Handling gravitational-wave sky maps for EM-followUP observations

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

Introduction

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**.

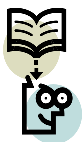
The following main topics are addressed.

1) Probability sky map visualization
2) Access to existing catalogs
3) Planning for follow-up observations

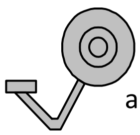
Here the simulated sky maps for compact binary Coalescence (CBC) sources from **The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo** (F2Y; Singer et al., 2014) and **Going the distance: Mapping Host Galaxies of LIGO and Virgo Sources in Three Dimensions Using Local Cosmography and Targeted Follow-up** (3D; Singer et al., 2016) are used.

The sky maps for burst events are simulated from **Localization of short duration gravitational-wave transients with the early advanced LIGO and Virgo detectors** (Essick et al., 2015).

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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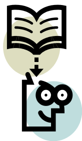
Sky Maps and Skymap Viewer 

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. 1).

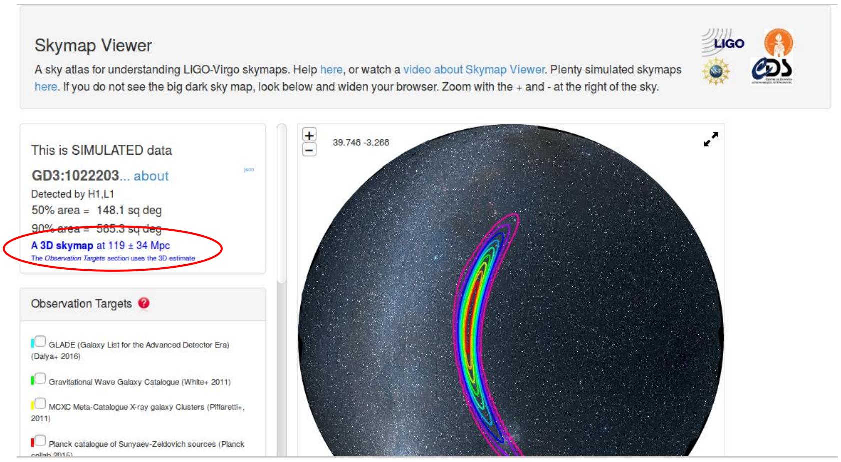


Fig. 1 Skymap Viewer is a sky atlas for understanding LIGO-Virgo sky maps based on AladinLite. In the red ellipse the marginal distance distribution integrated over the sky is shown when a 3D skymap is loaded.

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 choosen.

- ❖ 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.2) 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 type **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. 1.

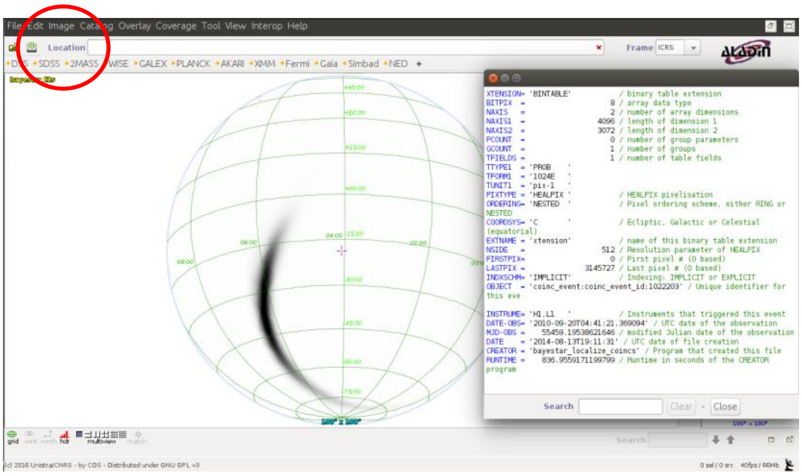
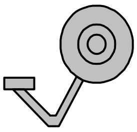


Fig. 2 Loaded a probability sky map in the first Aladin plane. The header is also shown: Edit -> Fits header [Alt+H].

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.

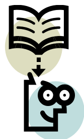


Ex. 1 Fill the table using the header information of the selected CBC simulated sky map.

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, same 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. 1 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[1]. The HEALPix pixels (ipix) inside a given contour plot are extracted and the ipix table is used to generate the MOC coverage; for more details see Handling gravitational-wave sky maps with Multi-Order Coverage.

[1] 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.

