

Multi-instrument, multi-wavelength study of high energy sources with the Virtual Observatory

Caroline Bot^{1,2}, François Bonnarel^{1,2}, René Goosmann² and Françoise Genova^{1,2}

1: Centre de Données astronomiques de Strasbourg, France

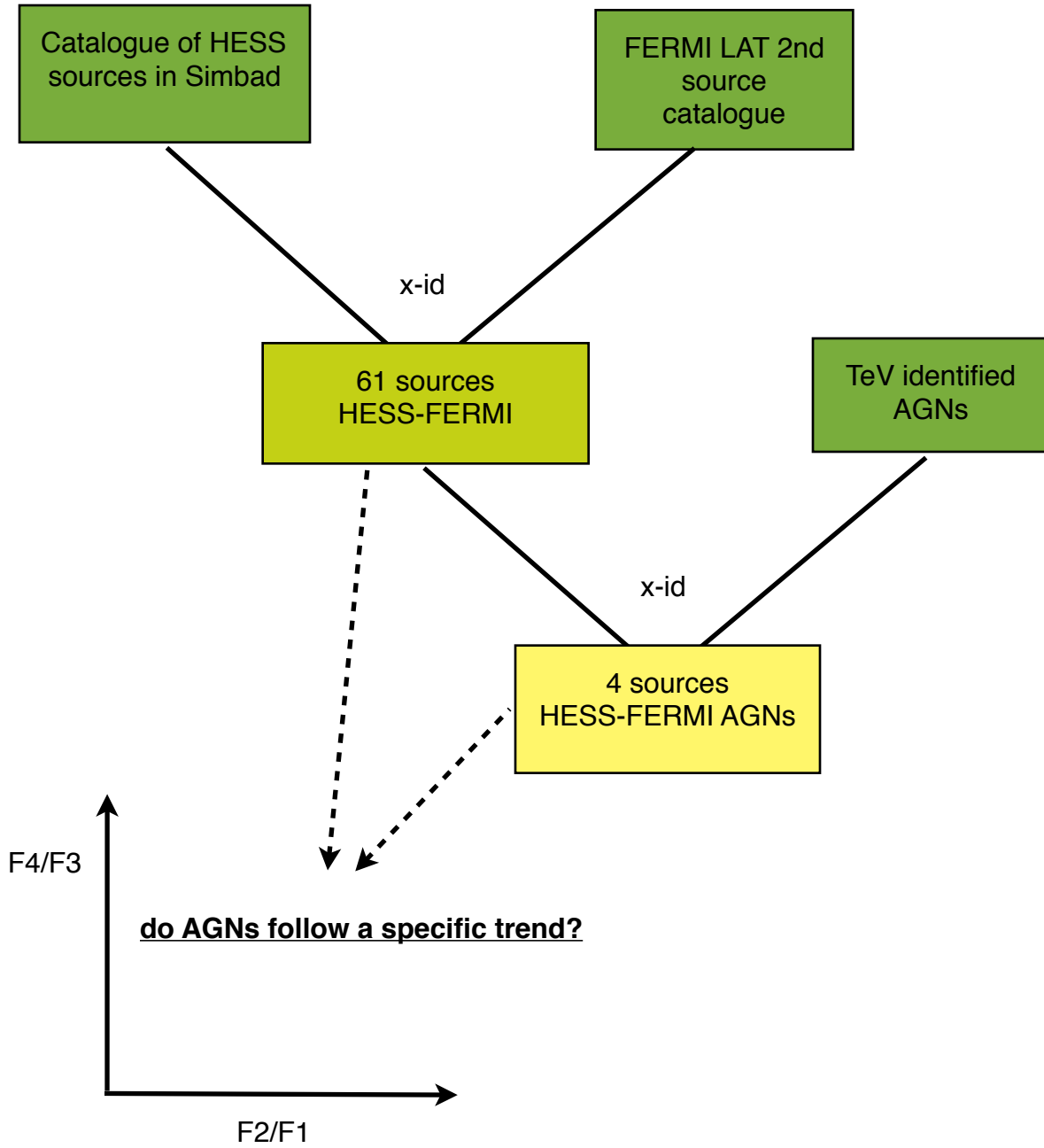
2: Observatoire astronomique de Strasbourg, France

Goal of this tutorial

This tutorial demonstrates how to use several standard tools of the Virtual Observatory (VO) for data mining and multiple waveband data analysis. The step-by-step application below focuses on towards applications in the gamma-ray and high energy domain, but also involves observational data from other wavebands. The user may explore how to...

- query astronomical catalogues in the gamma-ray and high energy spectral band using OV tools
- cross-correlate catalogues to find an object at different photon energy bands
- apply selection criteria when extracting sources from a catalogue
- use the observational measures of the selected objects to explore possible correlations
- visualize astronomical images from the radio up to the high energy domain
- display spectral energy distributions obtained from different photometric data sets

Schematic view of the scientific rationale of the tutorial

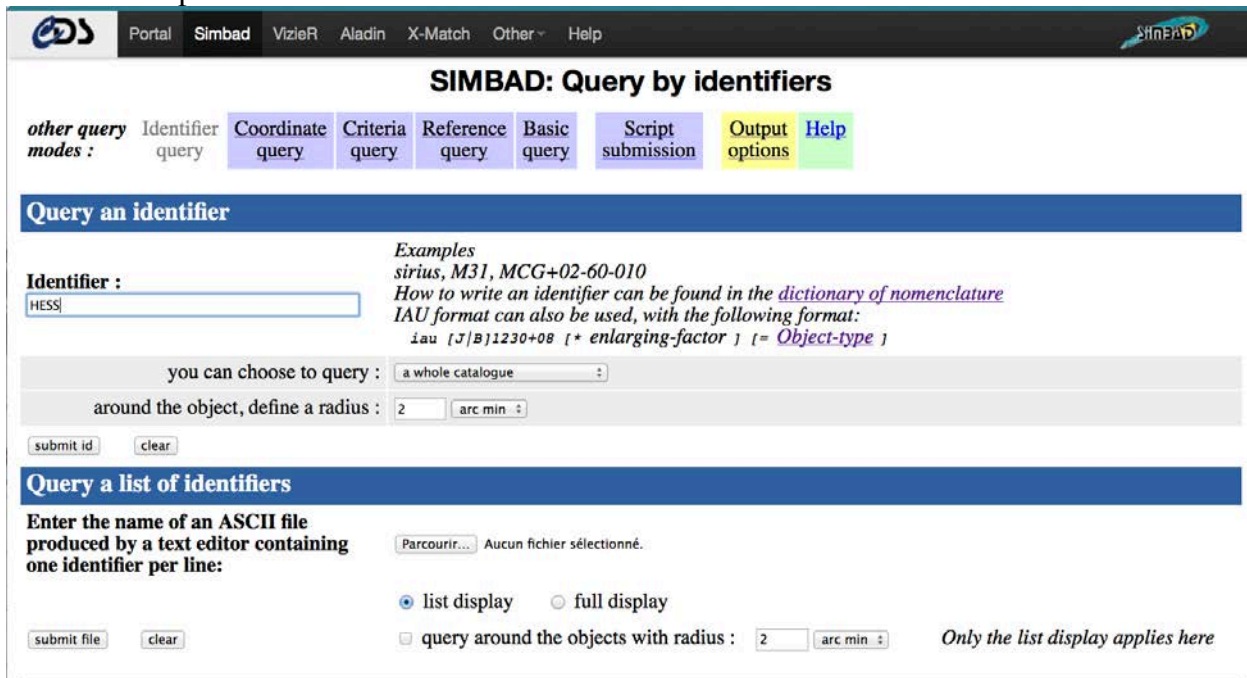


Step 1 - Obtaining all HESS sources from SIMBAD

How to obtain a catalogue of all published HESS sources from the astronomical database SIMBAD and save it as a VOTable.

The High Energy Stereoscopic System (HESS) is a Cherenkov telescope array detecting cosmic rays in the GeV–TeV range. Sources detected by HESS include supernova remnants, pulsars, active galactic nuclei and others. The number of detected sources steadily grows and makes it possible to study certain sub-samples of the HESS catalogue. In the following, the HESS sources should be investigated with respect to their gamma-ray properties obtained from the second Fermi-LAT catalogue.

