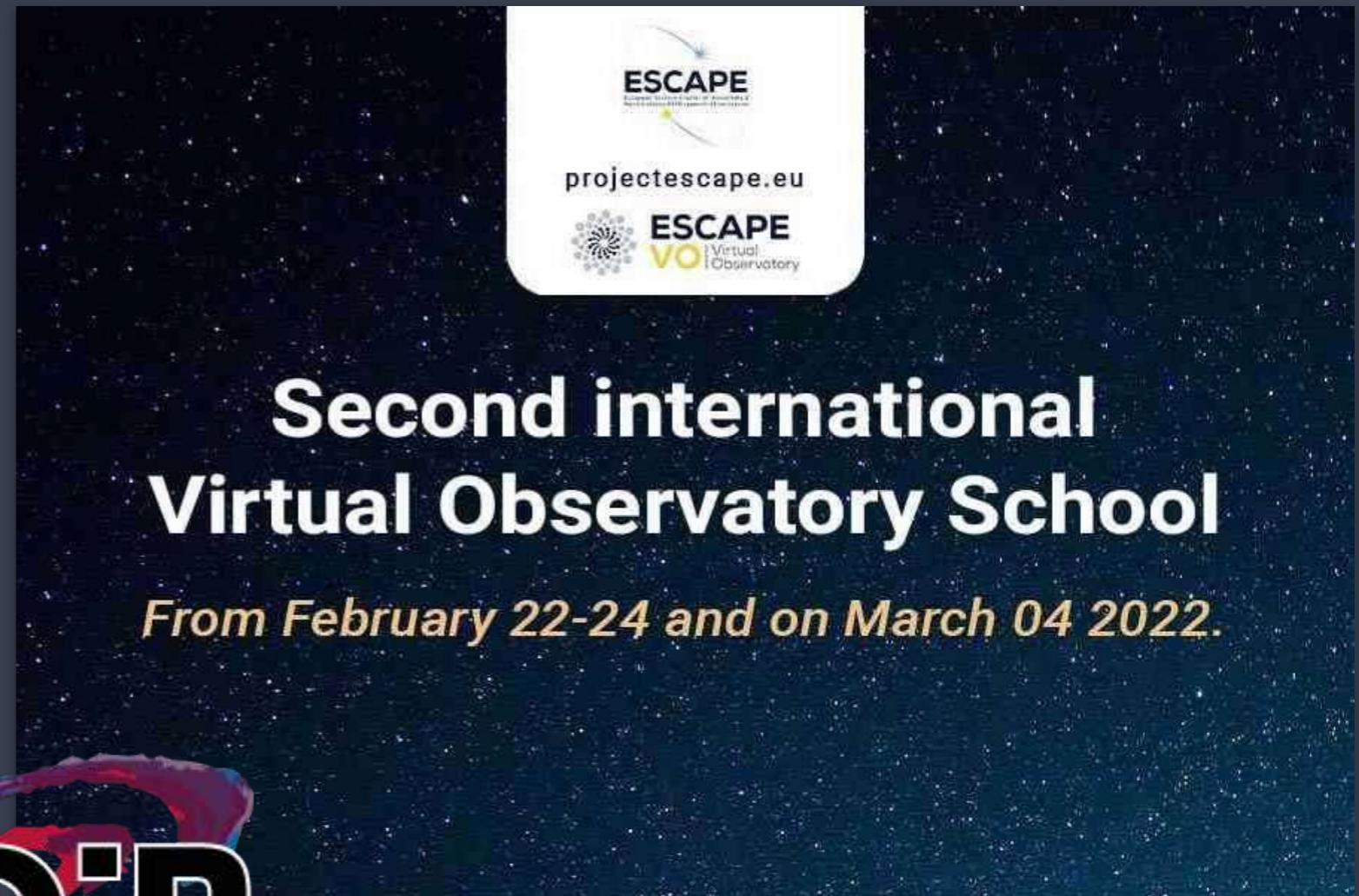


Multi-messenger astronomy

ALADIN DESKTOP AT WORK

ALADin



Practical examples to manage gravitational-wave sky localisations

VO standards and tools

CONTENTS

- Load a gravitational-wave sky map
- Build a credible area
- Space coverage analysis
- Spatial and temporal coverage analysis
- Catalog queries and filters
- Tiling
- Retrieve images in FITS format
- Visibility

On August 17, 2017 astronomers around the world were alerted to gravitational waves observed by the [Advanced LIGO](#) and [Advanced Virgo](#) detectors. This gravitational wave event, now known as GW170817, appeared to be the result of the merger of two neutron stars. Less than two seconds after the GW170817 signal, NASA's Fermi satellite observed a gamma-ray burst, now known as GRB 170817A, and within minutes of these initial detections telescopes around the world began an extensive observing campaign. The Swope telescope in Chile was the first to report a bright optical source (SSS17a/AT2017gfo) in the galaxy NGC 4993 and several other teams independently detected the same transient over the next minutes and hours. For the next several weeks astronomers observed this location with instruments sensitive across the electromagnetic spectrum; all these observations provide a comprehensive view of this cataclysmic event starting ~100 seconds before merger until several weeks after. The observations support the hypothesis that two neutron stars merged in the galaxy NGC 4993 - producing gravitational waves, a short-duration gamma-ray burst, and a kilonova. GW170817 marks a new era of multi-messenger astronomy, where the same event is observed by both gravitational waves and electromagnetic waves ([THE DAWN OF MULTI-MESSENGER ASTROPHYSICS: OBSERVATIONS OF A BINARY NEUTRON STAR MERGER](#)).

The tutorial aims to analyze the first multi-messenger event in the context of the Virtual Observatory standard (ST-MOC) and tool (Aladin).

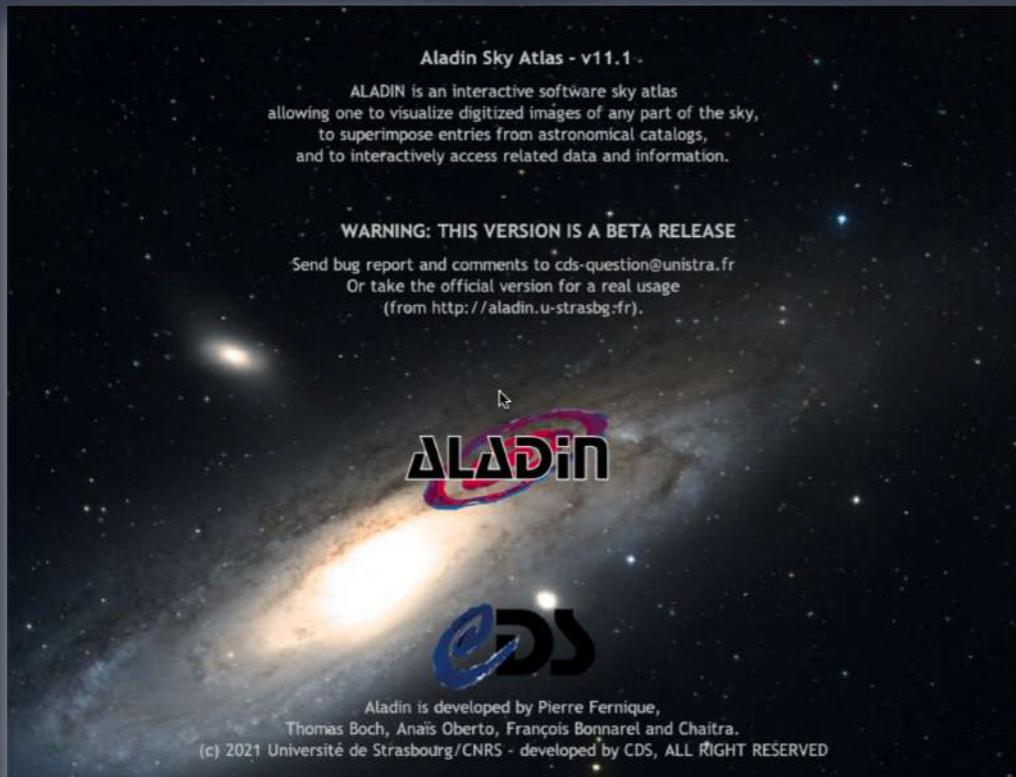


Fig.1 Input window that appears when the Aladin software was first launched.



Fig.2 Aladin Stack. Two planes are loaded.

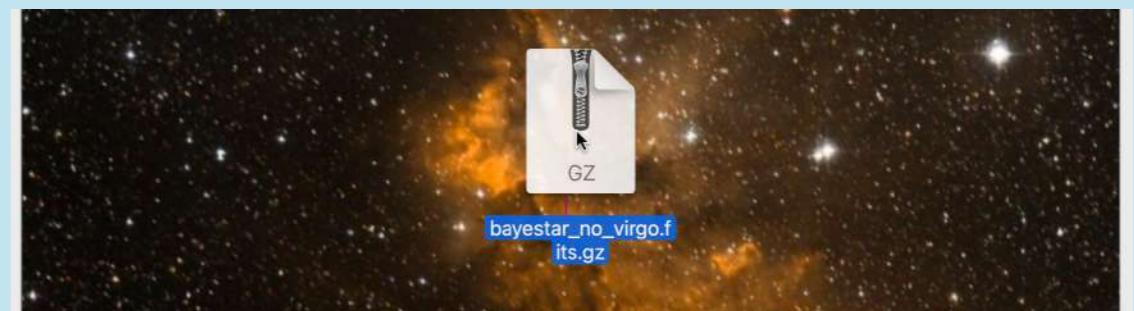
1. LOADING SKY MAPS

To load any (probability) sky map in the Aladin environment, you can:

- 1) **copy and paste** the sky map URL from the page into the Aladin command bar;



- 2) or **drag and drop** the HEALPix FITS file from your operating system's file browser in the main Aladin window.



Note. Before dragging the file, remember to initialize the Aladin Desktop section by clicking on the main window (**Fig.1**). By default the DSS2 color survey is loaded.

All loaded planes are stacked in the so-called Aladin Stack (**Fig.2**). For more information on the use of the Aladin stack, click on **Fig.2** to be directed to a specific video tutorial.

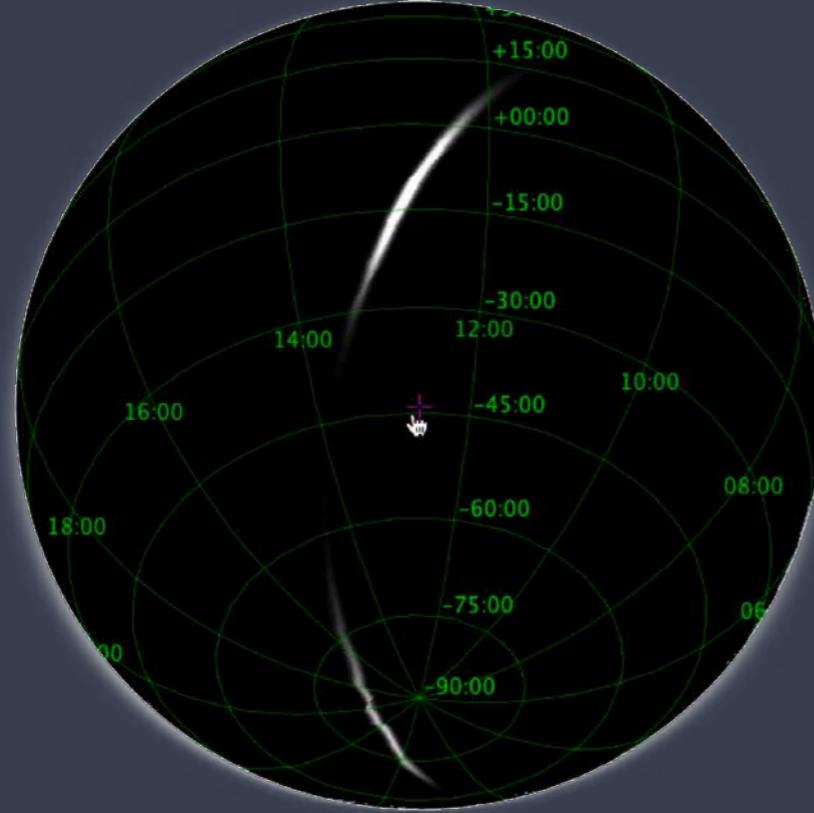


Fig.3 Initial sky localisation of GW170817 from the two LIGO detectors as shown in the main Aladin window.