MOC contour plot generation

The Figs 3-4 show the MOC contour plot from 0.1% to 0.9% (enclosed probability) in step of 0.1. 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*

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

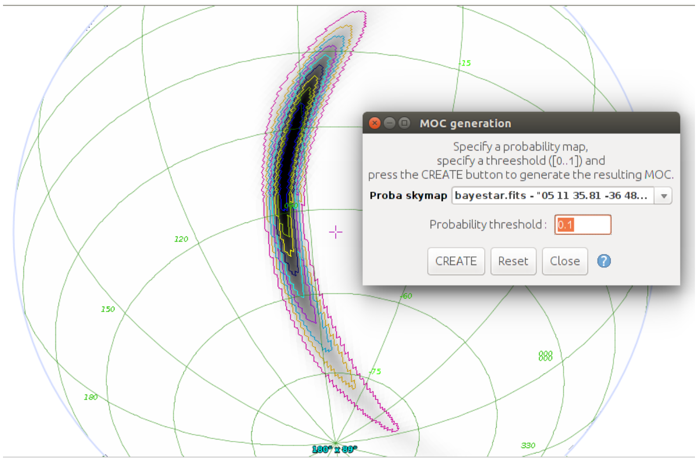


Fig. 3 Generation of MOC contour plot from 0.1% to 0.9% (enclosed probability) in step of 0.1 using Aladin console.

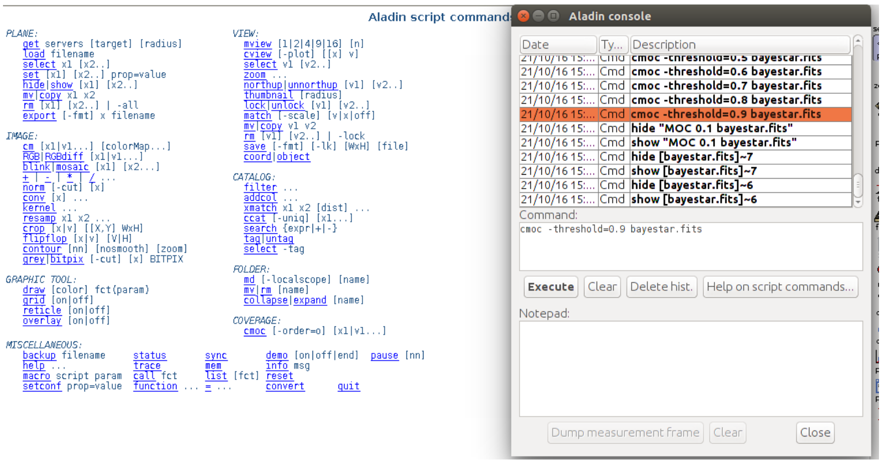
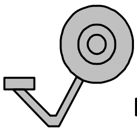


Fig. 4 Generation of MOC contour plot from 0.1% to 0.9% (enclosed probability) in step of 0.1 using Aladin script commands.



Ex. 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 use to query catalog objects that falls 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 GLADE catalog.

Fig. 5 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. 6.

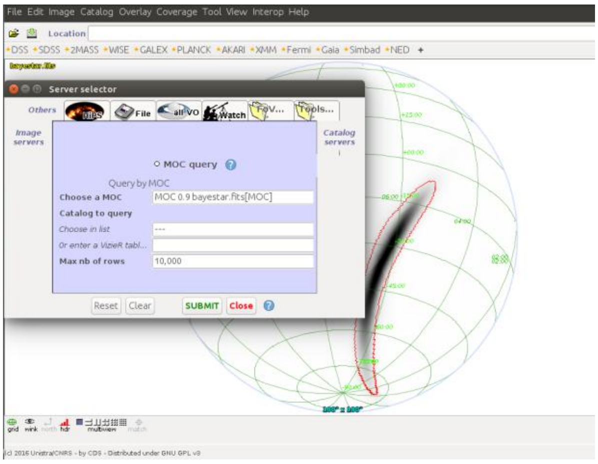
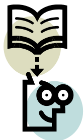


Fig. 5 Server selector to query catalog objects that falls into a MOC map in which the 90% of the probability is enclosed – red perimenter line.

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

SAMP 

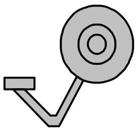
<u>SAMP</u> (Simple Application Messaging Protocol) is a messaging protocol that enables astronomy software tools to interoperate and communicate. It is a standard for allowing software tools to exchange control and data information, thus facilitating tool interoperability, and so allowing users to treat 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. 6 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 .