Go to the Simbad webpage (<http://simbad.u-strasbg.fr/simbad/>) and select “identifier query”. Ask for all HESS objects in the Simbad database by using the “whole catalogue” option or “with a wildcard” option searches.



The screenshot shows the SIMBAD web interface. At the top, there is a navigation bar with links for Portal, Simbad, Vizier, Aladin, X-Match, Other, and Help. The main heading is "SIMBAD: Query by identifiers". Below this, there are several tabs for different query modes: "other query modes", "Identifier query", "Coordinate query", "Criteria query", "Reference query", "Basic query", "Script submission", "Output options", and "Help". The "Identifier query" tab is currently selected. Underneath, there is a section titled "Query an identifier" with a text input field for the identifier, which contains "HESS". To the right of the input field, there are examples and instructions on how to write an identifier. Below the input field, there are two dropdown menus: "you can choose to query" (set to "a whole catalogue") and "around the object, define a radius" (set to "2 arc min"). There are "submit id" and "clear" buttons. Below this is another section titled "Query a list of identifiers" with a text input field for the name of an ASCII file. To the right, there is a "Parcourir..." button and the text "Aucun fichier sélectionné.". There are two radio buttons for "list display" (selected) and "full display". There is also a checkbox for "query around the objects with radius" (unchecked) and a "2 arc min" dropdown. A note says "Only the list display applies here".

Figure 1: Simbad interface: selection of HESS catalogue

Go to the “output options” of Simbad and save the list as a VOTable file on your disk. VOTable is the Virtual Observatory format for exchanging tabular data.

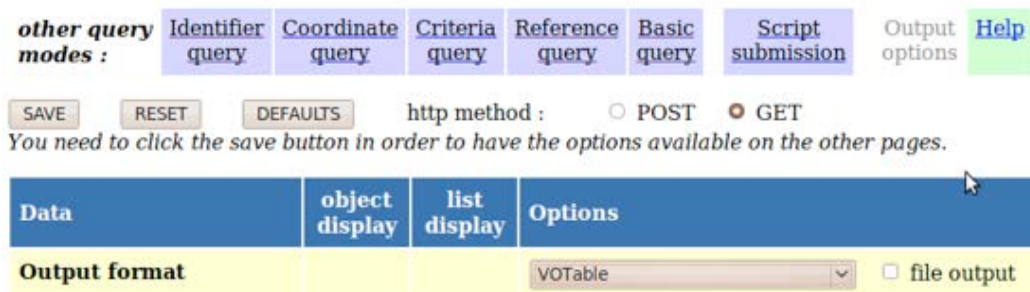
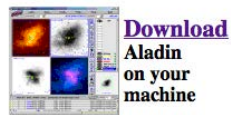


Figure 2: Simbad interface: selection of VOTABLE output format

Step 2 - Projecting HESS sources onto the Fermi sky

How to display the HESS sources stored in the VOTable in Galactic coordinates and overlay it on a view of an all-sky image survey conducted with Fermi LAT.

The VOTable data format is understood by all VO tools. Here, the VOTable file containing the HESS catalogue is loaded inside the ALADIN tool, designed to display and overlay astronomical images with additional informations (e.g. catalogues) and to project positions of sources onto the virtual sky.



Go to the Aladin web page (<http://aladin.u-strasbg.fr>) and click on

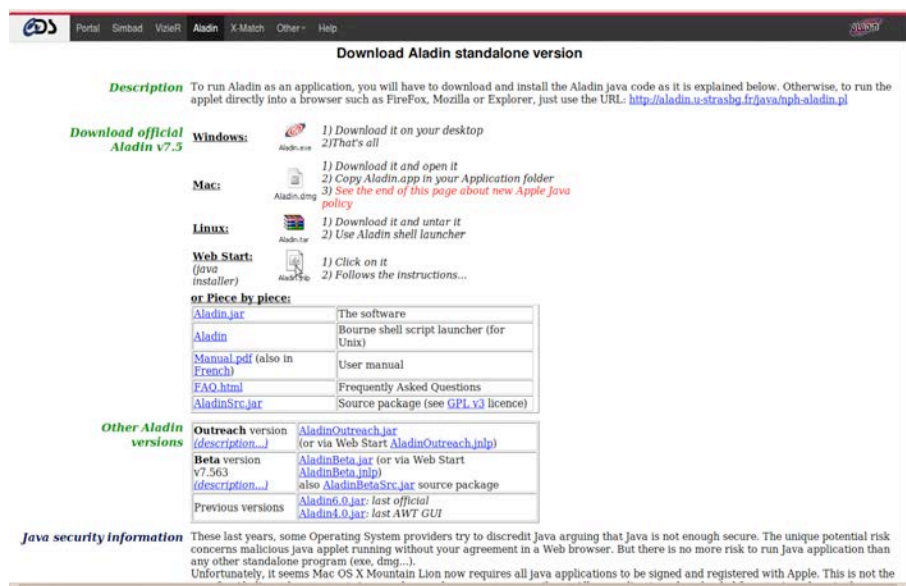




Figure 3: Aladin download webpage

Web Start:

(*java installer*)



From this webpage, start Aladin, by clicking on (), select the Allsky tab () and load a FERMI allsky survey image from the *Image>Gamma-ray* menu. Zoom out to see the full sky.

Tip: In fact, this option is doing the installation and launch of the .jar file for you.

You can reuse the installed .jar file later or download it directly from the webpage mentioned above. To start the Aladin.jar file from a terminal, type the command line:
`java -Xmx1024m -jar Aladin.jar`

The option `-Xmx` specifies the amount of memory to allocate (here, 1024Mo).

If you have trouble loading many images, this is a quantity you can change!

Open the server selector (), select the Allsky tab () and load a FERMI allsky survey image from the *Image>Gamma-ray* menu. Zoom out to see the full sky.

