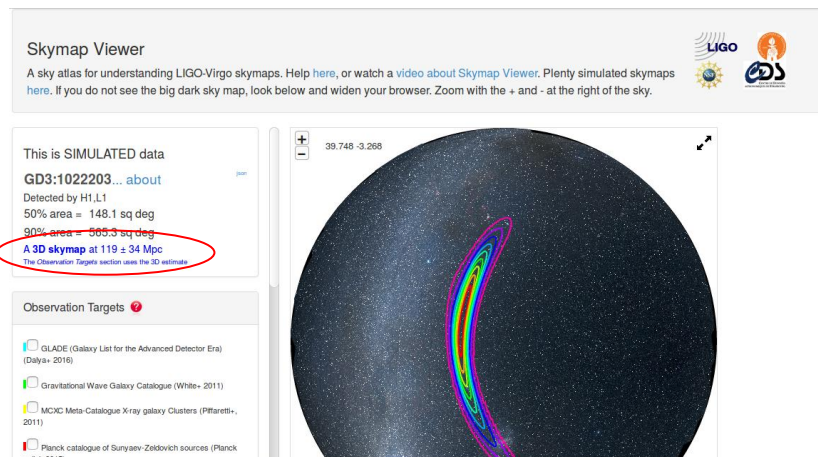


Figure 2. Skymap Viewer is a sky atlas for understanding LIGO-Virgo sky maps based on AladinLite. In the red ellipse the marginal distance distribution integrated over the sky is shown when a 3D skymap is loaded.



## Load a probability sky map

The sky maps for Compact Binary Coalescence (CBC) from the rapid pipeline *Bayestar* are considered in the tutorial. For associated data release, see these http URLs [F2Y](#) and [3D](#) ; a Skymap Viewer gallery of these sky maps is shown [here](#).



As an example, the simulated skymap with **id: 1022203** is chosen.

- ❖ Link to associated data release (F2Y): <http://www.ligo.org/scientists/first2years/2016/compare/1022203/bayestar.fits.gz>
- ❖ Link to Skymap Viewer: <https://losc.ligo.org/s/skymapViewer/aladin/index.html#F2Y:1022203>
- ❖ Link to Skymap Viewer (3D): <https://losc.ligo.org/s/skymapViewer/aladin/index.html#GD3:1022203>

• To load any file in the Aladin stack (Fig. 3) three methods are suggested.

**I. Using Aladin GUI.**

- file → Open local file *or*
- file → Open URL *or*
- drag the file into the Aladin window

**II. Using the Aladin console.**

- To open the Aladin console execute **F5** otherwise Tool → Script Console.

```
load http://www.ligo.org/scientists/first2years/2016/compare/1022203/bayestar.fits.gz
load your folder location on your local PC
```

**III. The script commands as well as coordinates, object, filename and URL can be type in the Location box.**

- The Location box is indicated with a red circle in Fig. 3.

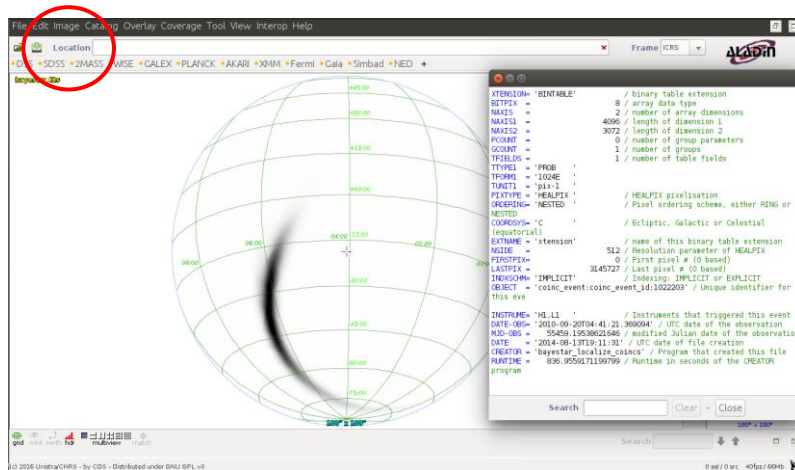


Figure 3. Loaded a probability sky map in the first Aladin plane. The header is also shown: Edit -> Fits header [Alt+H].

The image header can be shown from the menu:

Edit → Fits header or by typing [Alt+H].

The metadata of the FITS file are described in [LIGO-Virgo EM Follow-Up Tutorial](#).