2. BUILDING A CREDIBLE REGION

We analyze the initial gravitational-wave sky localisation of [GW170817](#). The data are stored in a public web page: [LIGO Document G1701985-v001](#).

We start with loading the initial gravitational-wave sky localisation from the two LIGO interferometers [BAYESTAR without Virgo localization](#) (**Fig.3**). For this sky map, we calculate the 90% credible area and visualize the result in the Aladin Desktop.

In the Aladin Desktop application a dedicated function is available to generate a credible region at a defined confidence level. This is accomplished by selecting the menu bar item called:

Coverage → Generate a spatial MOC based on → The current probability skymap (Fig.4).

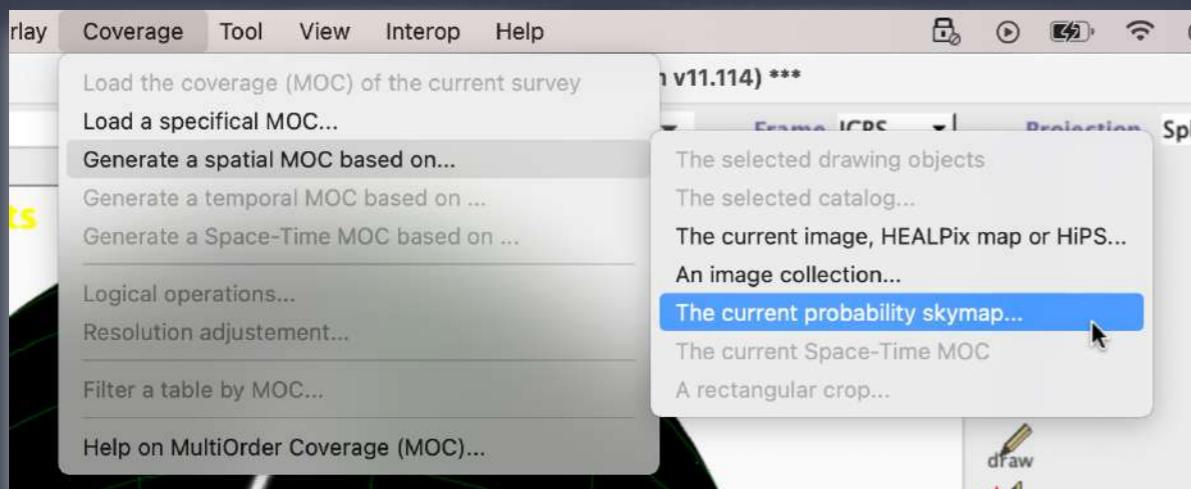


Fig. 4. Aladin GUI commands to generate a credible area. The contextual window is shown in Fig.5.

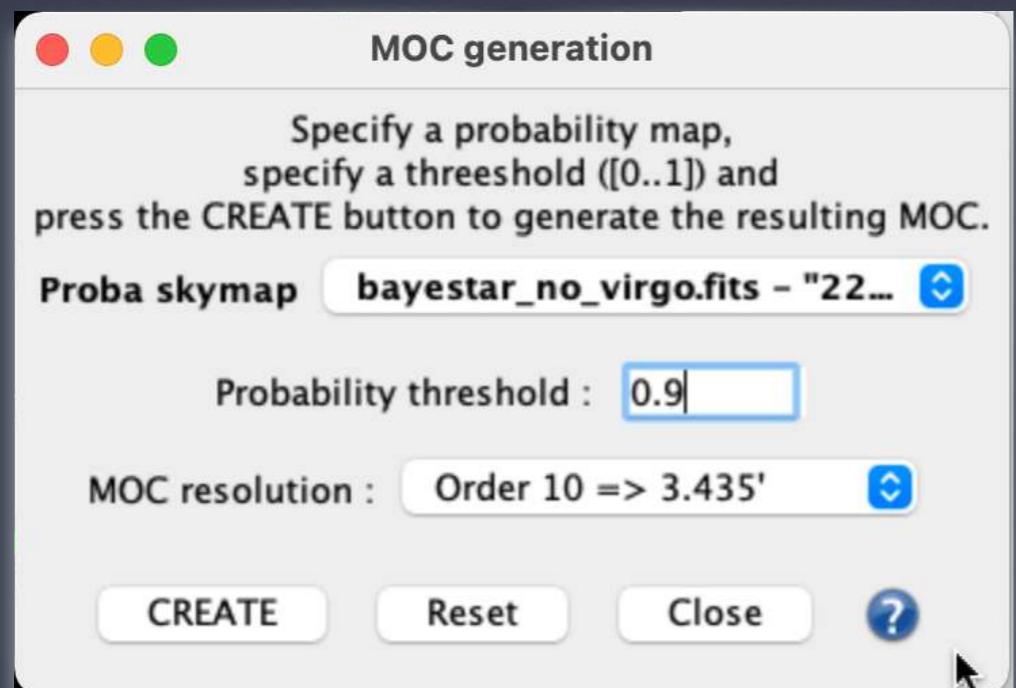


Fig.5 MOC generation window to create a spatial MOC coverage from a probability sky map. The contextual window opens by executing the commands in Figure 4.

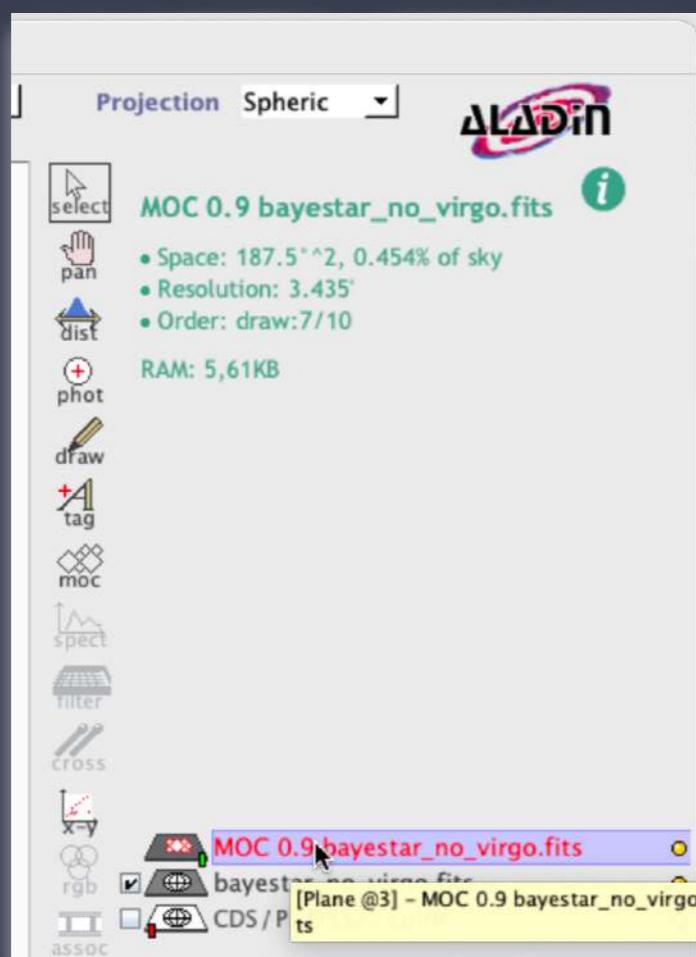


Fig.6 Aladin stack in which a credible region encoded in a MOC data structure is loaded.

The MOC generation window, shown in **Fig. 5**, offers three options.

- Proba skymap:** the dropdown menu lists the image files loaded during your Aladin Desktop session. To preselect a gravitational-wave sky localisation in the dropdown menu, click on its name in the Aladin Stack.
- Probability threshold:** a number between 0 and 1 for the credible level you wish to select.
- MOC resolution:** the dropdown menu lists the MOC resolution options and the corresponding pixel resolution.

Pressing the **CREATE** button, the credible region, encoded in a MOC data structure, is created and loaded in the Aladin Stack. Repetition of this process for different credible levels builds up a set of credible regions that can be selected independently from the Aladin stack.

Among the most important interactive features is the ability to access information on the size of the region. The area in square degrees and the percentage of the sky are reported in the top-right corner of the Aladin stack when you hover the cursor over the MOC name (**Fig. 6**).

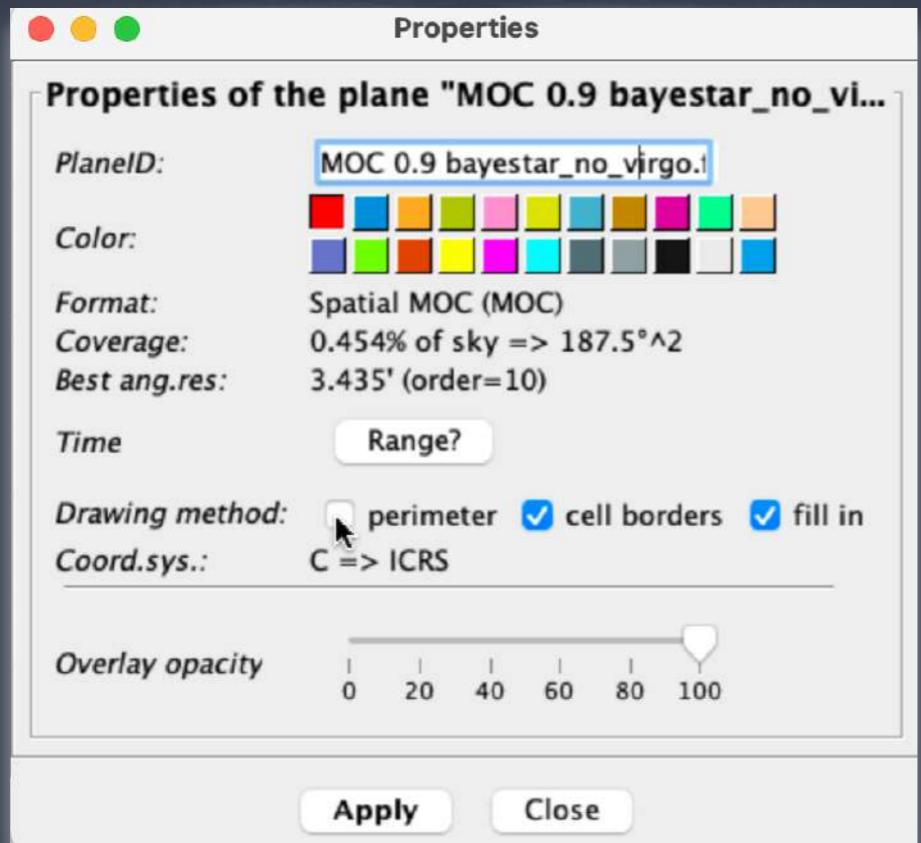


Fig.7 Properties window; right-click the credible region in the Aladin stack.

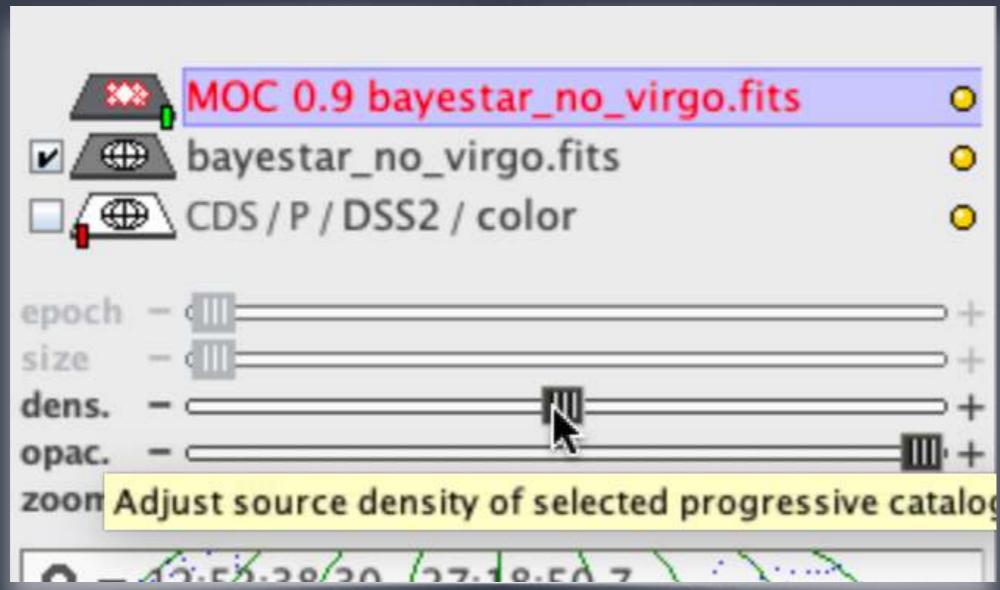


Fig. 8 Stack Sliders.