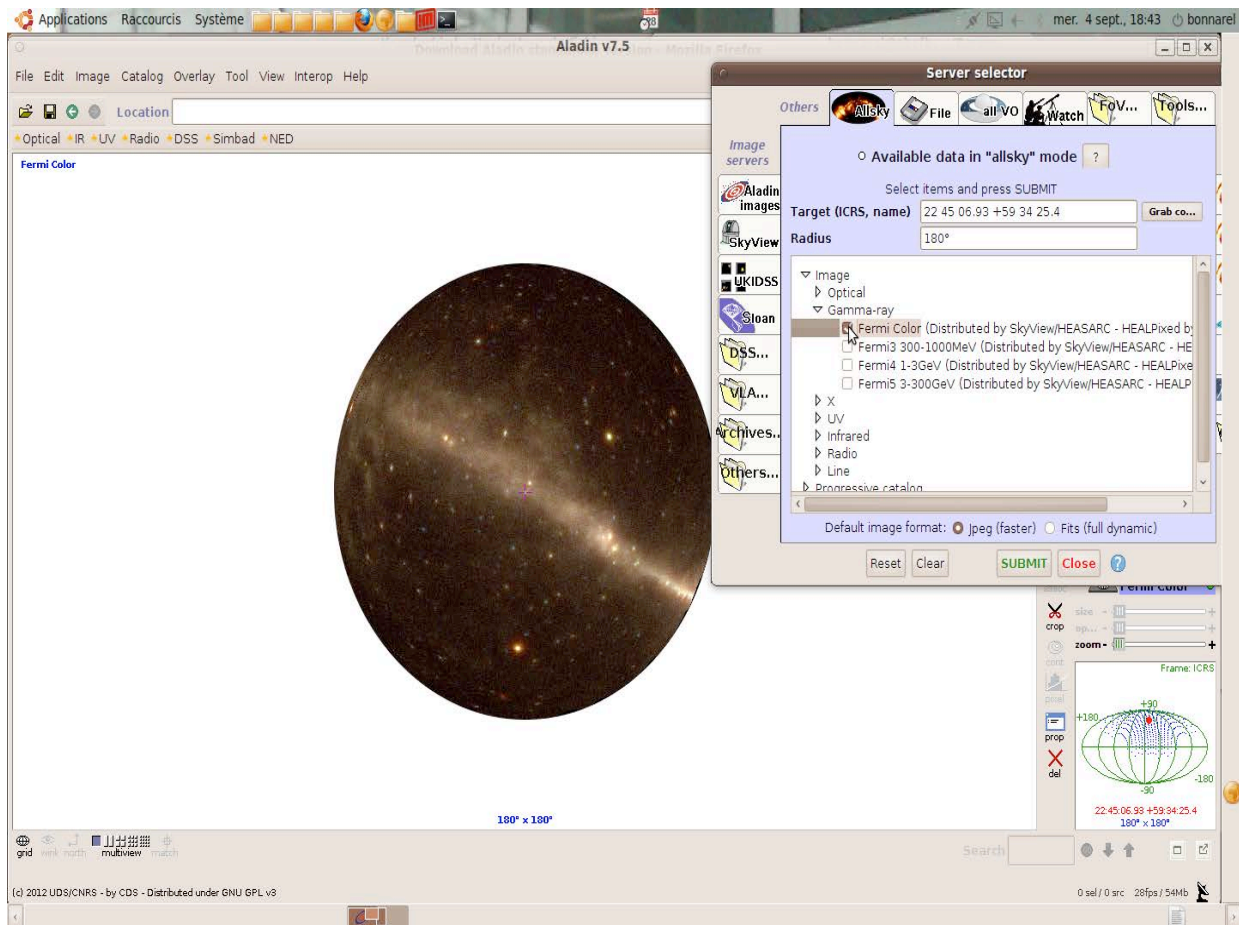



Figure 4: selecting the FERMI color allsky image to display in Aladin

Change the projection to AITOFF (select the “Fermi color” plane in the list of planes on the right of the main Aladin window and go to the properties of the plane - )

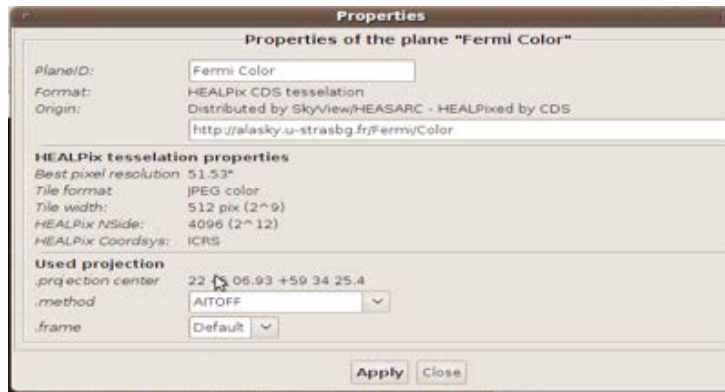



Figure 5: How to change the projection of an allsky map

Change the coordinates to galactic coordinates (in the main window, upper right corner).

Load the VOTable file containing the HESS sources from Simbad (go back to the server selector and use the File tab -  File). These sources get overlaid on the FERMI allsky survey.

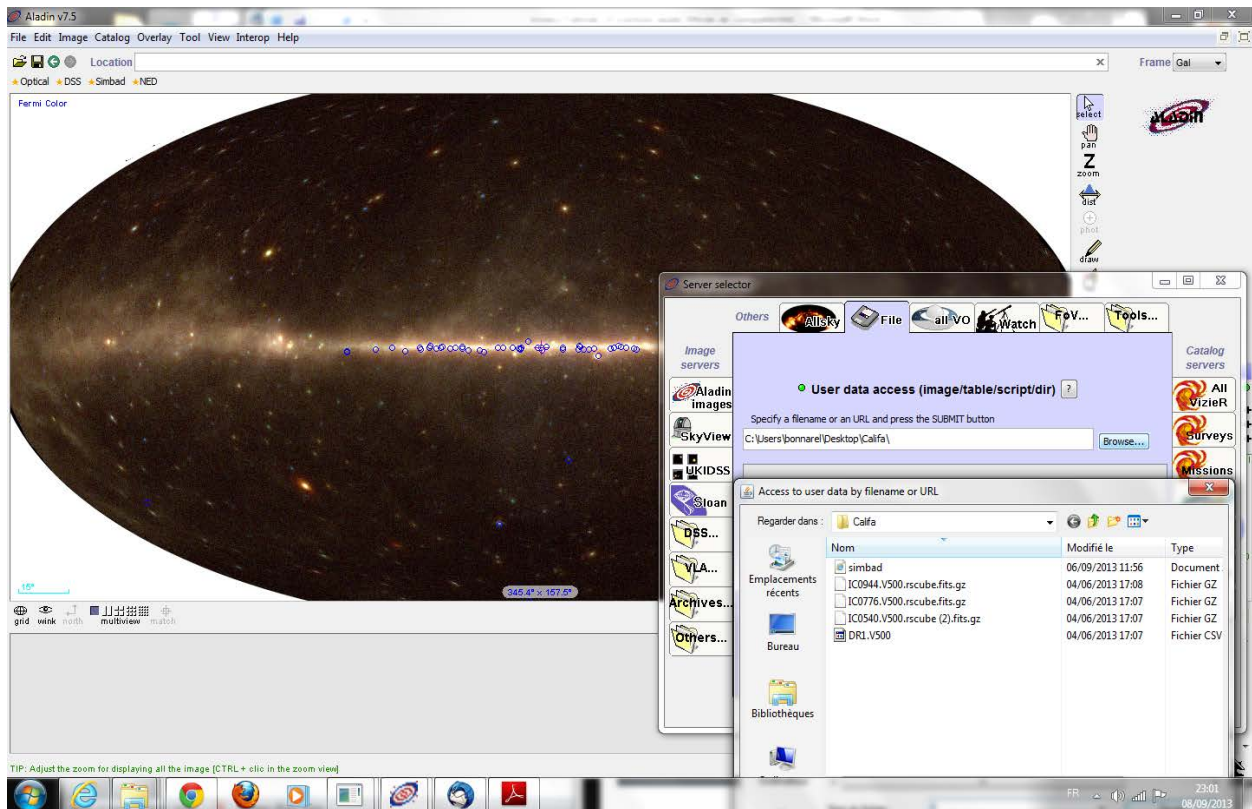


Figure 6: overlay of the HESS sources from Simbad on the FERMI color allsky image

Step 3 – Cross-identify HESS and Fermi LAT sources

How to cross-correlate the HESS source list with the complete set of objects appearing in the second Fermi LAT catalogue.

TOPCAT is a very powerful tool to deal with tables. In this tutorial, TOPCAT is used to cross-identify and combine sources from two catalogues and to work with the combined set of properties of all objects. The cross-identification will create a new, sub-catalogue of all HESS sources found in SIMBAD that also appear in the second Fermi-LAT catalogue.

The Fermi Gamma Ray Space Telescope was launched in 2008 and observes astronomical objects across the 10 keV – 300 GeV band. The main instrument of the Fermi satellite is the Large Area Telescope (LAT), an imaging high-energy gamma-ray telescope covering the spectral range of 20 MeV – 300 GeV. The LAT has a very wide field of view, covering 20% of the sky at any time and scanning the complete sky every three hours. In the second Fermi-LAT catalogue (2FGL) all identified Fermi sources after 2 years of continuous survey were published together with basic measurements such as photometric fluxes in different spectral bands, an estimated gamma-ray spectral slope, or a variability flag.

In the following cross-identification process, it is assumed that the HESS source and its Fermi counterpart have an apparent angular distance of less than 1° , which is guided by the average angular resolution of the Fermi-LAT across the gamma-ray waveband. The angular resolution of the Fermi-LAT drops from 3° at 100 MeV to 0.04° at 100 GeV. Choosing a different limit for the angular distance thus favors associations with more objects at the low or at the high energy end of the Fermi-LAT band.