Ex. 3 Make the Histogram Plot of the distance **.**

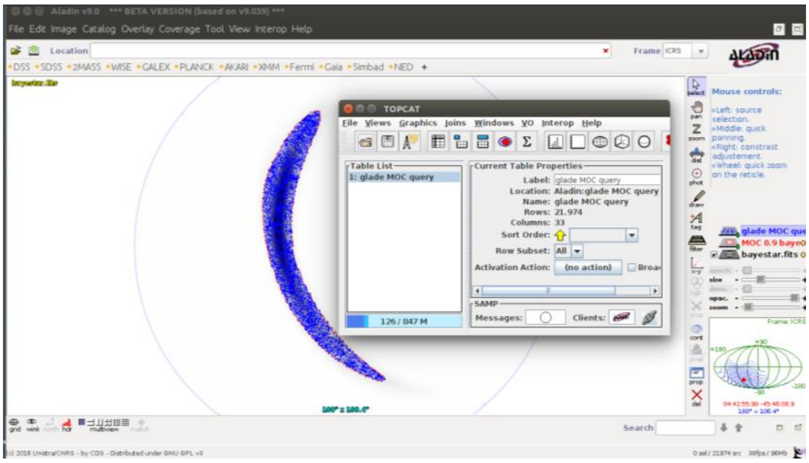
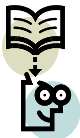


Fig. 6 SAMP at work: broadcast selected tables to → TOPCAT. The TOPCAT GUI with the loaded query catalog is shown superimposed to the Aladin window.

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. 1. 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. 7.

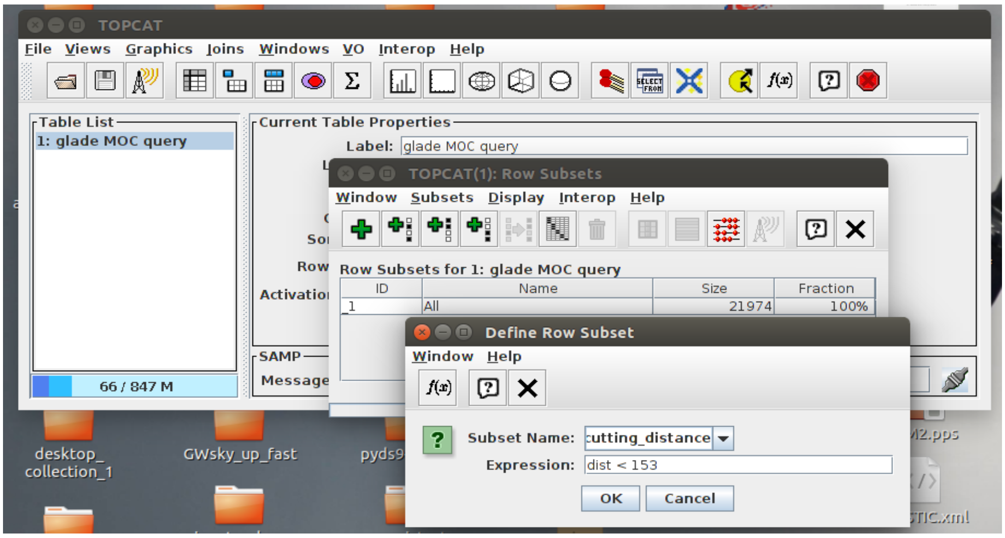
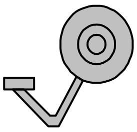


Fig. 7 A new subset from a catalog using the TOPCAT GUI. The algebric expression is define in the "Define Row Subset" window.



Ex. 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. 8.