3. THE PROPERTIES WINDOW AND THE DENSITY BAR

Alternatively, to visualize the area of a credible region, you can right-click the credible region in the Aladin stack and select **Properties** from the contextual menu (**Fig.7**).

The **Properties** window allows you to change the color, rename the plane, modify the opacity and improve the visualization. The shaded areas, useful for quick visual comparisons, are obtained using as drawing methods **perimeter** and **fill in**. In **Section 5**, we will analyze the button **Range?** for adding temporal information to a spatial MOC map.

Aladin provides several control sliders displayed on the bottom of the Aladin stack; **Stack Sliders** shown in **Fig.8**. We focus on the **dens.** bar to increase the resolution of the MOC for large field of views. By default, the resolution of the displayed MOC is slightly degraded for large field of views. **Use of this feature is recommended for all-sky plots published with Aladin.**

4. SPATIAL COVERAGE

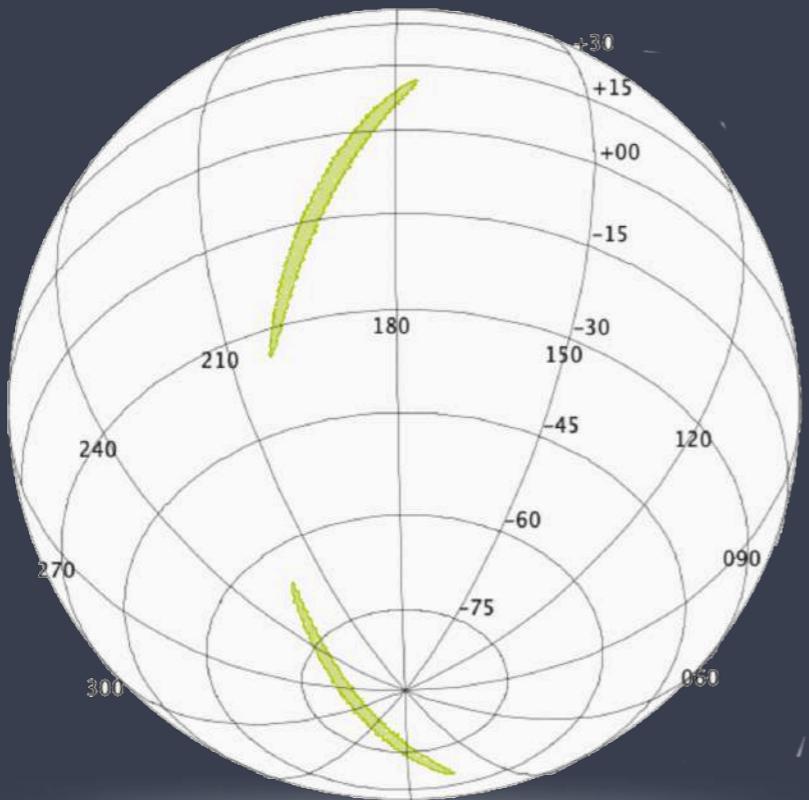


Fig. 9 The credible region (90%) of GW170817 from the two LIGO interferometers.

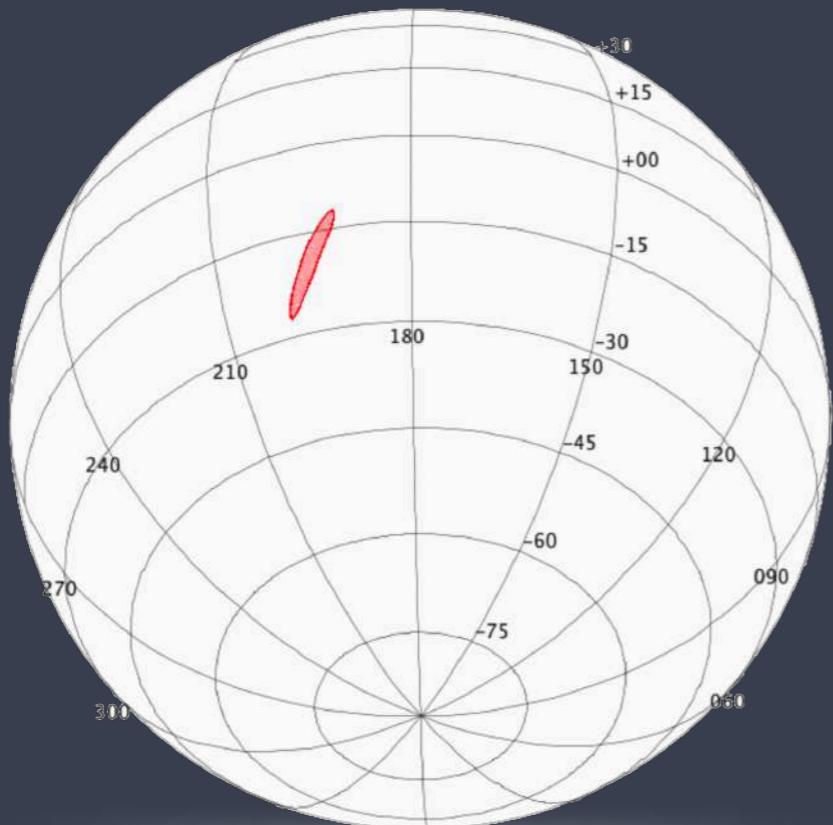


Fig.10 The credible region (90%) of GW170817 from the two LIGO and Virgo interferometers.

As results of such applications, we show the localisations of the gravitational-wave, GW170817, and gamma-ray burst, [GRB 170817](#). **Fig.9** shows the 90% credible region of GW170817 from the two LIGO interferometers and **Fig.10** depicts the same event when the Virgo data are added. In both Figures the low-latency (initial) sky localisations are provided by the [BAYESTAR algorithm](#). **Fig. 11** shows the 90% credible area of GW170817 from the first [Gravitational-Wave Transient Catalog of Compact Binary Mergers](#) (GWTC-1). **Fig.12** displays the error box of GRB 170817 provided by the GBM instrument on board the Fermi Gamma-Ray Space Telescope. **Fig.13** shows the [IPN triangulation from the delay between Fermi and INTEGRAL](#) for the same gamma-ray event. Finally, in **Fig.14** the superimposition of all these sky maps is plotted. While the credible regions can be generated using the Aladin Desktop commands, the annulus of the IPN localisation is generated by the Python module [mocpy](#) with the method [.from_ring](#). The resulting MOC file can be downloaded from following link [IPN-GRB170817.fits](#). The annulus is provided using the code [here](#). **Click on Figs.9-12 to download the corresponding sky localisation.**

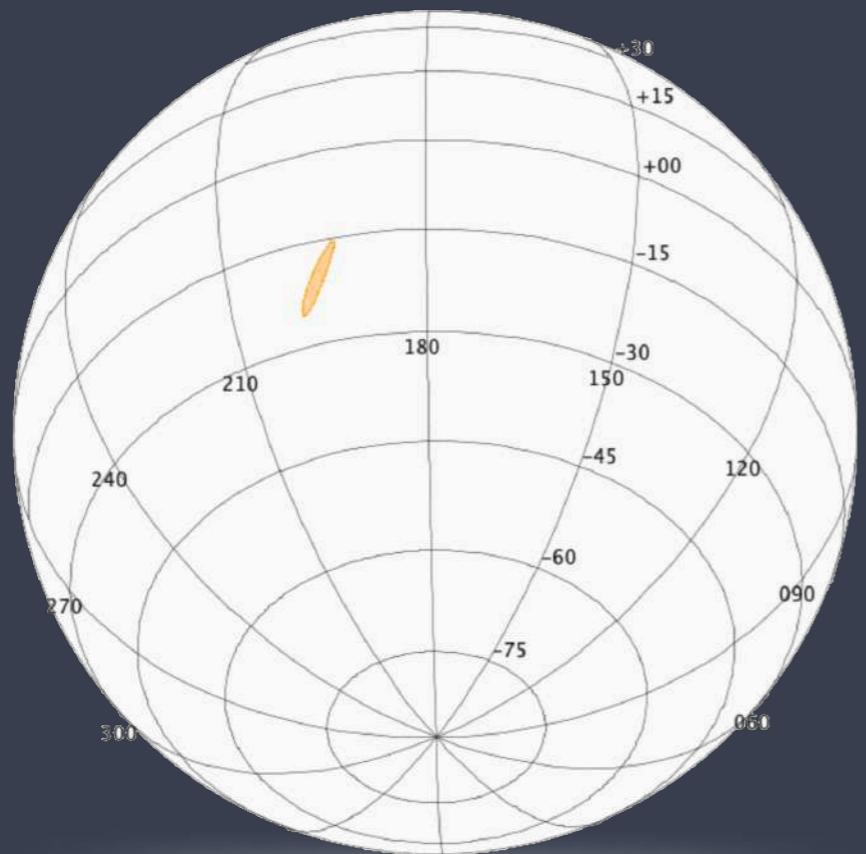


Fig.11 The final sky localisation of GW170817 from the GWTC-1.

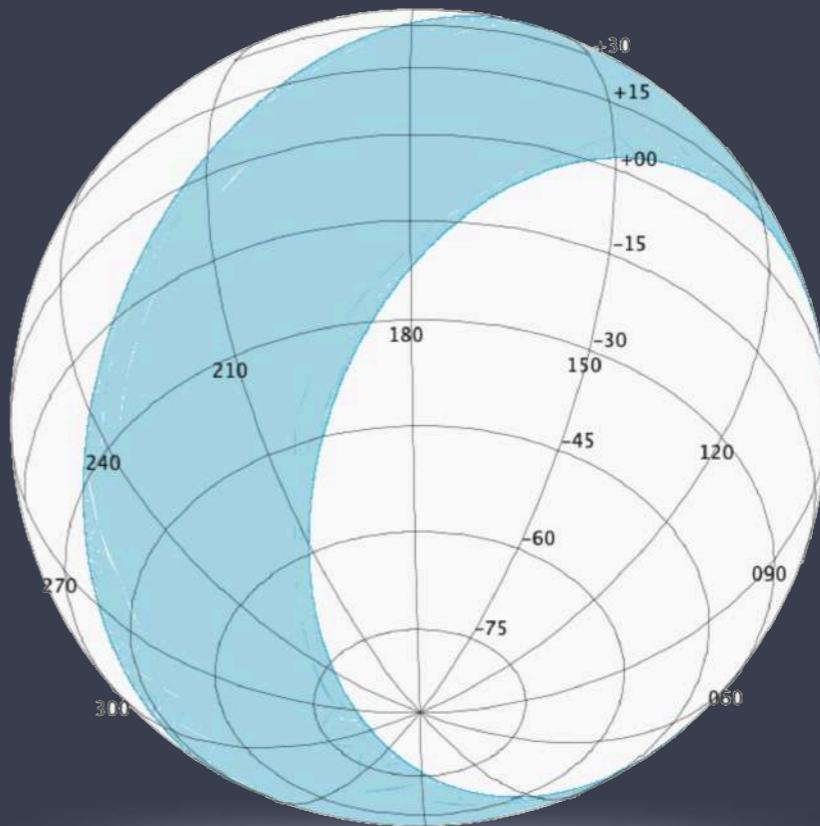


Fig.13 The IPN triangulation of GRB 170817 from the time delay between Fermi and INTEGRAL.