The TOPCAT software is available at <http://www.star.bris.ac.uk/~mbt/topcat/>:

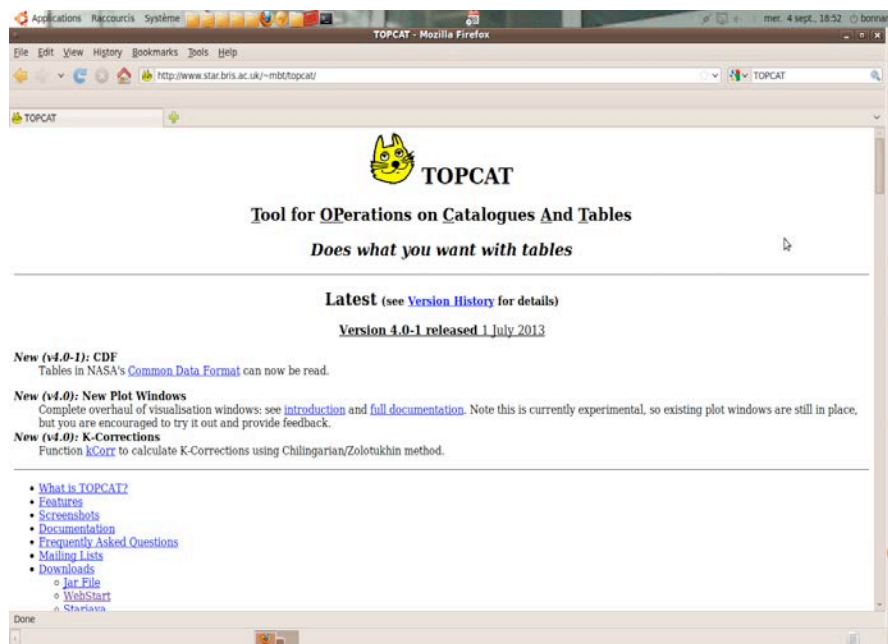


Figure 7: TOPCAT main webpage with the WebStart link

As for Aladin, TOPCAT can be started with the Webstart option from this web page or you can download a .jar file on your computer and start it.

One of the strengths of the Virtual Observatory is that different tools can interact as if they were one single tool. Broadcast the HESS list of sources from Aladin to TOPCAT (in Aladin, right click on the plane name for the Simbad HESS catalogue and choose *Broadcast selected tables to ...> topcat*).

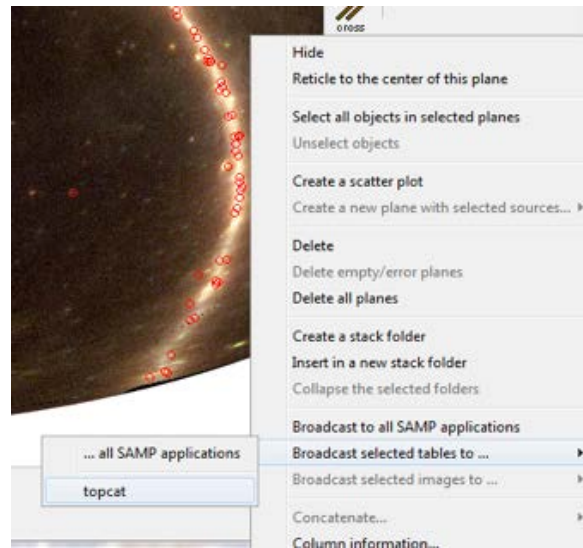



Figure 8: how to broadcast a table from Aladin to TOPCAT

The simbad.xml file is then loaded in TOPCAT. You can view the tabular informations by clicking on . Informations on the different columns of the table is obtained by clicking on

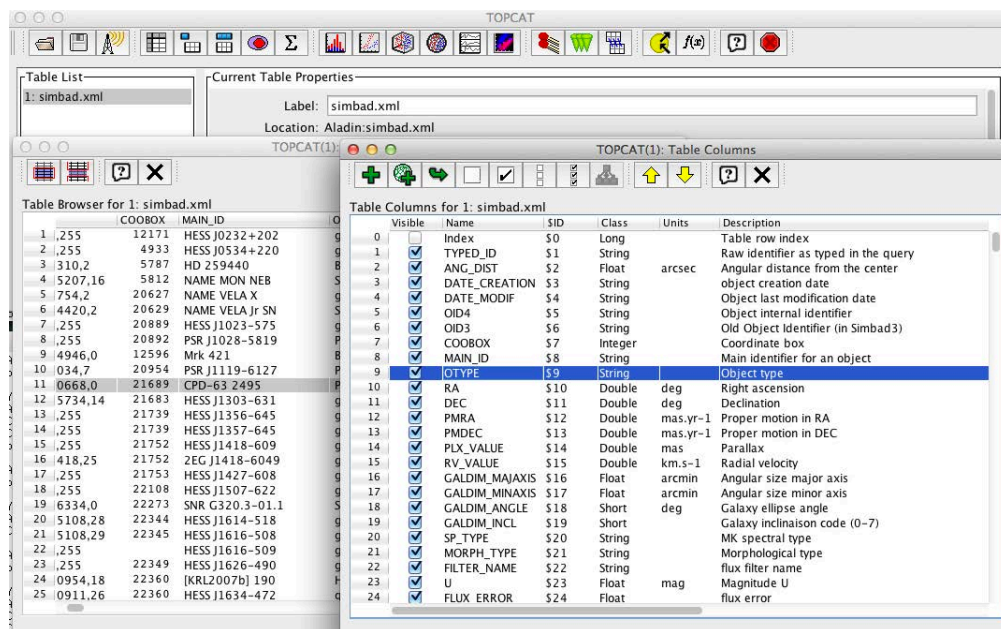




Figure 9: displaying the informations on the HESS table from Simbad in TOPCAT

In TOPCAT, load the FERMI LAT 2nd source catalogue (2FGL) from VizieR with all rows and all columns selected:

- click on  to get different ways to open new tables. Use the  button to open the VizieR Catalogue Service window.

- Select *All Rows* in the Row selection and *all* in the column selection

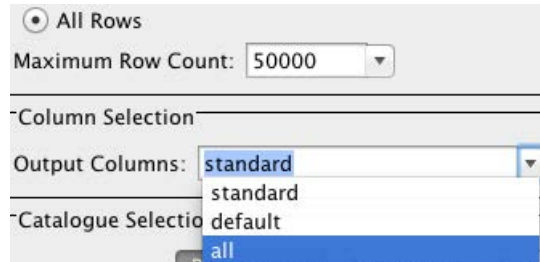




Figure 10: all column selection in the VizieR query from TOPCAT

- select catalogues  and type “2FGL” in the *Keywords window*

- select the Fermi LAT second source catalogue (2FGL) and press 

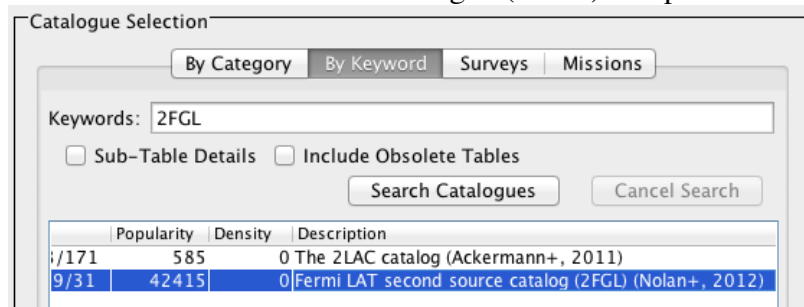


Figure 11: selecting the 2FGL catalogue from VizieR in TOPCAT

4 different tables from the 2FGL catalogue are then loaded in the TOPCAT main window:

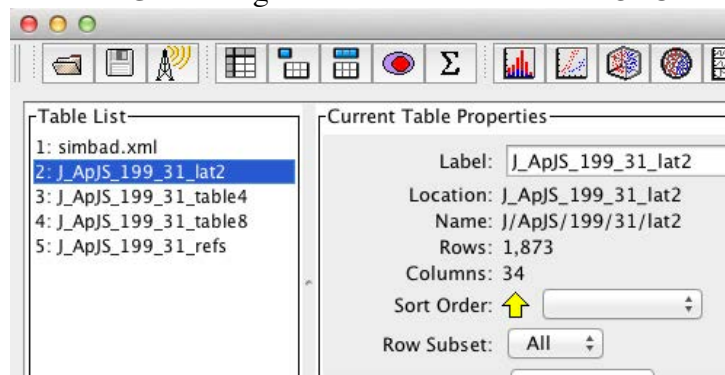




Figure 12: the different 2FGL tables loaded in TOPCAT

Information on each table is obtained with the button . Doing so, we learn that the first table (J_ApJS_199_31_lat2) contains the Second LAT catalogue while others contain the associations to the 2FGL sources, the list of sources from the 1FGL that were not included in this catalogue, and a list of references.

We will now make a cross-identification of the two catalogues (HESS sources from Simbad and 2nd FERMI LAT sources):

- TOPCAT offers a cross match tool with the  button.
- Select the *sky* algorithm (positional x-match) with a Max Error parameter of 1.0 degrees (coherent with the FERMI LAT resolution).
- select J_ApJS_199_31_lat2 (=2FGL) as the first table
- select simbad.xml (=HESS sources) as the second table
- and *Go*

We obtain a new catalogue containing the 61 best-match sources observed with both HESS and FERMI. This catalogue is named “match(2,1)” in the TOPCAT main window. It can be renamed (e.g. “HESS-FERMI”) in the *Label* field in the *Current Table Properties*.