**Exercise 1.** Fill the table using the header information of the selected CBC simulated sky map.

NSIDE	
INSTRUME	
OBJECT	
DATE-OBS	
CREATOR	

Table 1. Main header information of a LVC probability sky map.



## MOC representation of sky areas enclosed into iso-contour lines

[The Multi-Order Coverage](#) (MOC) method is based on the HEALPix tessellation algorithm and it is essentially a simple way to map irregular and complex sky regions into hierarchically grouped predefined cells. The operations between MOC maps (union, intersection, subtraction, difference, complement) are extremely simple and fast (generally a few milliseconds) even for very complex sky regions. In addition to this, some data servers, such as Vizier, can be “queried by MOC” in order to return data (catalog sources/list of images) only inside the MOC coverage.

As mentioned above - in Fig. 2 each line encloses a given percentage of the total probability. These contours were constructed using a “water-filling” algorithm: the pixels from most probable to least are ranked, and finally the pixels are summed up to get a fixed level of probability; see [The First Two Years of Electromagnetic Follow-up with Advanced LIGO and Virgo](#) (Singer *et al.* 2014).

The enclosed area within a given probability level of a GW sky map can be effectively described through the Multi-Order Coverage (MOC) method<sup>1</sup>. The HEALPix pixels (ipix) inside a given contour plot are extracted

<sup>1</sup> Skymap Viewer does not implement the “MOC contour plot”; interpolation techniques are preferred using the four nearest points. Here only the MOC methods are discussed – however the results are quantitatively comparable.

and the ipix table is used to generate the MOC coverage; for more details see [Handling gravitational-wave sky maps with Multi-Order Coverage](#).



## MOC contour plot generation

The Figs 4-5 show the MOC contour plot from 10% to 90% credible levels (enclosed probability) in step of 10%. A better graphical display is obtained choosing “perimeter” in the *Drawing method* from the **Properties** window. The **Properties** window is opened by the right-click action on the selected MOC plane

Two equivalent approaches are proposed.

### 1) Using Aladin GUI

➤ Coverage → Generate a MOC based on... → The current probability skymap

### 2) Using the Aladin console

```
cmoc -threshold=0.9 the current probability sky map loaded in the Aladin plane
```

NOTE: The drawing method “perimeter” is not implemented in the script commands in Aladin Beta version v9.039.

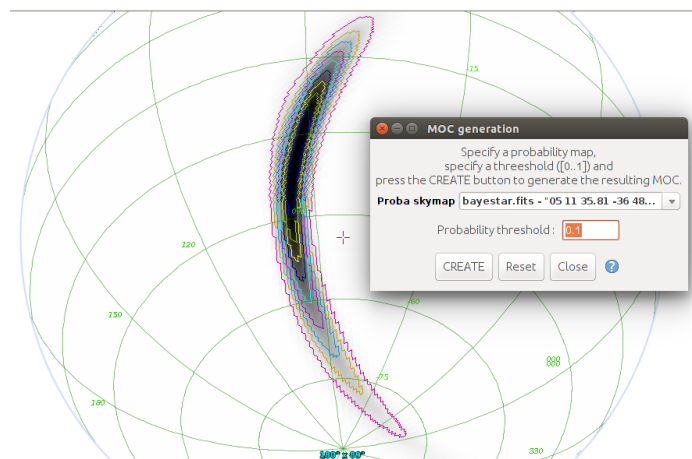


Figure 4. Generation of MOC contour plot from 0.1 to 0.9 probability threshold (enclosed probability) in step of 0.1 using Aladin console.



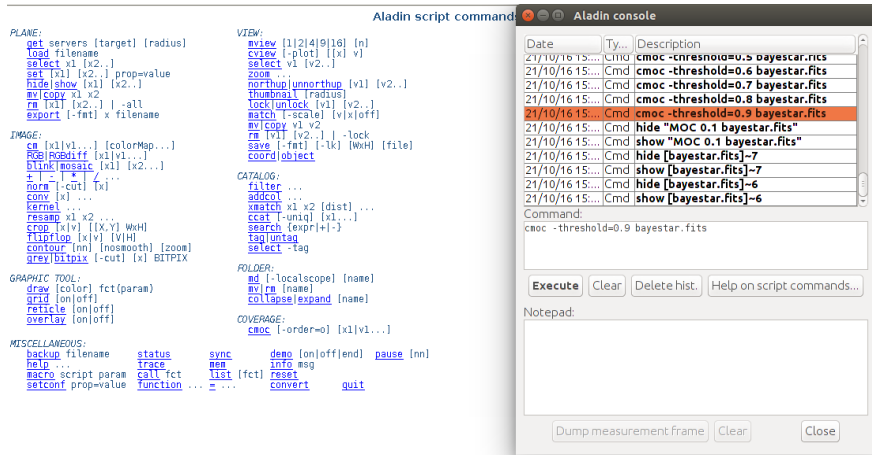


Figure 5. Generation of MOC contour plot from 0.1 to 0.9 probability threshold (enclosed probability) in step of 0.1 using Aladin script commands.