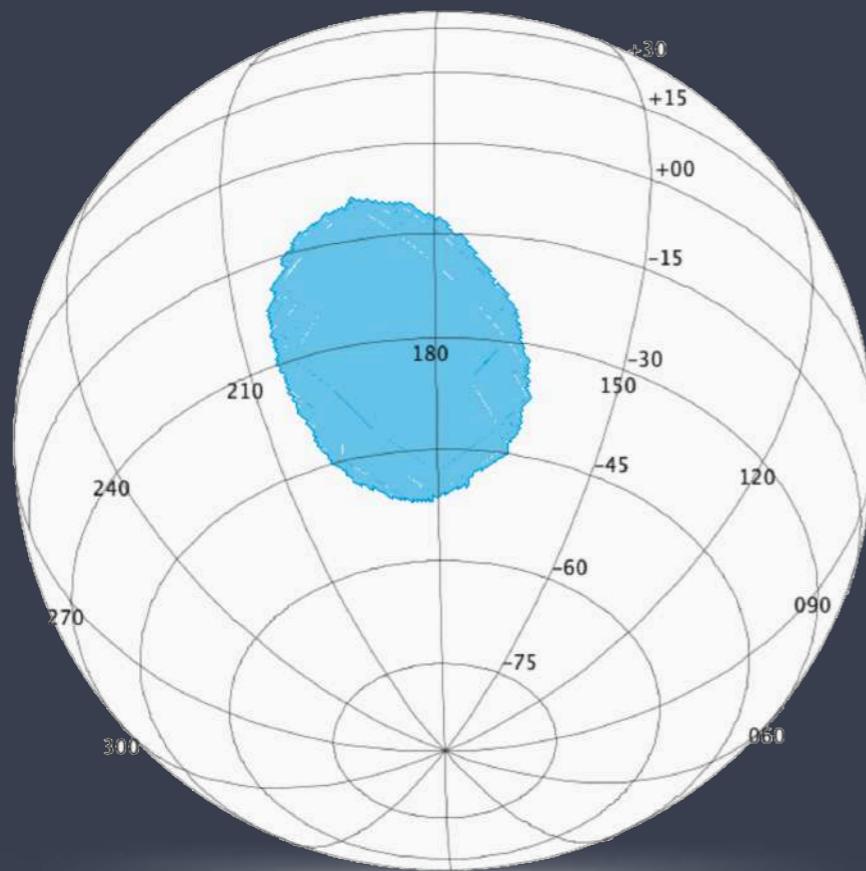


Fig. 12. The error Box of GRB 170817 from Fermi/GBM.

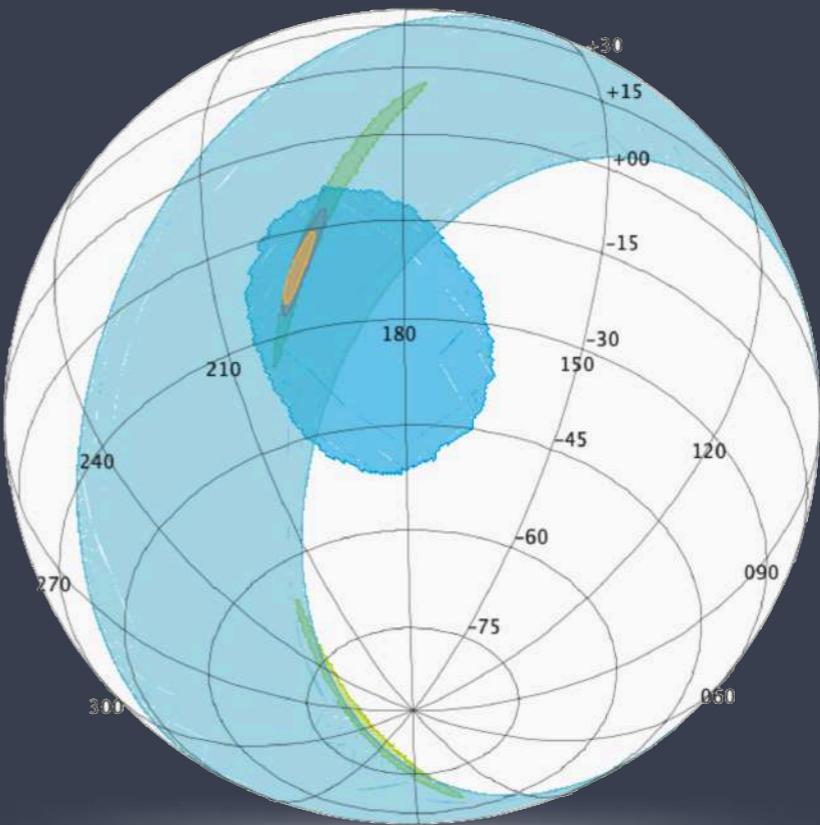


Fig. 14. Overlapping sky maps from Fig.9 to Fig.13.

4. SPATIAL AND TEMPORAL ANALYSIS

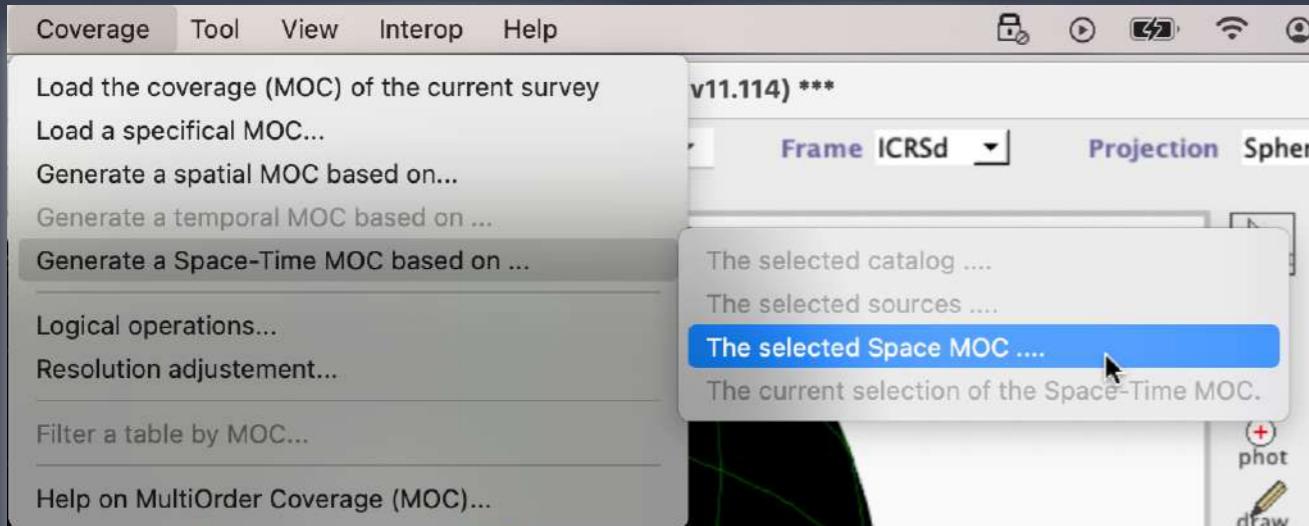


Fig. 15. Aladin GUI commands to add temporal information within a spatial MOC coverage. The contextual window is shown in Fig.16

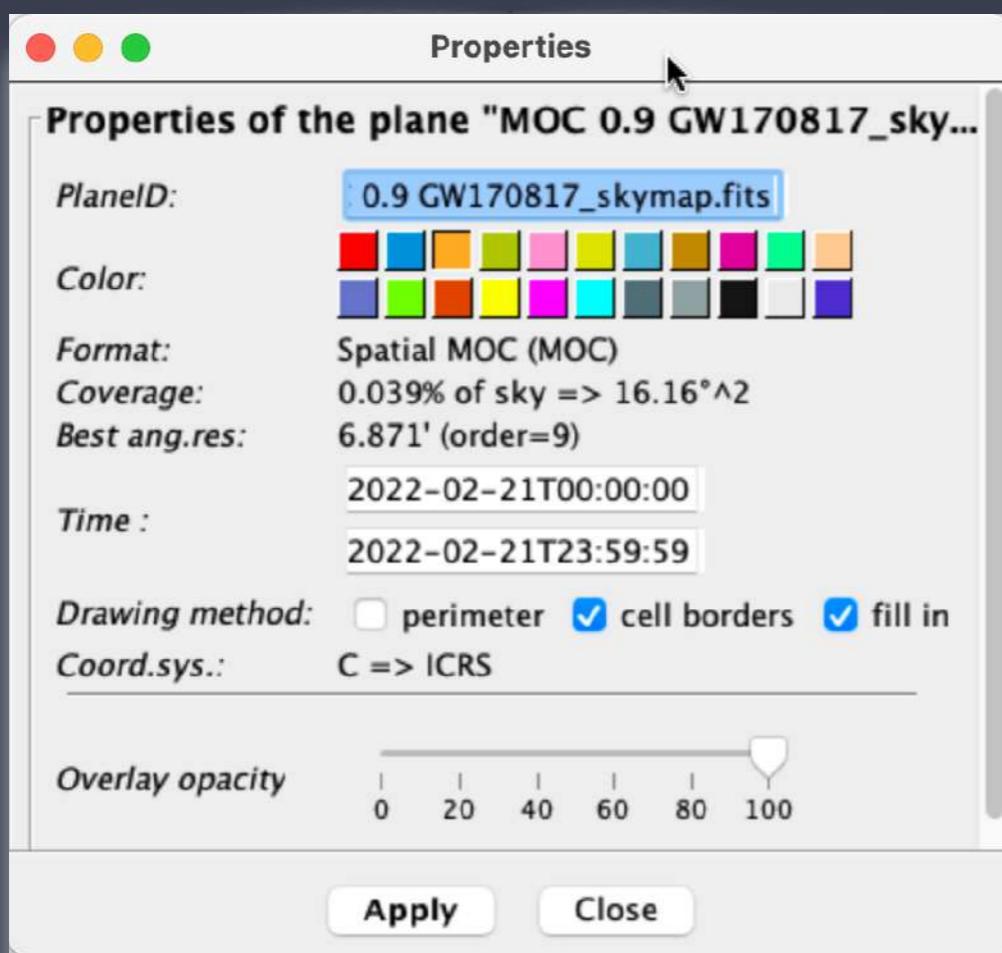


Fig.16. Properties window to insert a time range within a spatial coverage MOC. The contextual window opens by executing the commands in figure 15.

Fig.14 confirms a spatial intersection between the error box of GRB 170817 provided by Fermi/GBM and IPN and the sky localisation of GW170817 from the LIGO and Virgo detectors. However, the spatial analysis alone is not sufficient to associate the short GRB with the GW phenomenon. Simultaneous spatial and temporal analysis must also be applied, with in-depth astrophysical analysis.

Here we provide a practical approach in the context of the proposal IVOA (International Virtual Observatory Alliance) standard “[Space and Time MOC \(ST-MOC\)](#)” to operate in space and time, simultaneously.

New functionalities are added to the Aladin Desktop (v11) to encode time information in a spatial MOC. This is accomplished by selecting the menu bar the item called Coverage → Generate a Space-Time MOC based on → The selected Space MOC; see **Fig.15**.

These sequence of GUI commands opens the Properties window displayed in **Fig.16**. The boxes corresponding to the item **Time** accept a time range in UTC time scale: 1999-01-01T00:00:00.123.