When loading a catalogue from Vizier, it can be made of different tables compiling preselected sub-samples of objects. The *2LAT* catalogue (Ackermann et al. 2011) for instance contains a table of FERMI-AGN that were previously detected at TeV energies (either by HESS or by other high-energy observatories). It is useful to identify which HESS-FERMI sources are part of this table (i.e. are identified as AGNs).

Go back to the main TOPCAT window and load the 2LAC catalogue (Ackermann+2011) from Vizier (same steps as above) in order to get the table 9 (J_ApJ_743_171_table9 - TeV AGNs detected by FERMI).

Rename this table “*TeV selected AGNs*”

This time, we want to combine this table with our HESS-FERMI catalogue based on the 2FGL identification. To do so, open the x-match tool again and select

Algorithm:

select the HESS-FERMI (x-matched catalogue) as Table 1 and the TeV selected AGNs as the second table. In each case, select the *2FGL* identification column as the “Matched Value Column” and press *Go*.

We find 4 sources that fulfill these criteria (TeV selected AGNs observed with HESS and FERMI). Rename the new table accordingly (e.g. “HESS-FERMI AGNs”).

Step 4 – Searching for relative locations in a “high-energy color-color diagram”

How to trace various object properties of a given catalogue against each other and to point out specific sub-samples in the resulting plot.


The next goal is to look for correlations between different high-energy gamma-ray colors of the HESS sources that are also detected by Fermi. In stellar astronomy, tracing optical colors against each other gives a rather robust classification of different star types without having to do (more ambitious) spectroscopy. In the HESS-FERMI catalogue there is not much spectroscopic information available, but the different fluxes in F1—F5 coming from the 2FGL part can be used to eventually discriminate different sub-samples of the catalogue. Since a color is basically an observed flux ratio between two bands, constructing a color-color diagram has the great advantage to be independent of the distance to the objects.

Inside TOPCAT it is possible to plot against each other various properties of the cross-identified HESS-FERMI catalogue. The “color-color” diagram to be computed involves the following high-energy gamma-ray fluxes as measured by Fermi-LAT:

- F1: flux over 100 – 300 MeV
- F2: flux over 300 - 1000 MeV
- F3: flux over 1 - 3 GeV
- F4: flux over 3 - 10 GeV
- F5: flux over 10 - 100 GeV

TOPCAT offers many plotting options (histogram, scatter plots, 3D plots, spherical coordinates plot, stacked line plot, density plot). For this tutorial, we want to trace a logarithmic F4/F3 versus F2/F1 diagram of all FERMI sources, and overlay on this diagram subsamples of sources to see whether they share the same or a distinct distribution:

- the HESS sources detected also with FERMI,
- the TeV selected AGNs observed by HESS and FERMI,
- BL Lac (according to the Simbad data base) observed by HESS and FERMI
- Supernova Remnants (according to the Simbad data base) observed by HESS and FERMI

To do so, select the 2nd LAT catalogue and click on the scatter plot tool  and write “F2/F1” for the X Axis, “F4/F3” for the Y Axis. Put both axis on log scale.

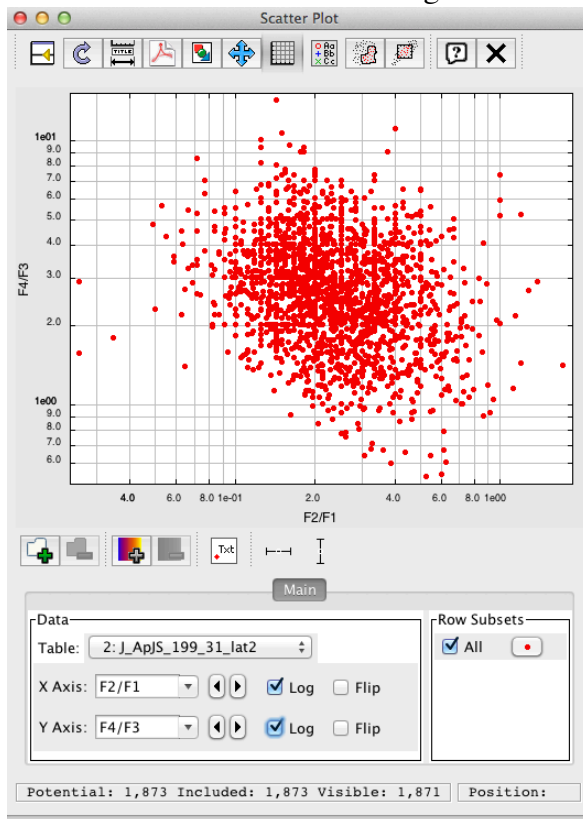



Figure 13: color-color diagram of all FERMI sources in TOPCAT

Add a new dataset to this plot by clicking on . Select the HESS-FERMI x-matched catalogue. The resulting plot shows that the “GeV colors” F_4/F_3 and the “sub-GeV colors” F_2/F_1 of the Fermi-LAT sources that are also detected by HESS do not occupy the same location. On average, the HESS sources prefer lower GeV colors and higher sub-GeV colors with respect to all the Fermi sources.

Add another dataset again and select the HESS-FERMI AGNs this time. You can change the size of the symbols, their colors, the name to be given in the legend, ...

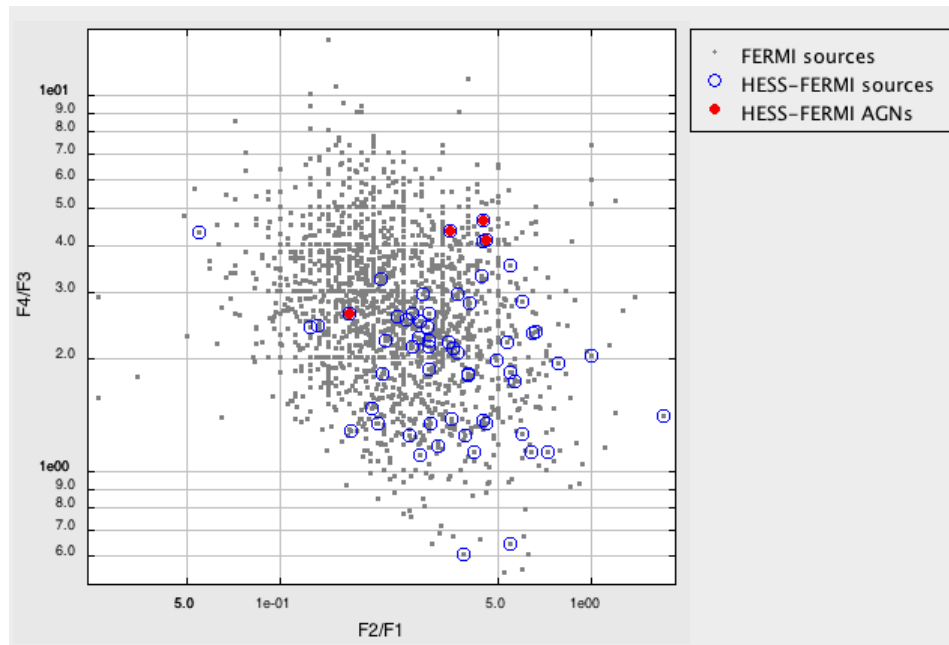



Figure 14: color-color diagram of FERMI sources, HESS-FERMI sources or AGNs only

Since the HESS sources were obtained from the Simbad database, we can take advantage of their classification (Object type column: OTYPE). We will now create subsets of the HESS-FERMI x-matched catalogue to select only the sources that have been classified as supernova remnants (SNRs) or BL Lacertae (BLLac) objects in Simbad.

Go to the main TOPCAT window, select the HESS-FERMI x-matched table and click on .

In the Row subsets window that just opened, click on  to define a new subset from an algebraic expression. Give a subset name (e.g. “SNRs”) and write the following expression:

`OTYPE == "SNR"`

in the row subset window, we see that this subset contains 6 objects that do not seem to have a preferred localization on the color-color plot.