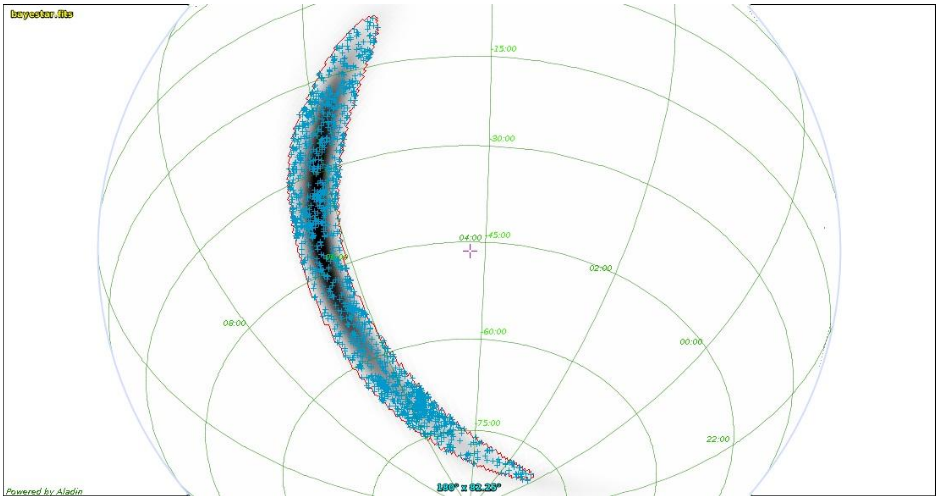
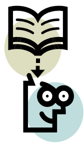


Fig. 8 The new subset processed by TOPCAT is shown in the Aladin plane via SAMP.

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

Tiling the skymap: 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. GWsky make use of astropy and healpy packages. Here a basic version of the script is used. The GUI is shown in Fig. 9

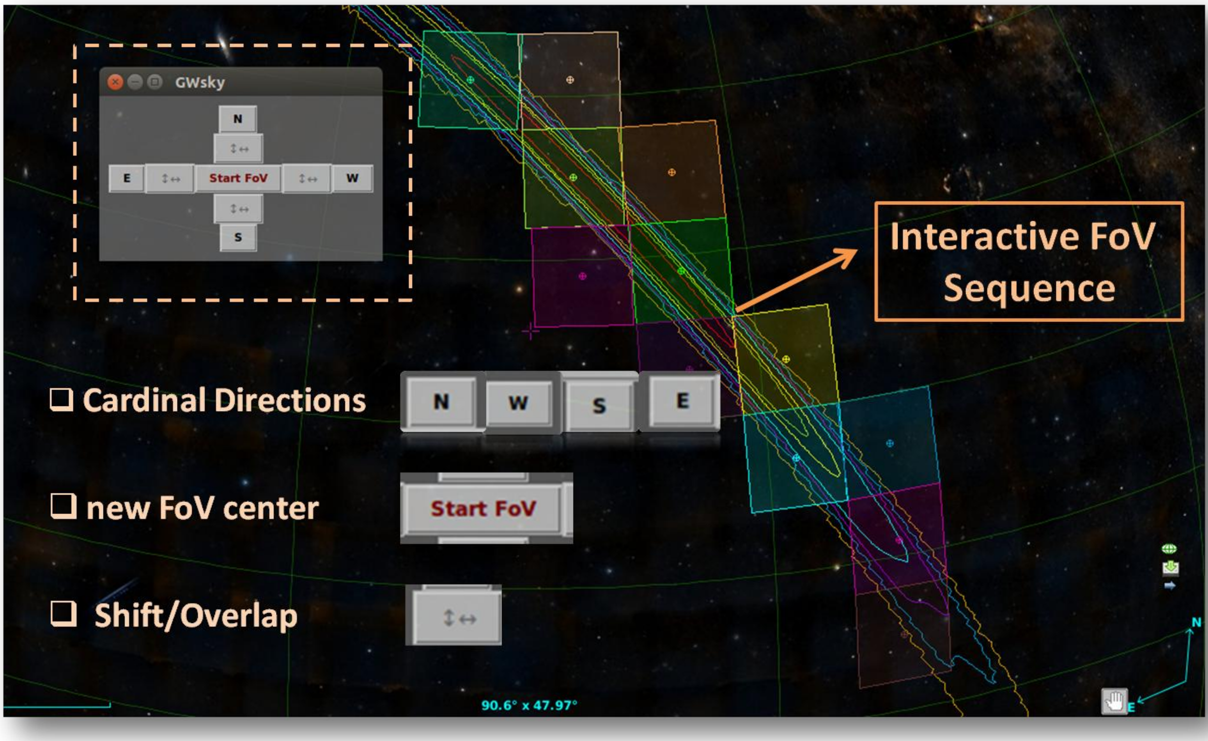


Fig 9 GWsky Graphycal User Interface. The GUI is written using the TKinter module.

Planning for follow-up observations 

We tile the gravitational wave sky localization using the GWsky tools for preparing a telescope schedula. As an example the observational plane requires 10 observations using

A telescope with a FoV 3°x3° located in Paranal Observatory is used. The allowed values of the airmass can ranges from 1 to 2.5. in progress