4.1 ADDING PROPER TEMPORAL VALUES

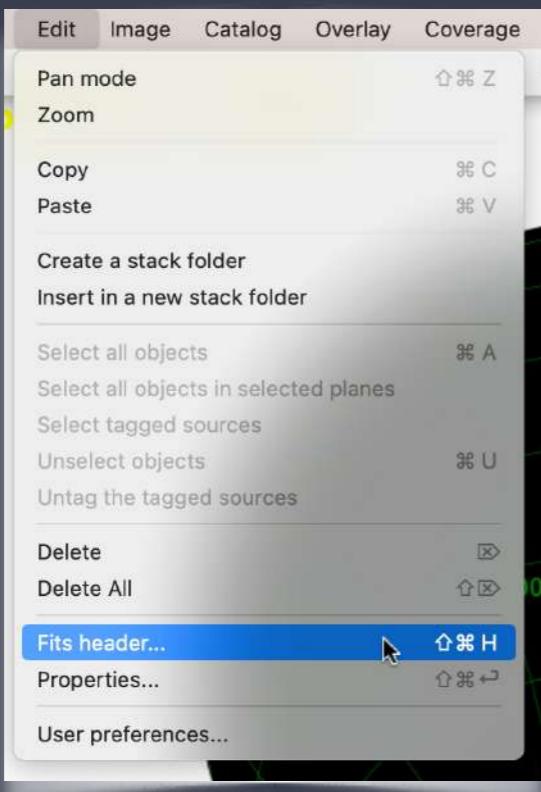


Fig. 17. Aladin GUI commands to print the Fits header.

```

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   = 1024 / Resolution parameter of HEALPIX
INDEXCHM= 'IMPLICIT'         / Indexing: IMPLICIT or EXPLICIT
OBJECT  = 'GW170817'          / Unique identifier for this event
DATE-OBS= '2017-08-17T12:41:04.429464' / UTC date of the observation
MJD-OBS = 57982.52852348908 / modified Julian date of the
observation
DATE   ='2019-05-08T21:51:56.613850' / UTC date of file creation
CREATOR = 'ligo-skymap-from-samples' / Program that created this
file
ORIGIN  = 'LIGO/Virgo'         / Organization responsible for this
FITS file
DISTMEAN= 38.03408225450563 / Posterior mean distance (Mpc)
DISTSTD = 7.499686641911211 / Posterior standard deviation of
distance (Mpc)
VCSVERS = 'ligo.skymap 0.0.15' / Software version
VCSREV  = '65fc6500a1e117fec2e27550a8e9b10c9792ffca' / Software
revision (Git)
DATE-BLD= '2018-09-04T14:19:20' / Software build date
HISTORY
HISTORY Generated by running the following script:
HISTORY ligo-skymap-from-samples --seed 170817 --outdir . --objid
GW170817 --fi

HISTORY soutname MCMC_TF2_LowSpin_AllSky.fits.gz
MCMC_TF2_LowSpin_AllSky_post.d

HISTORY t

```

Fig.18. Fits Header of a gravitational-wave sky localisation.

We add temporal information to the following spatial MOC coverages.

- 1) The credible region of GW170817 published in the first [Gravitational-Wave Transient Catalog of Compact Binary Mergers](#) (GWTC-1).
- 2) The error box of GRB 170817 generated from the Fermi/GBM.

In the first case, we consider the merger time from a compact binary coalescence. We can look at the metadata inside the FITS file by printing its header with the GUI commands: **Edit** \Rightarrow **Fits header** (see Fig.17).

The header is reported in Fig 18. The keyword **DATE-OBS** is the UTC time of the event. For GW170817, DATE-OBS = 2017-08-17T12:41:04 UTC. The header can be also printed using the keyboard shortcut indicated in the corresponding item of the dropdown menu, according with the various OS.

User Guide

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

Navigation

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- [Superevents](#)
- [Candidate Vetting](#)
- [Sky Localization and](#)
- [Distance Estimation](#)

Event Type	Time window (s)		Notice Type Considered (see full list)
	CBC	Burst	
GRB (<i>Fermi, Swift</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
Low-energy Neutrinos (SNEWS)	[−10,10]	[−10,10]	SNEWS

Fig. 19. Time window used in the external coincidence in LIGO and Virgo User Guide for coincident with external trigger.

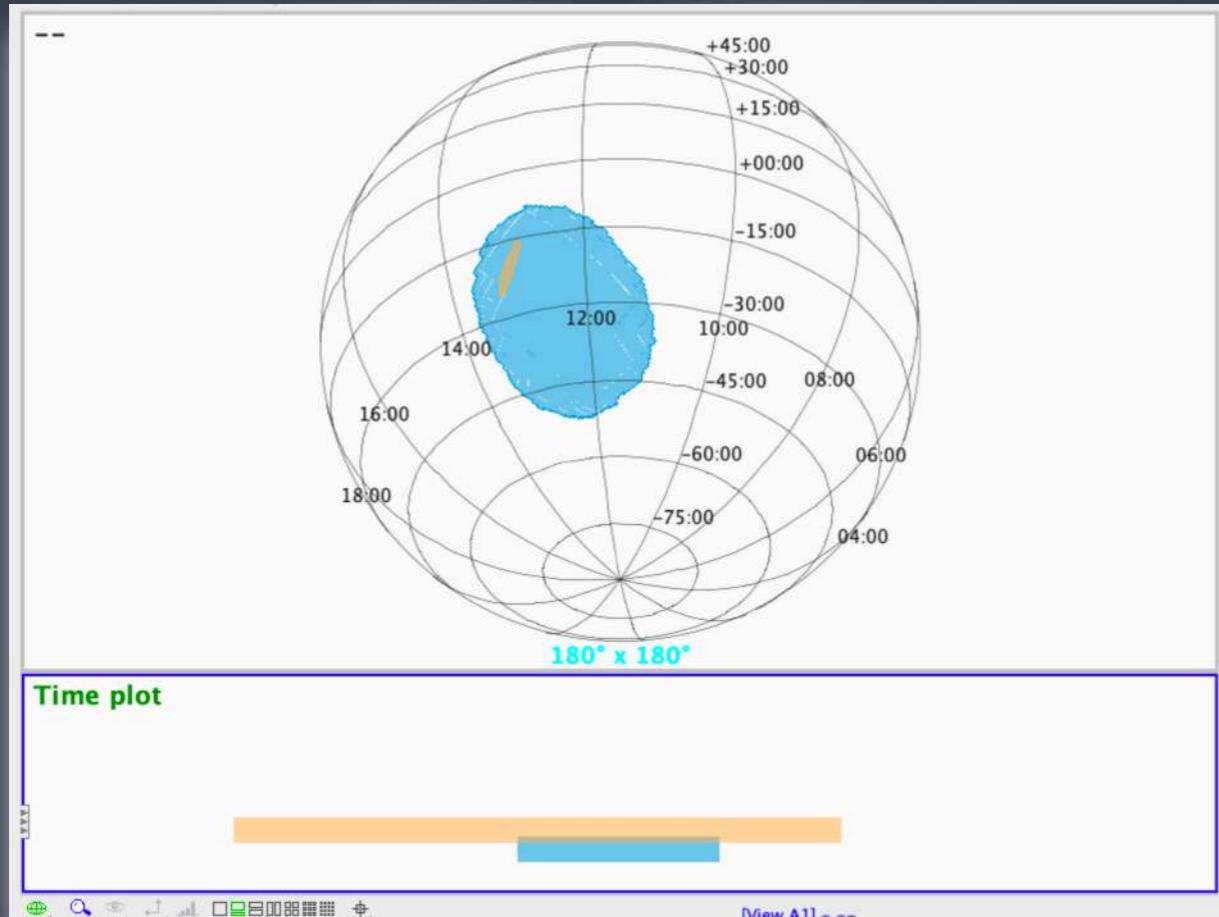


Fig. 20. The spatial coverages (upper) associated with the corresponding temporal information (bottom). The associated time ranges are shown in the **Time plot** box.

RAVEN will process alerts for gamma-ray bursts (GRBs) from both the *Fermi*-GBM instrument and the Neil Gehrels Swift Observatory, 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.

Two astrophysics events are considered coincident if they are within a particular time window of each other.

Following the [LIGO-Virgo Public Alert User Guide](#) in the section [Coincident with External Trigger Search \(Fig.19\)](#), we use the time window from −1 s to 5 s around the GW time. It means that we take into account GRBs up to one second before or up to 5 seconds after the GW time.

Following this prescription, the temporal interval to define the Space and Time MOC ranges from

2017-08-17T12:41:03 UTC to 2017-08-17T12:41:09 UTC.

In the case of the GRB 170817, we added the trigger time reported in "[An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: Fermi-GBM Detection of GRB 170817A](#)". The event was observed on 2017 August 17 at 12:41:06 UTC triggered by the Fermi gamma-ray Burst Monitor (GBM). T_{90} is 2.0 ± 0.5 s, starting at $T_0 - 0.192$ s. With these values, we set an approximate time window from 2017-08-17T12:41:05.80 to 2017-08-17T12:41:07.80.

The upper window of **Fig.20** shows the sky localisations of GW170817 (in orange) and GRB 170817 (in blue) and the bottom window **Time plot** displays the associated time lines. From a visual analysis, the two astrophysical events are in spatial and temporal coincidence. This can be quantitatively confirmed following the GUI command:

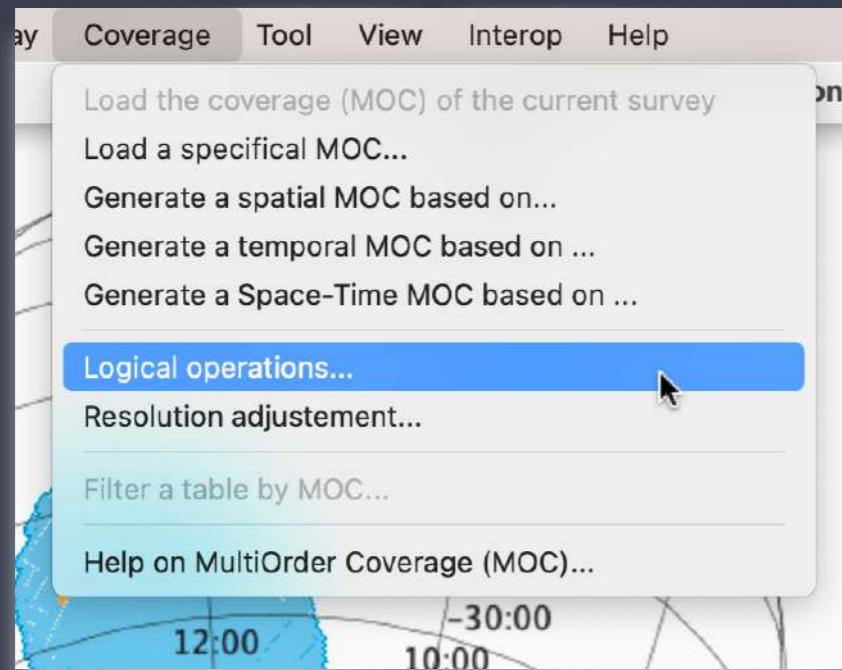


Fig. 21. Aladin GUI commands to launch the MOC operation window in Fig.22.