Repeat these steps to create a subset of the HESS-FERMI catalogue that contains only the objects catalogued as BL Lac (4 objects). These 4 objects happen to be the same as the ones resulting from the cross-match between the HESS-FERMI catalogue and the TeV-selected AGN. On the color-color diagram of the HESS-FERMI sources they seem to prefer relatively high

“GeV-colors” $\log(F4/F3)$. However, statistics with only 4 objects are risky - even in the field of high-energy astronomy!

Go back to the scatter plot window and overplot these subsets as new symbols:

- select the HESS-FERMI tab (A)
- click the new subsets that you want to display
- again, you can change the size, color, shape of the symbols and change the labels

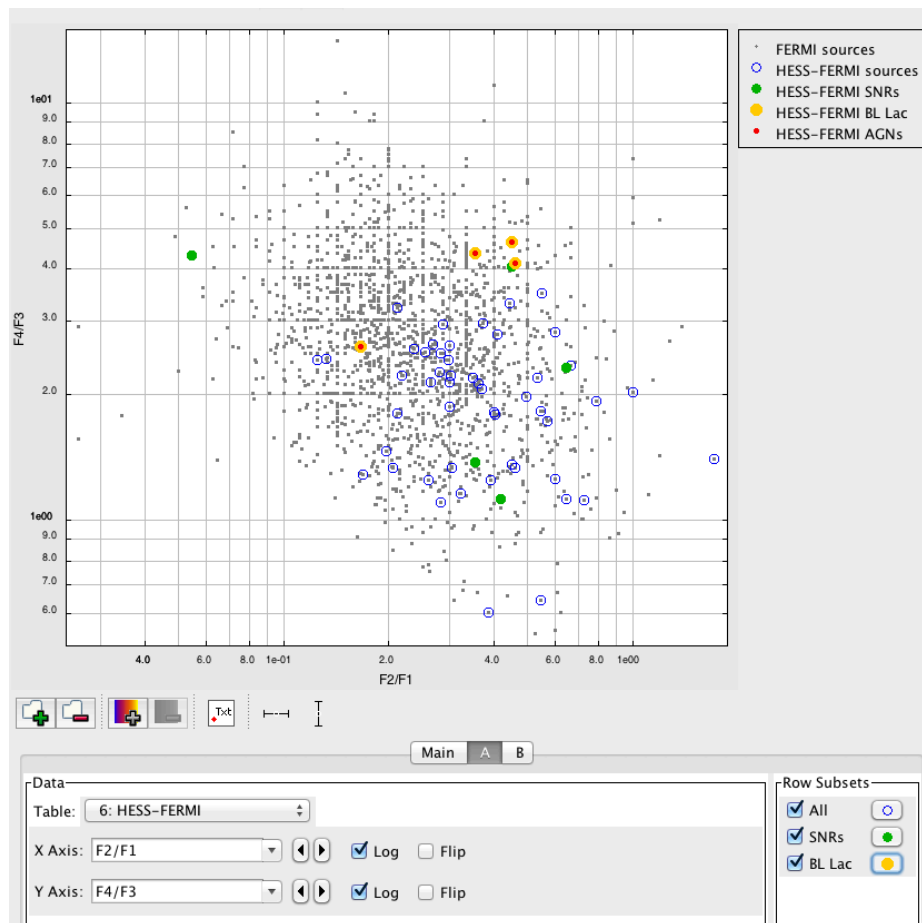


Figure 15: same as Fig. 14, but additional subset of sources have been tagged and overlaid with different symbols

A word of caution in this context: the number of sources identified as AGNs or SNRs in the literature for the HESS-FERMI sources is very small at the moment (4 and 6 sources respectively). One needs to wait for future new identification of gamma ray FERMI sources and/or HESS sources to make conclusive remarks on this type of plots. However, the technique will be the same.

Step 5 – Display the location of interesting sources and search multi-wavelength data around them

How to obtain multi-wavelength images for the source you are interested in

After isolating the 4 SIMBAD-confirmed BL Lac objects on the gamma-ray “color-color” diagram, this last step focuses on one particular object, PKS 2155-304. This peculiar BL Lac object is known to be very variable on a wide spectral range and to show recurrent outbursts. A BL Lac object is a sub-type of active galactic nuclei, where the central engine around the accreting supermassive black hole launches magnetized, ballistic jets that reach out to kiloparsec scales while being nearly aligned with the line of sight of the observer. The emission from the jets is modeled as relativistically beamed synchrotron-self-Compton (SSC) emission produced in the hot plasma of the ejected jet material. The very hot electrons produce synchrotron emission that peaks in the radio band and then the very same electrons comptonize the synchrotron photons and up-scatter them to gamma-rays and beyond. However, in reality the question of the seed photons and the structure of the jet are still under investigation. A simple SSC interpretation of the broad band spectrum is challenged by the partially correlated variability seen between different spectral bands.

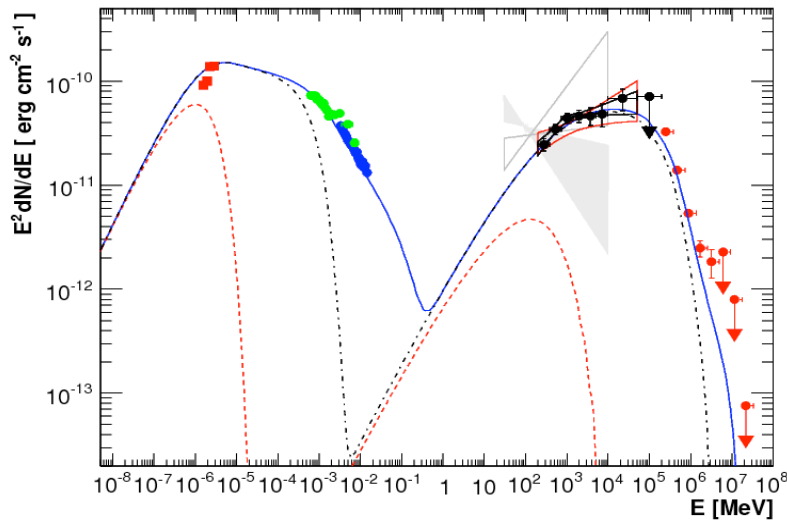



Figure 16: Broad-band spectrum reaching from the radio to the high-energy band (H.E.S.S., Fermi-LAT collaborations, ApJ 696, L150)

In the following, this tutorial shows how to obtain multi-waveband imaging for this source (PKS 2155-304).

Again, we can take advantage of the interoperability of the tools and broadcast the HESS-FERMI x-matched catalogue from TOPCAT back to Aladin by clicking on . The table is now loaded in Aladin.

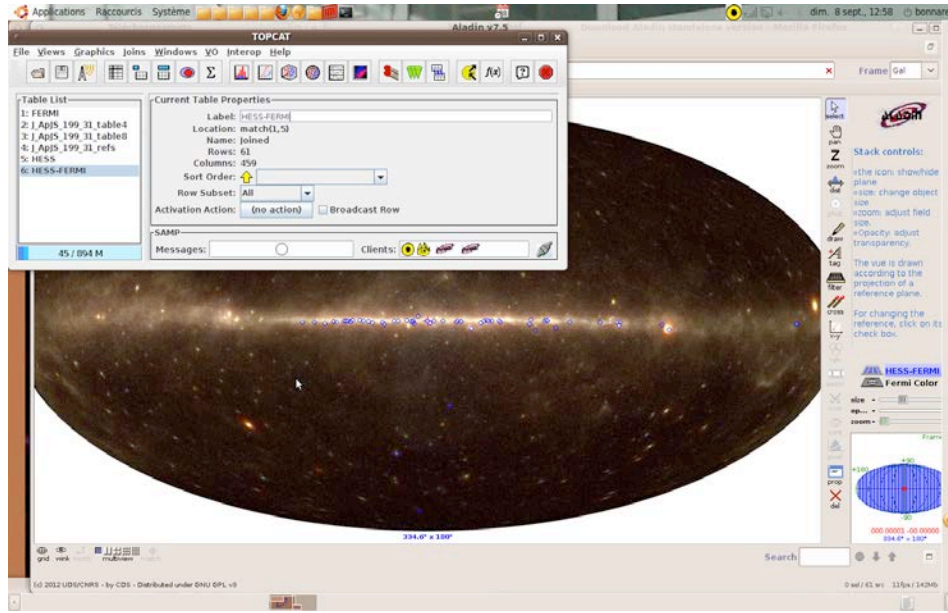


Figure 17: broadcasting the HESS-FERMI x-matched catalogue from TOPCAT to Aladin

Notice the interaction between TOPCAT and Aladin windows: if you click on a source in Aladin, it gets highlighted in the TOPCAT table and TOPCAT plot. Conversely, if you click on a point in the plot window it becomes selected in Aladin (make sure the “broadcast row” option is checked for the broadcasted table in the main TOPCAT window).