**Exercise 2.** Fill the table of a MOC contour plot.

sky coverage (in square degrees) in MOC 0.9	
sky coverage (in square degrees) in MOC 0.5	
% of sky coverage in MOC 0.9	
% of sky coverage in MOC 0.5	

Table 2. Coverage values using the MOC approach optimized for the gravitational-wave sky localization.

## Query Catalogs from MOC contour plots



In this section, we show how MOC contour plots can be used to query catalog objects that fall into the sky map region. The MOCs of all VizieR tables footprints are available [on line](#) (about 16.000 tables) and can be queried in few seconds. As an example, we query the VizieR table of the [GLADE](#) catalog.

Fig. 6 shows the **Server selector** window for sending the query:

File → Load catalog → MOC.

The source positions are displayed in blue inside the MOC region drawn in red – see Fig. 7.

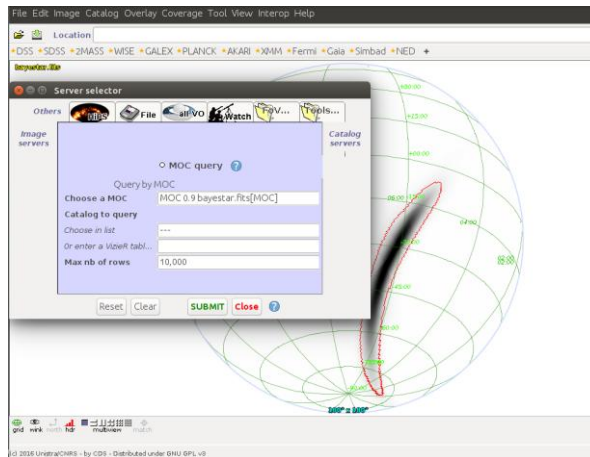


Figure 6. Server selector to query catalog objects that falls into a MOC map in which the 90% of the probability is enclosed – red perimeter line.

NOTE: pay attention to the *Max nb of rows* in the *Server selector* window.



[SAMP](#) (Simple Application Messaging Protocol) is a messaging protocol that enables astronomy software tools to interoperate and communicate. It is a standard for allowing software tools to exchange control and data information, thus facilitating tool interoperability, and so allowing users to treat separately developed applications as an integrated suite. An example of an operation that SAMP might facilitate is passing a source catalogue from one GUI application to another, and subsequently allowing sources marked by the user in one of those applications to be visible as such in the other.



## Send Aladin planes to TOPCAT via SAMP



Fig. 7 shows the interoperability between Aladin and TOPCAT. To send the Aladin plane “glade MOC query” to TOPCAT:

right-click on the selected plane → broadcast selected tables to → TOPCAT

In TOPCAT window, double-click on the table in the Table List to see the table. You can also display the

table metadata  or column metadata .



### Exercise 3. Make the Histogram Plot of the distance

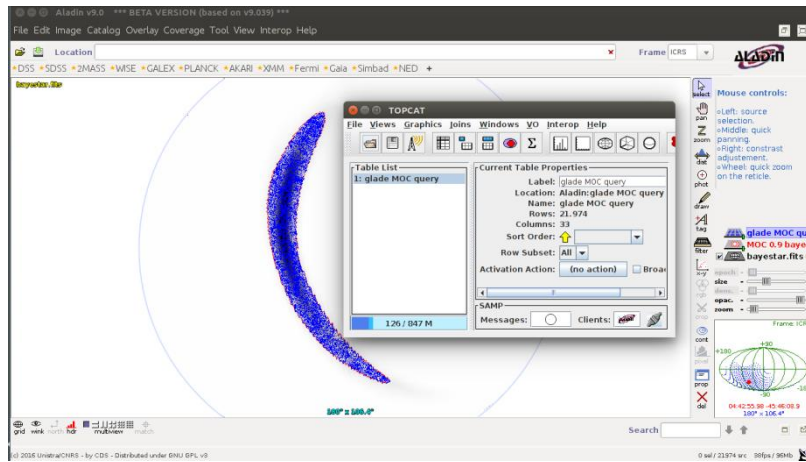


Figure 7. SAMP at work: broadcast selected tables to TOPCAT. The TOPCAT GUI with the loaded query catalog is shown superimposed to the Aladin window.