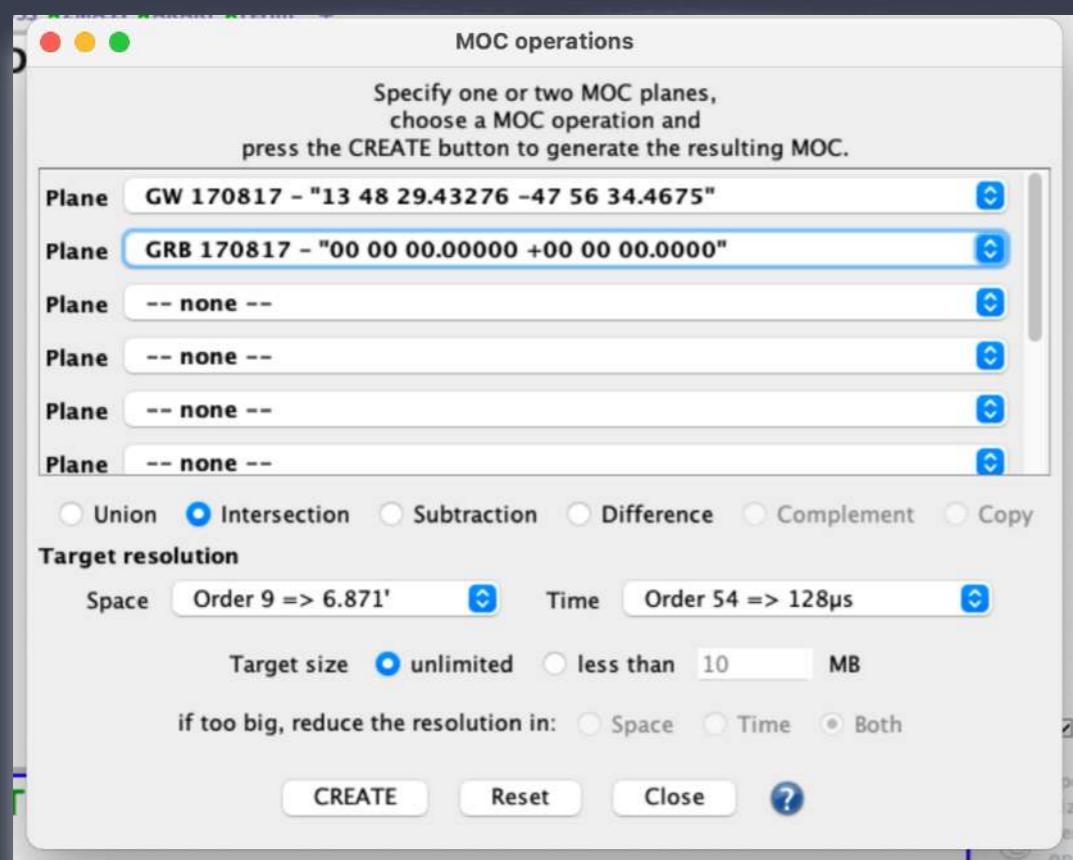
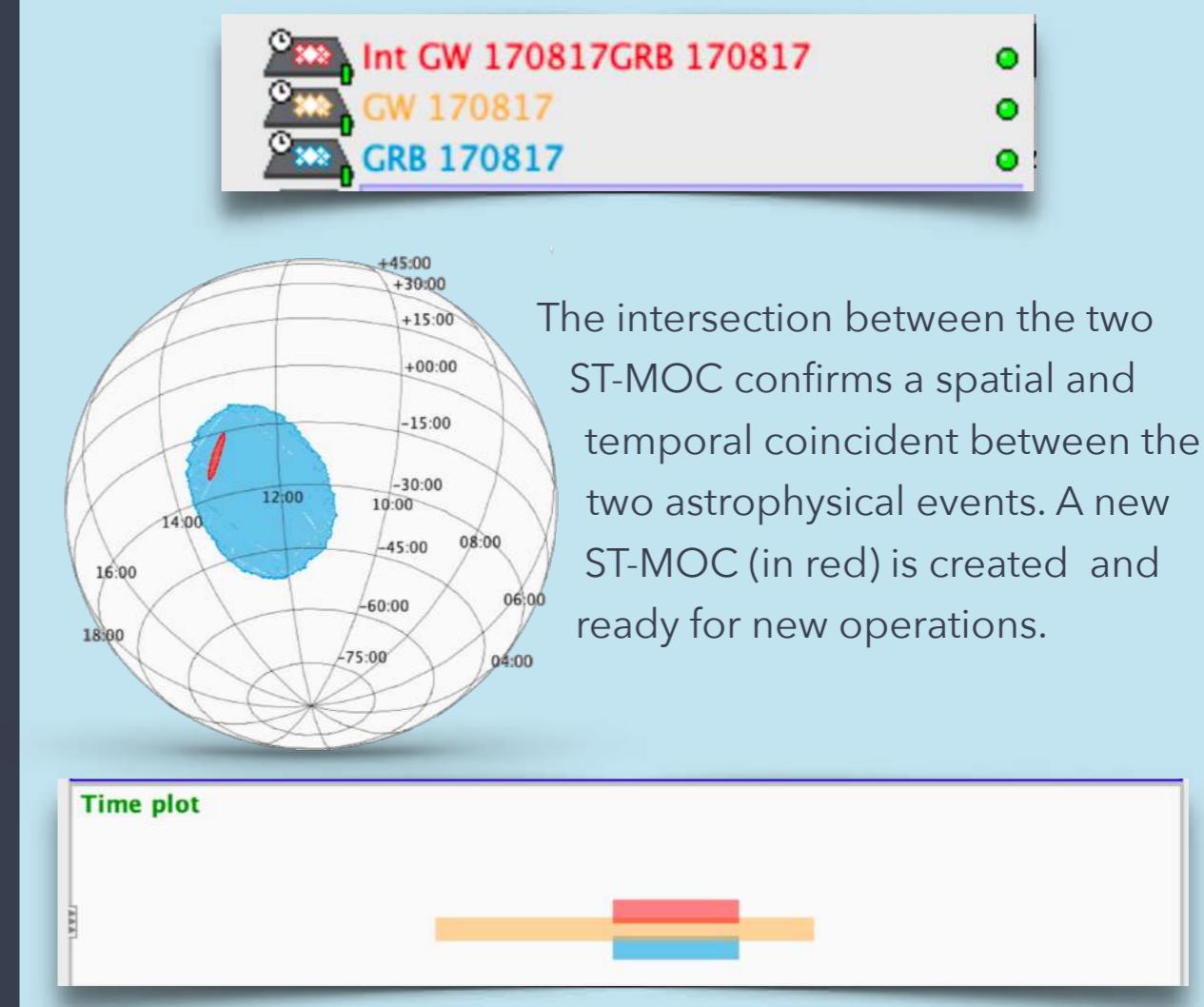


Fig. 22 MOC operation window. The contextual window opens by executing the commands in Figure 21.

Coverage ⇒ Logical operation (Fig.21) to open the operation window displayed in **Fig. 22**. The MOC provides a set of MOC functions: union, intersection, subtraction and difference for manipulating spatial and/or temporal coverages by selecting the corresponding radio button. The planes are selectable from the dropdown menus. In **Target resolution**, different MOC orders for space and/or time resolutions can be independently chosen. If no temporal information is stored in the selected MOCs; the time resolution dropdown menu appears disabled. In the Aladin stack a ST-MOC is indicated with a clock at the end of the plane:



The intersection between the two ST-MOC confirms a spatial and temporal coincident between the two astrophysical events. A new ST-MOC (in red) is created and ready for new operations.

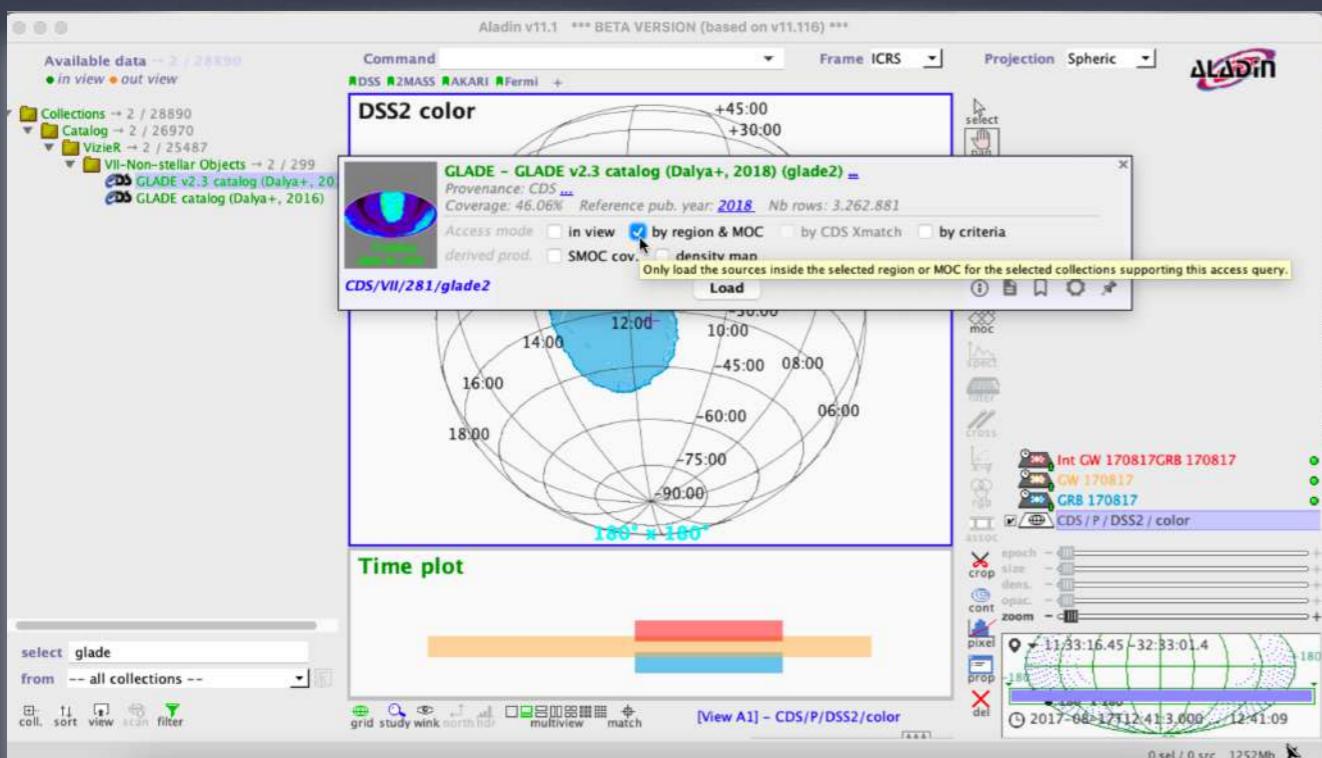


Fig.23 **by region & MOC** checkbox is chosen in the popup window to query the galaxies only inside the selected MOC region

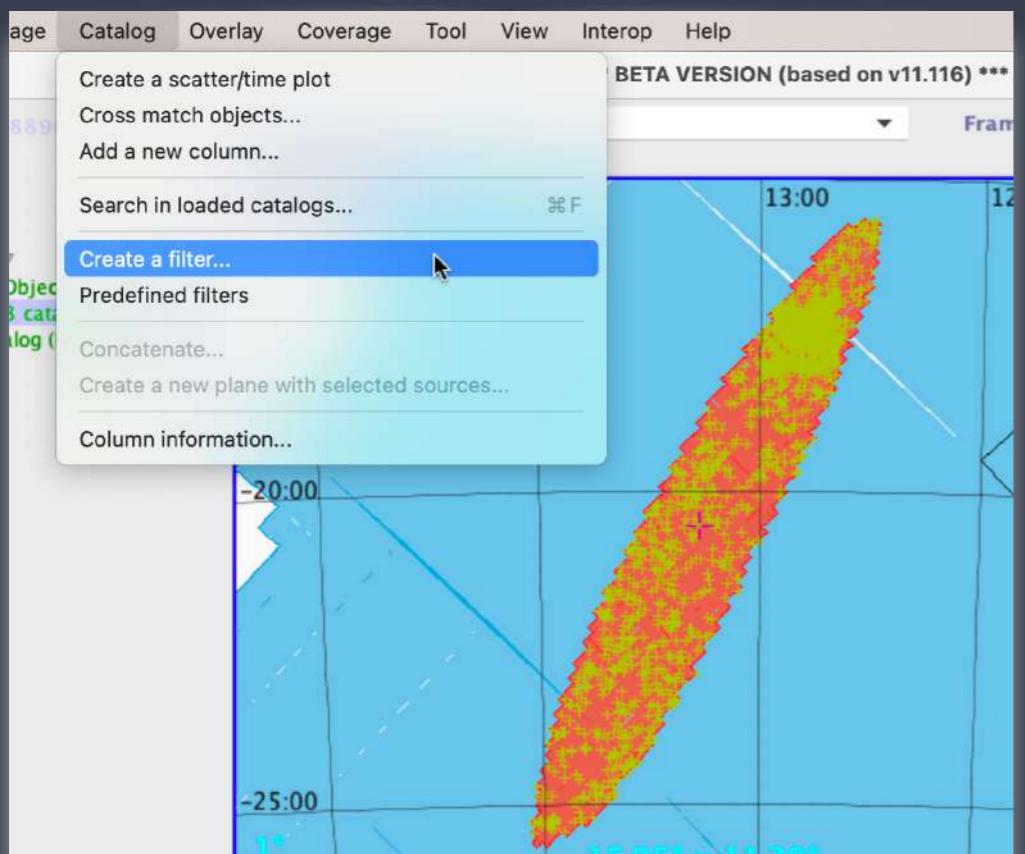


Fig.24 Aladin GUI commands to launch the window in Fig. 25 dedicated to the filter definition.

5. QUERY AND FILTER GALAXY CATALOGUES

Here we query the galaxies collected in the [GLADE catalog](#) inside the intersection area between the GW170817 and GRB 170817. Then we filter those galaxies according to the marginal distance posterior distribution integrated over the whole sky. The value reported in the header of GW170817 published in GWTC-1 ([GW170814_skymap.fits.gz](#)).

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 (**Fig.23**).

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 Mpc and DISTSTD = 7.5 Mpc.

Select Catalog ▶ Create a filter from the menu bar (**Fig.24**). 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 (**Fig.25**).