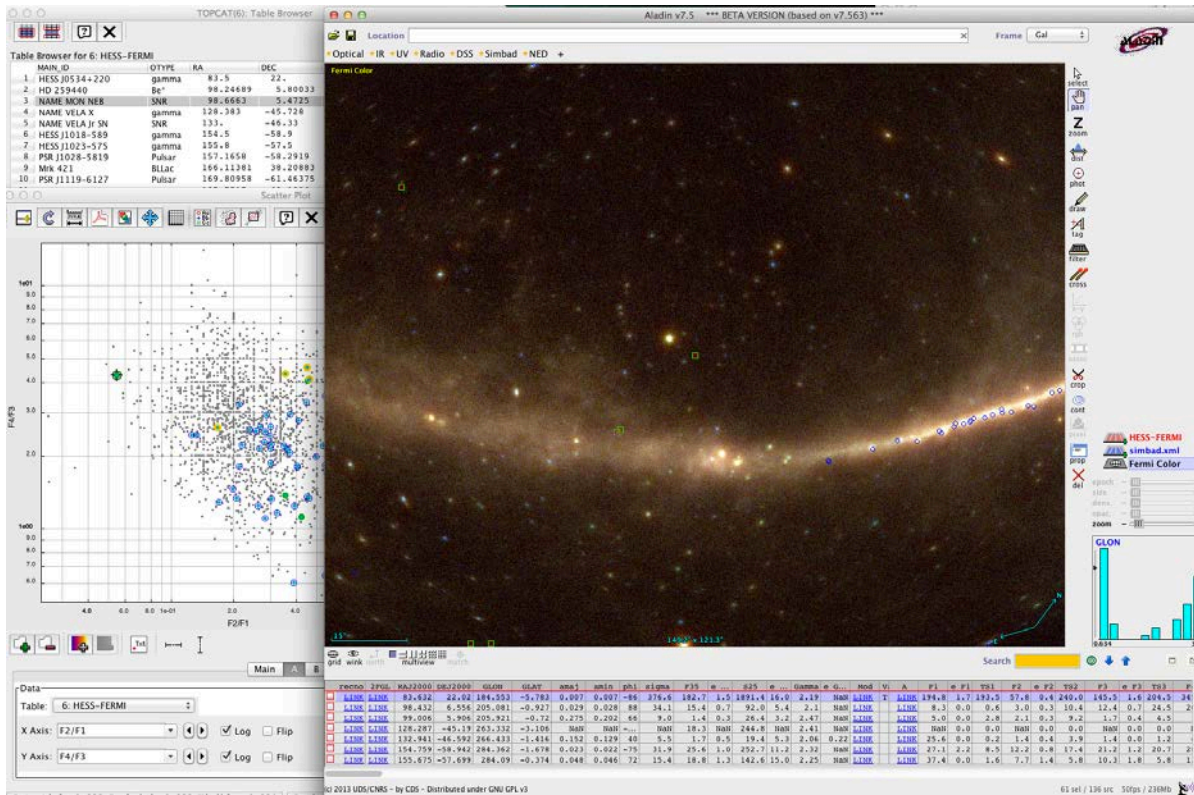


Figure 18: interaction between the Aladin and TOPCAT tools when selecting a source

In Aladin, go to PKS 2155-304. This source is one of the BL Lac objects observed both by HESS and FERMI. By clicking on this source in Aladin, the record from the HESS-FERMI cross-matched catalogue is displayed at the bottom.

Search for X-ray XMM data for this source:

- open the server selector and select the Missions tab
- click on the XMM row and *SUBMIT*

XMM images are directly retrieved from ESA XMM archive

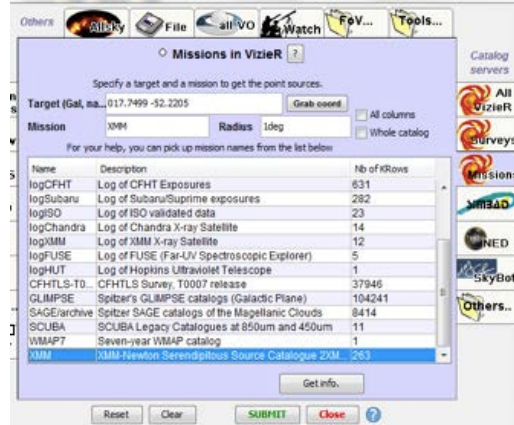


Figure 19: the XMM mission individual observations accessible from Aladin

Pointers to XMM images appear in the record list at the bottom of the Aladin main window. Load an image for the PKS2155-304 object.

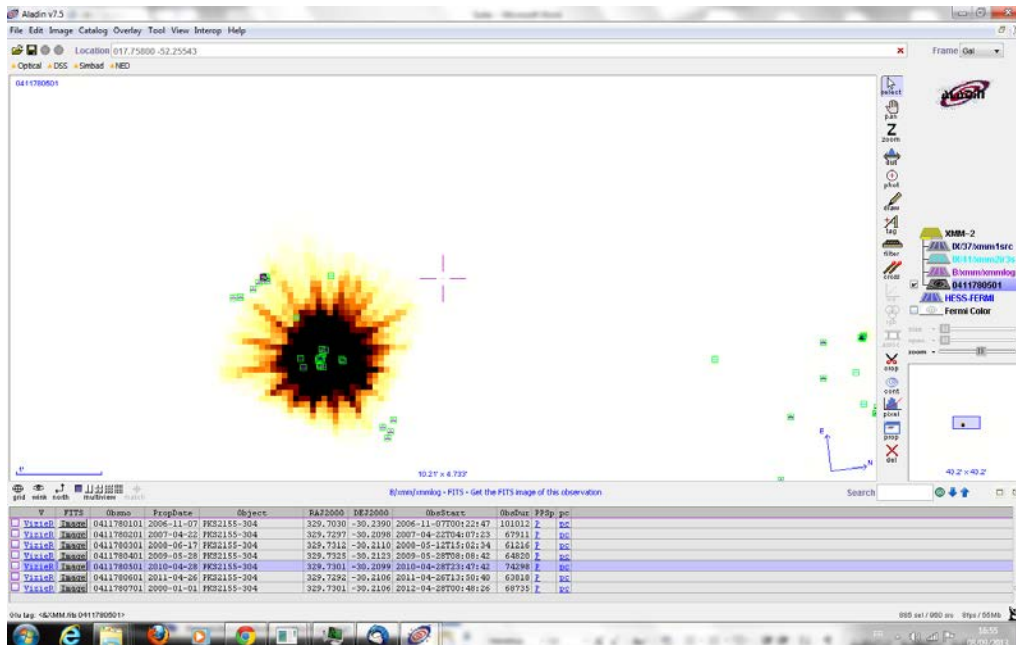


Figure 20: XMM image of PKS 2155-304. Note that because this source was very bright, the detectors around were turned off (square shape)

Search for SCUBA submm data for this source from the Allsky menu in the Server selector. Load the 850 microns map. This allsky Healpix view has been produced and archived at CDS from original data.