## 3D sky maps



Singer *et al.* (2016) discuss a rapid algorithm for obtaining joint three-dimensional estimates of sky location and luminosity distance from observations of binary neutron star mergers with Advanced LIGO and Virgo. They argued that combining the reconstructed volumes with positions and redshifts of possible host galaxies can provide a manageable list of targets to search for optical or infrared emission.



## The Marginal Distance Distribution Integrated over the Sky

The marginal distance distribution integrated over the sky is reported in the Skymap Viewer – see the value position in Fig. 2. As a first approximation such value can be use to cut the distance galaxy distribution plotted in Ex. 3.

By using TOPCAT:

Display row subset  → define a new subset using algebraic expression  → fix a subset name and define an expression in the **Define Row Subset** window. Such steps are shown in Fig. 8.

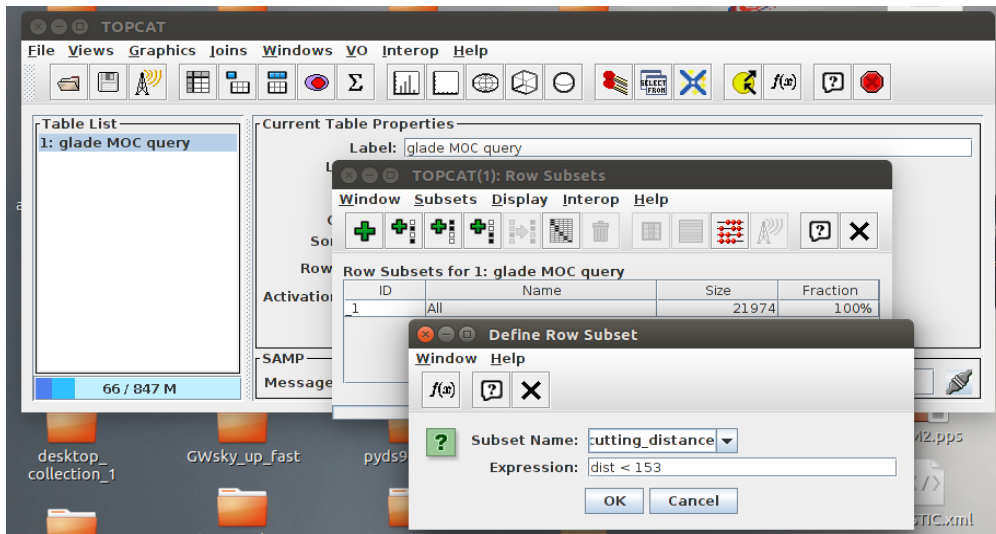



Figure 8. A new subset from a catalog using the TOPCAT GUI. The algebraic expression is defined in the “Define Row Subset” window.



**Exercise 4.** Plot the galaxy distance of the new subset obtained by the probability density per unit distance integrated over the entire sky.

Finally, send your post-processing subset “cutting\_distance” to Aladin plane using the Interop . The result is shown in Fig. 9.

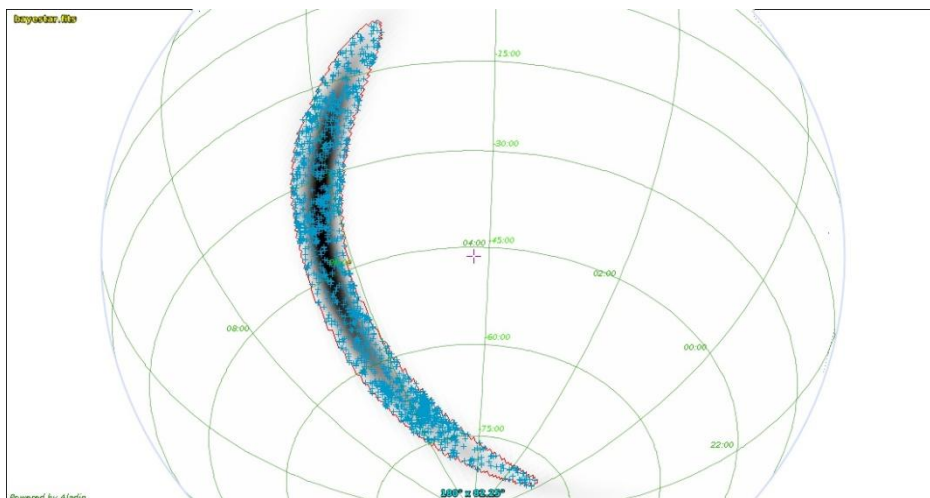


Figure 9. The new subset processed by TOPCAT is shown in the Aladin plane via SAMP.