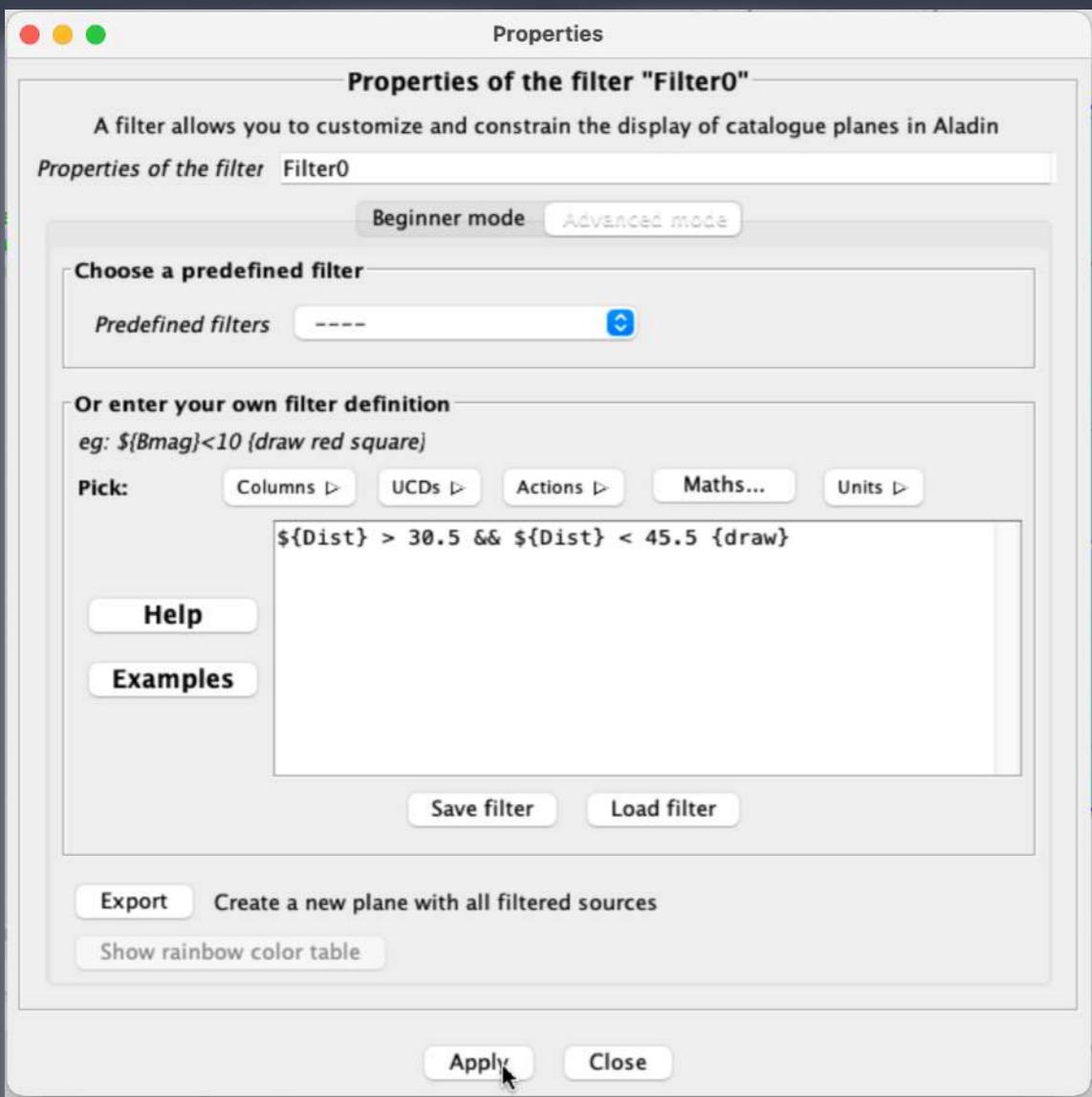


Fig.25 Properties window to manage Aladin filter syntax following the GUI commands in Fig.24.

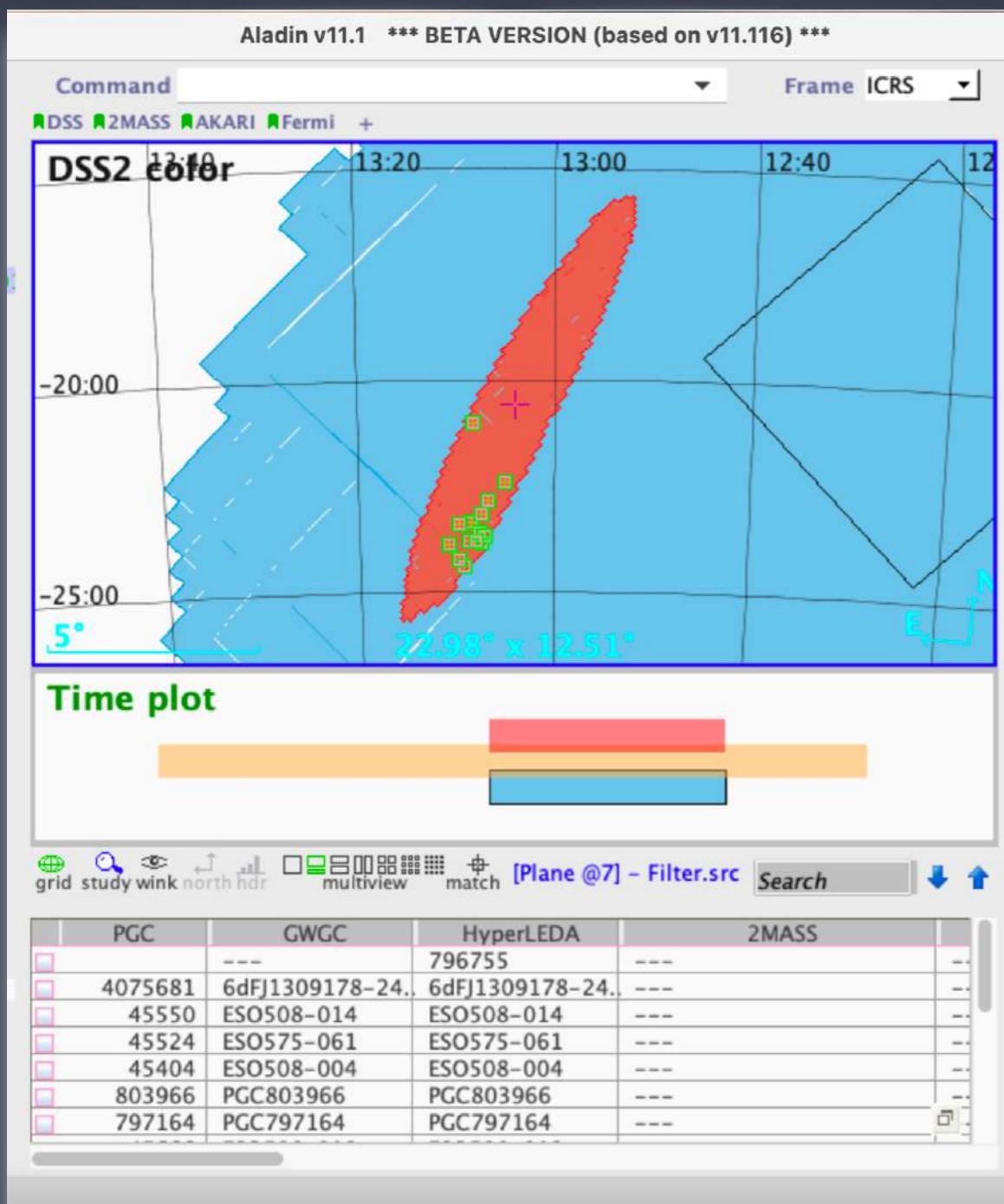


Fig.26 Creating a new plane with all filtered sources by pressing the **Export** button in Fig.25.

Click on **Apply** and then on **Export** to create a new level in the Aladin stack consisting only of sources selected by the filter. **Fig.26** shows the galaxies as a result of the filter application.

NOTE. 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. Dedicated functionalities are provided in the Python library [ligo.skymap](#).

6. RETRIEVE IMAGES IN FITS: HIPS2FITS

hips2fits
Fast generation of FITS cutouts from HiPS datasets

The hips2fits service enables generation of FITS images cutouts of arbitrary size and resolution from a given HiPS.

Fig.27 Web user interface of the hips2fits server to retrieve the reference images:
<https://alasky.u-strasbg.fr/hips-image-services/hips2fits>

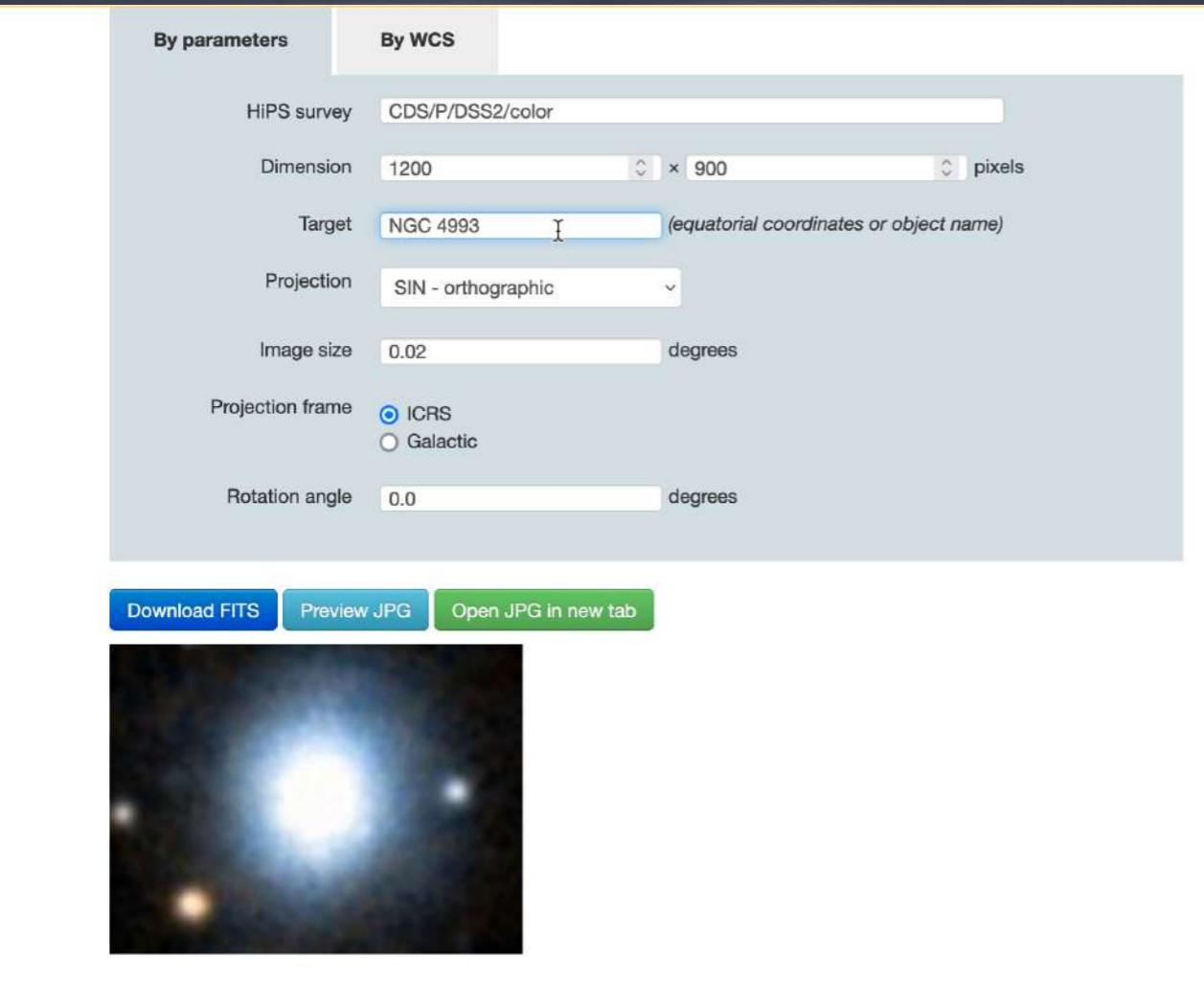


Fig.28 Retrieving FITS images from the DSS2 color catalogue from the galaxy list filtered in the intersection region between the GW/GRB 170817.

Cut-out images, in the FITS (Flexible Image Transport System) format, may be extracted from HiPS data sets using the online [hips2fits](#) service (**Fig.27**). This provides a very efficient and flexible way to generate cut-outs from many surveys, which can be useful for many purposes.

To collect reference images of the galaxies, to identify any new possible electromagnetic transient from a GW source, we fill out the form of the hips2fits web server (**Fig.28**). In the **Target** we insert the object name as reported in the filtered list in **Fig.25**. The image survey is specified in the **HiPS survey** box from a large HiPS collection; see the [HiPS list aggregator page](#).

Note that the extracted FITS files do differ from the original data because they have been converted to HiPS which involves re-sampling onto the HEALPix grid, and then extracted with a user-defined sampling into a FITS cut-out by hips2fits. These transformations would need to be taken into consideration when making scientific measurement from these FITS files.

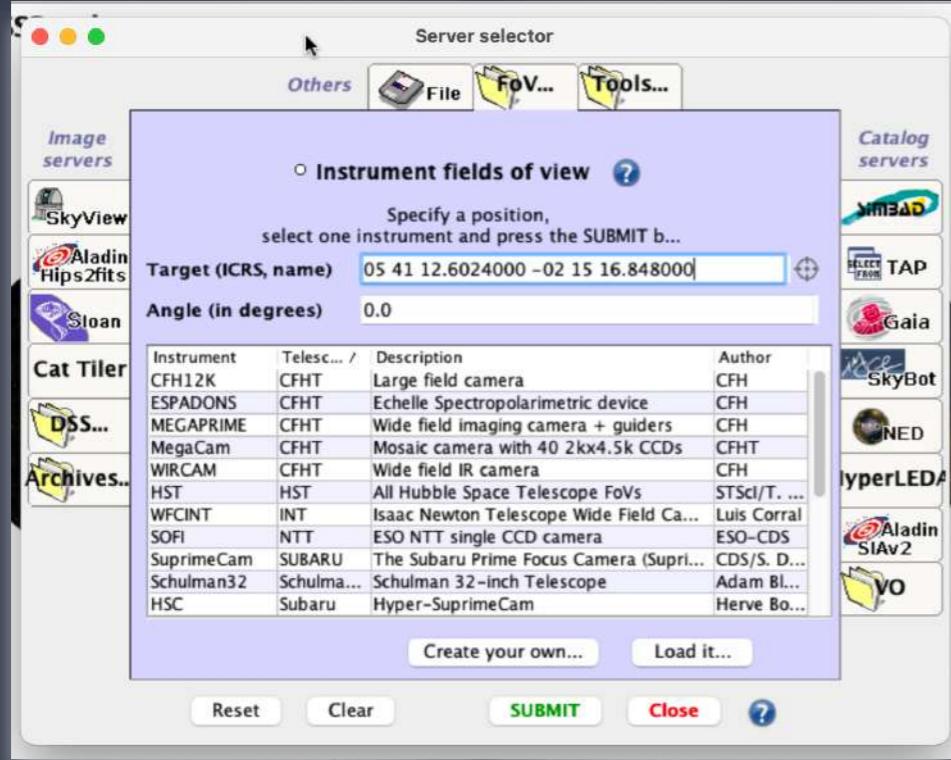


Fig.29 Server selector.

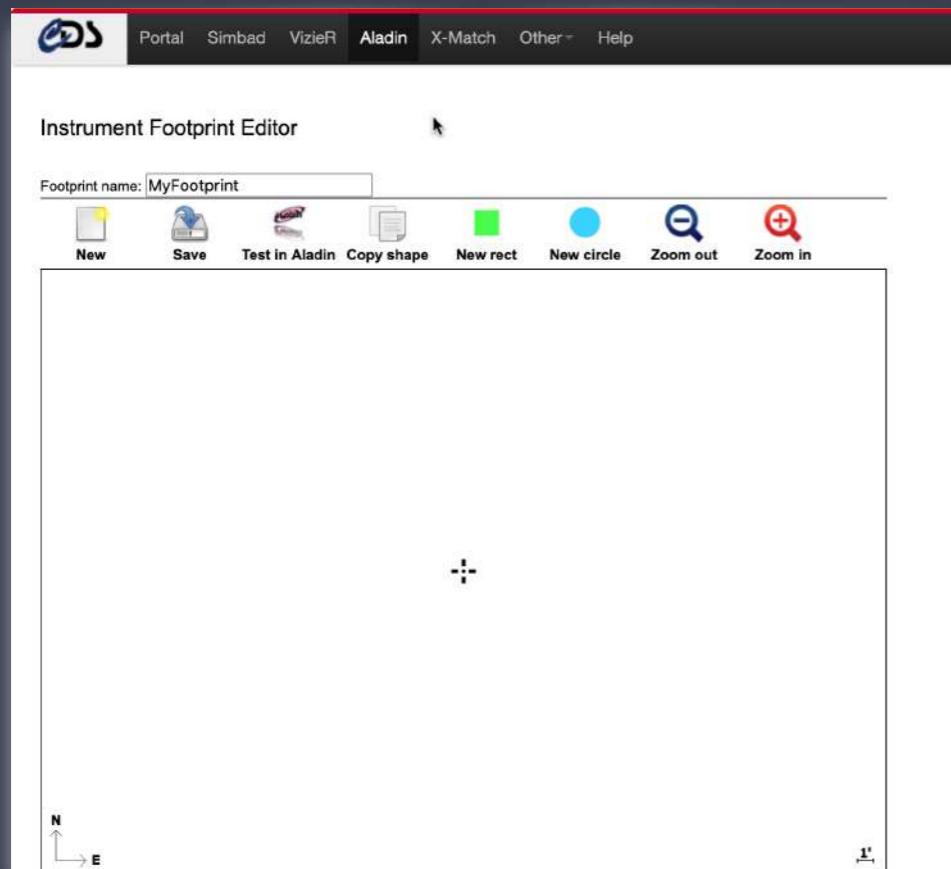


Fig.30 Instruments footprint editor.

6. TILING

The tiling patterns to split the sky areas proportional to the instrument footprints can also be generated using the Aladin Desktop functionality (from **File** → **Load Instrument FoV** → **Server selector**). The server selector window, in which the instrument field-of-view can be chosen/added, is shown in **Fig.29**.

The sky position centred at the field-of-view instrument can be taken opening the properties window associated with the current field-of-view instrument. Finally the cut-out images can be obtained by filling out the form of the hips2fits web server as shown in Figs.27-28.

If a field-of-view footprint is not present in the Server selector, you can create it using the tool at the web page (**Fig.30**). The new field-of-view footprint can be load in the Server select from **Load it** file input.

6.1 EXERCISE: VST TILING OF GW170814

You are at ESO-Paranal Observatory in Chile and your team are planning to observe the [LIGO and Virgo trigger G297595](#) (confirmed as GW170814), with the VLT Survey Telescope (VST) equipped with OMEGACAM. The observations are divided in 9 regions - $3^\circ \times 3^\circ$ - centered on the following coordinates RA, Dec (ICRSd):

Pointings	RA [deg]	DEC [deg]
P1	041.06842	-45.48795
P2	036.78869	-45.48795
P3	045.34815	-45.48795
P4	042.42450	-42.48795
P5	042.42450	-39.48795
P6	039.71234	-48.48795
P7	044.97423	-36.48795
P8	046.17326	-33.80461

- 1) Generate a sky chart with all pointings overlapping the 90% credible area of GW170814.
- 2) Retrieve reference image for each observation from the DSS2 color survey.

7. VISIBILITY MOC

The new application of MOC reported [here](#), enables the efficient computation of sky regions and the visibility of these regions from a specific location on the Earth at a particular time. As an example, **Fig.31** shows visibility MOC maps of the gravitational-wave sky localisation of GW190425. The original sky map was previously processed taking into account the all-sky Galactic reddening map from Schlegel et al. (1998) and overlapping the PanSTARRS DR1 survey as reference images.

The visibility refers to three astronomical observatories: Haleakala Observatories in Hawaii (USA), Paranal Observatory in Chile and Siding Spring Observatory (SSO) in Australia. The time interval is defined from 08:18:05 UTC to 14:18:05 UTC, from top to bottom, in two hour steps with airmass $1 \leq X \leq 2$.

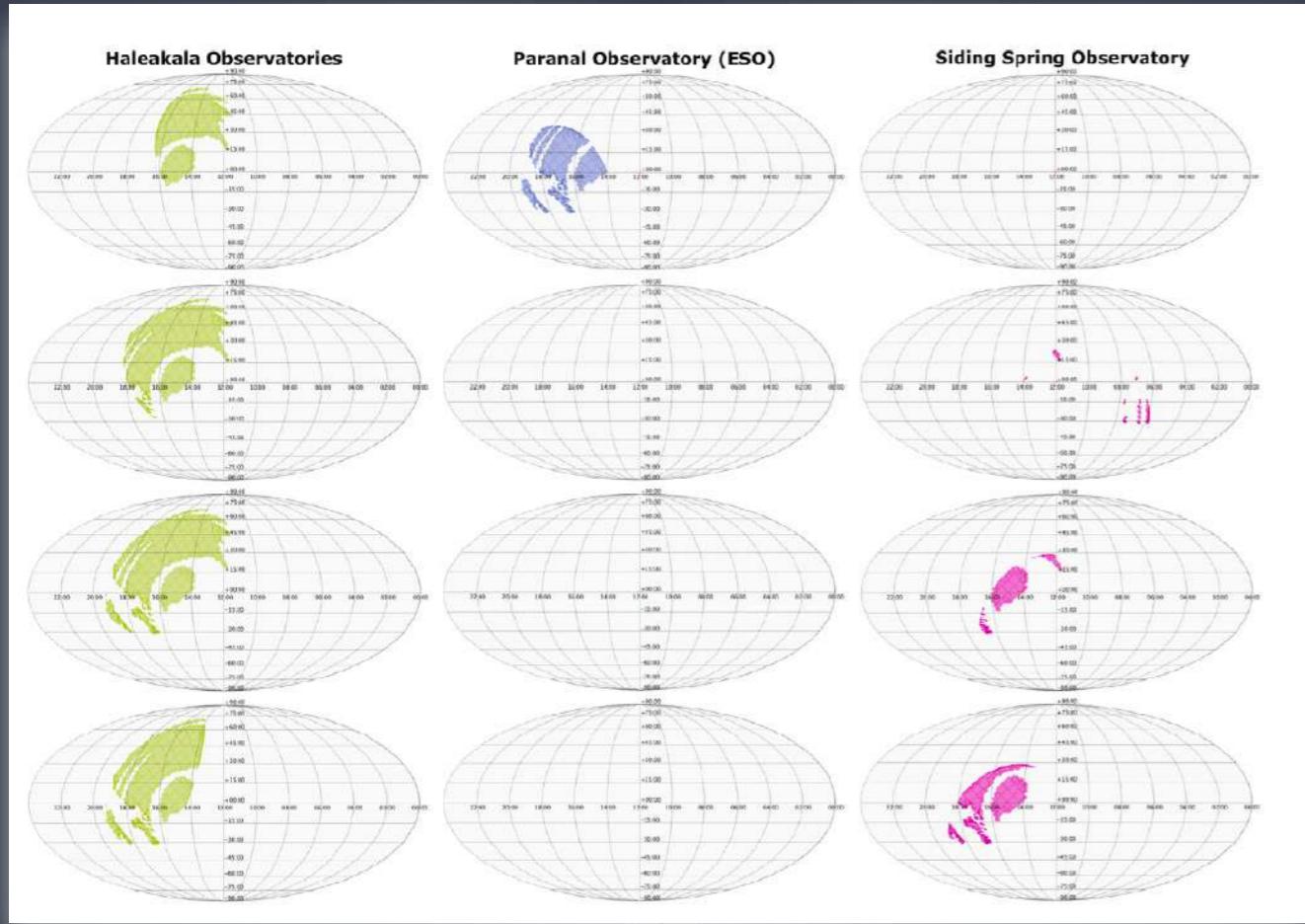


Fig.31 Visibility MOC maps of the gravitational-wave sky localisation of GW190425. The visibility refers to three astronomical observatories: Haleakala Observatories in Hawaii (USA), Paranal Observatory in Chile and Siding Spring Observatory (SSO) in Australia. The time interval is defined from 08:18:05 UTC to 14:18:05 UTC, from top to bottom, in two hour steps with airmass $1 \leq X \leq 2$.

The complete code is reported in a [public GitHub repository](#) which indicates all of the Python modules necessary for this analysis with a [Jupyter notebook](#). A [video demonstration](#) is also provided focusing on the Aladin functionalities used through the analysis.