NOTE: pay attention on selecting the "Row Subset" box in the main TOPCAT window.



## Planning for follow-up observations

The LIGO-Virgo data are analyzed in near real-time to search for GW transients due to compact binary coalescence (CBC) events or unmodeled "burst" sources. For each detection candidate, a series of alerts are produced and distributed via the Gamma-ray Coordinates Network/Transient Astronomy Network (GCN/TAN, Fig. 10). It has been in use since the early 1990s to transmit times and coordinates of gamma-ray bursts (GRBs) detected by gamma-ray space missions to ground-based observers.

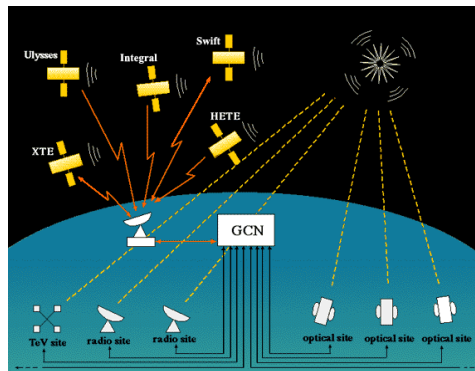


Figura 10. The GCN network.

You are at [ESO-Paranal Observatory](#) in Chile and your team are planning to observe 72 deg<sup>2</sup> of the sky map of the advanced [LIGO and Virgo trigger G211117](#) (confirmed as [GW151226](#)), with the VLT Survey Telescope ([VST](#)) equipped with OMEGACAM. The observations are divided in 8 regions 3 x 3 deg<sup>2</sup> each, centered on the following coordinates RA, Dec (J2000):

**02:29:55.200 +16:13:12.00**

**02:38:02.208 +19:13:12.00**

**02:46:35.712 +22:12:33.84**

**02:59:40.800 +25:13:12.00**

**03:06:55.128 +28:13:12.00**

**03:18:23.712 +31:13:12.00**

**13:45:53.208 -26:48:00.00**

**13:39:47.208 -23:48:00.00**

Table 3. Data from GCN 18734; LIGO/Virgo G211117: INAF VST-ESO PARANAL observations.

Your team ask you to prepare a skychart using Aladin and TOPCAT in which are showed

1. the VST FoVs
2. the MOC contour plot using the bayestar sky map – from 10% to 90%.
3. the GLADE galaxy catalog in 90% of probability threshold
4. the galaxy distance < 150 Mpc

**BAYESTAR low latency:** <https://losc.ligo.org/s/skymapViewer/aladin/index.html#GW151226:BG>

**BAYESTAR low latency FITS DATA:** <https://losc.ligo.org/s/events/GW151226/P1500227/bayestar.fits.gz>

The resulted observational plan is shown in <https://www.grawita.inaf.it/highlights/> while the step 2 is described in the Appendix I.

*NOTE: the exercise can be easily done with the GWsky tool. GWsky is briefly described in Appendix II for illustrative purposes but it is outside the scope of this tutorial.*

## Appendix I: load instrument FoV

You can describe your FoV in a simple XML/VOTable document and you can load this file in Aladin to draw it. More specifically as shown in Fig. 11:

From File → load Instrument FoV → server selector → Create your own

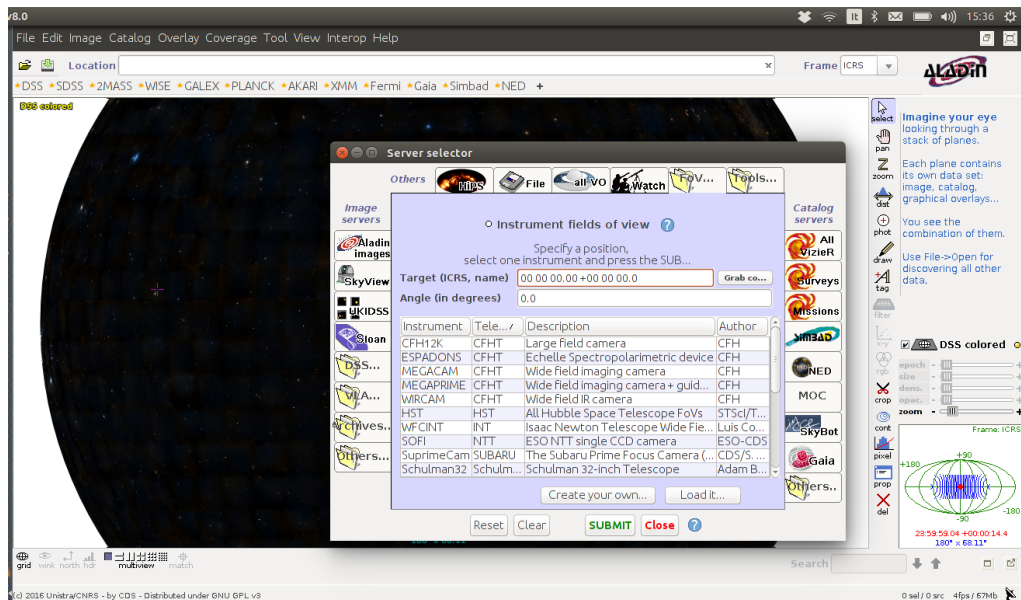


Figure 11. Server selector window.

You are directed to the page [Instrument Footprint Editor](#) in which we can draw your suitable FoV. Save the file from the page and load in Aladin using the *Load it...* button in the **Server selector** window. Once all



previous operations have been carried out, specify a position in the Target (ICRS, name) and press the **SUBMIT** button. The FoVs will be drawn as new Aladin plans.

## Appendix II: GWsky

GWsky is an interactive Python script to generate a sequence of pointings given a specific Field of View (FoV). The script aims to split the large GW sky localization into several independent areas. The FoVs are evenly spaced assuming that the shortest angular distance between two points on the celestial sphere is measured along a great circle that passes through both of them. The results are displayed in Aladin Sky Atlas using the *SAMPIntegratedClient* class. The airmass and the integrated probability are provided in real time. The GUI is shown in Fig. 12; GWsky can be downloaded from <https://github.com/ggreco77/GWsky>.

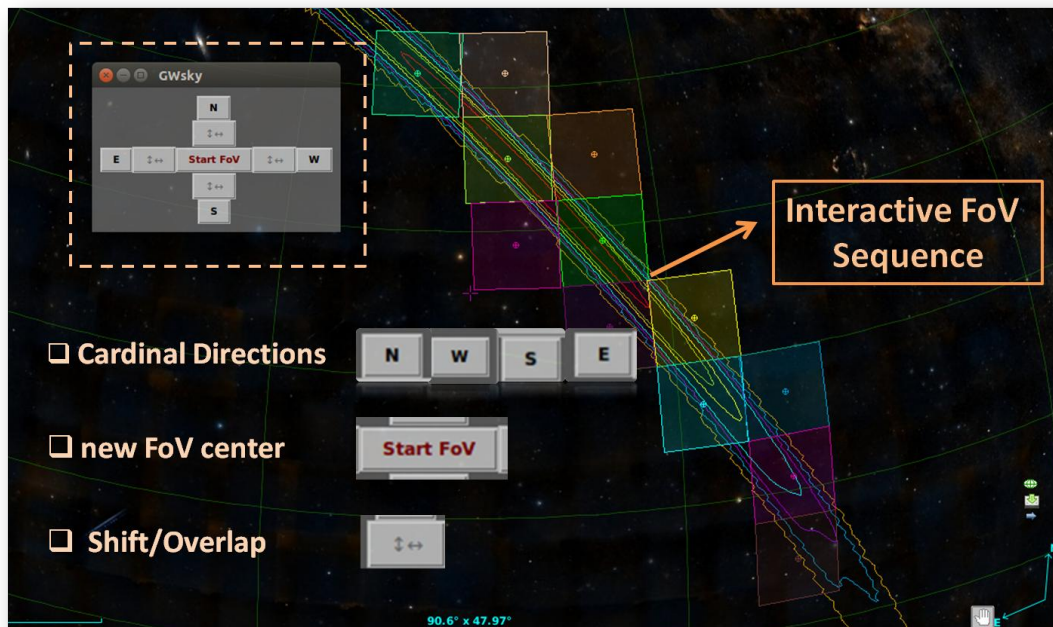


Figure 12. GWsky Graphical User Interface.