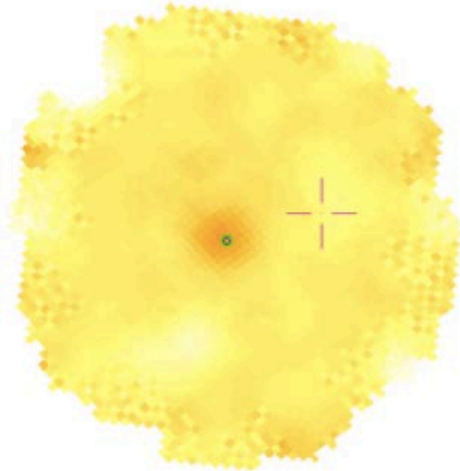


Figure 21: left: how to load the SCUBA 850um image from the Allsky menu
right: SCUBA 850um image of PKS 2155-304

The low energy spectral energy distribution (SED) of many radio sources has been constructed in the SPECFIND catalogue from Vizier. We can search for PKS 2155-304 in this catalogue and show the shape of the radio SED for this source. To do so:

- go to the server selector, select the Vizier tab on the right
- type *SPECFIND* in the catalogue field and *SUBMIT*.
- Select the most recent SPECFIND catalogue (VIII/85A), it gets overlaid on the images in the main Aladin window.
- select the SPECFIND sources corresponding to PKS 2155-304
- different records corresponding to SPECFIND are shown at the bottom of the window.
- click on SED to visualise the SED found for this source

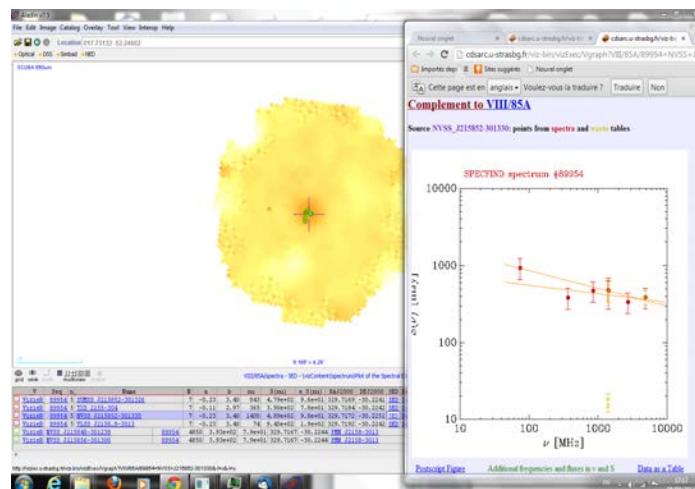


Figure 22: SPECFIND SED for object PKS 2155-304

Step 6 – Broad band photometry of PKS 2155-304 from VizieR

There is a new feature in VizieR, a photometry tool that enables you to search for all VizieR catalogues that have photometry information around a position on the sky and plot the resulting photometry data points as a function of wavelengths. In the following, we will use this tool to get an idea of the spectral energy distribution of PKS 2155-304.

Go to the VizieR photometry tool: it is accessible from a link at the bottom of the VizieR webpage (<http://vizier.u-strasbg.fr/viz-bin/VizieR>) or directly at <http://vizier.u-strasbg.fr/vizier/sed/>

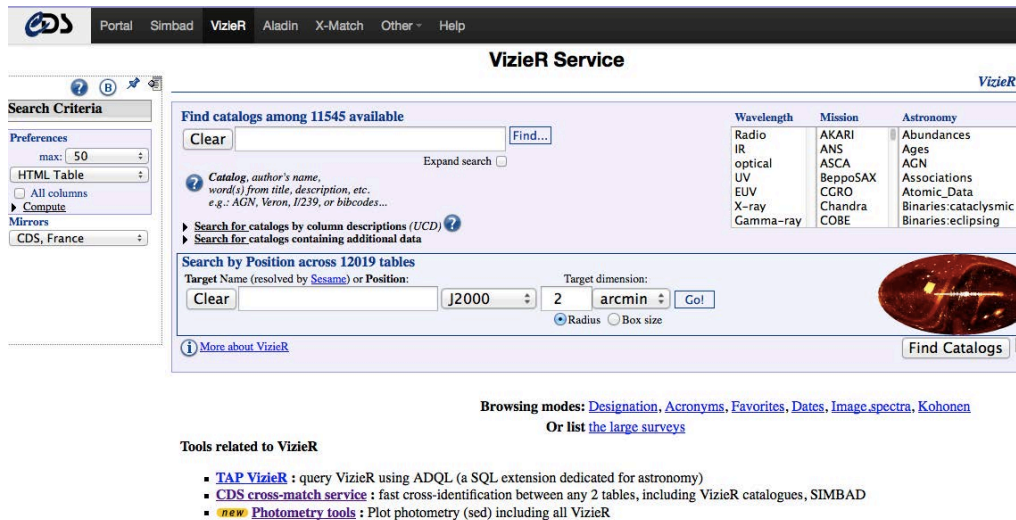


Figure 23: the VizieR photometry tool is available as a link at the bottom of the VizieR webpage

Search for photometric data around 20'' of PKS 2155-304 and press *SUBMIT*



Figure 24: VizieR photometry viewer search interface

All the photometric data points available from VizieR catalogues get plotted as a function of wavelengths and the spatial position around the requested location is shown on the right.

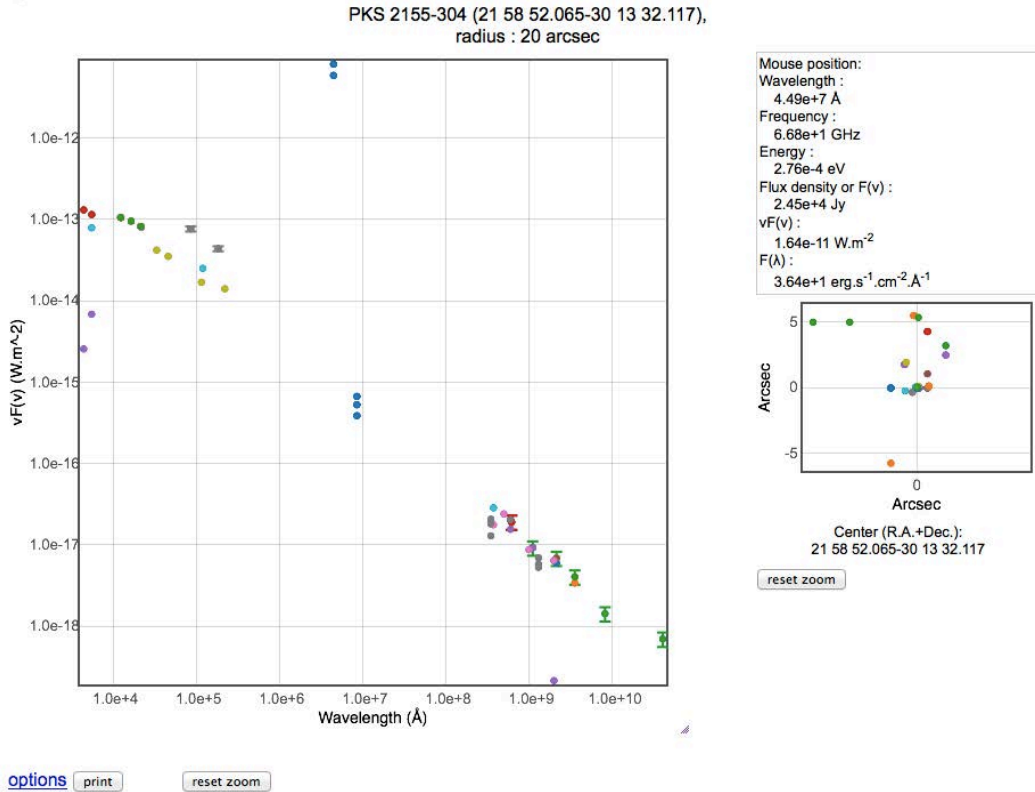


Figure 25: display of the photometric data points from VizieR catalogues found for PKS 2155-304

In this plot, each color represents data points coming from different catalogues. The list of the corresponding catalogues with the individual records (one for each photometric measurement) is show at the bottom of the page:

		Search:							
show	source	_RAJ2000	_DEJ2000	_tabname	_sed_freq	wavelength	_sed_flux	_sed_eflux	_sed_filter
all		(deg)	(deg)		(GHz)	(Å)	(Jy)	(Jy)	
<input checked="" type="checkbox"/>	I/289/out								
<input checked="" type="checkbox"/>	2UCAC=19300255	329.716941	-30.225596	I/289/out	138.55e+3	2.16e+4	58.8e-3		2MASS:Ks
<input checked="" type="checkbox"/>	2UCAC=19300255	329.716941	-30.225596	I/289/out	181.75e+3	1.65e+4	52.4e-3		2MASS:H
<input checked="" type="checkbox"/>	2UCAC=19300255	329.716941	-30.225596	I/289/out	241.96e+3	1.24e+4	43.5e-3		2MASS:J
<input checked="" type="checkbox"/>	I/297/out								
<input checked="" type="checkbox"/>	NOMAD1==0597-1038713	329.716941	-30.225596	I/297/out	138.55e+3	2.16e+4	58.8e-3		2MASS:Ks
<input checked="" type="checkbox"/>	NOMAD1==0597-1038713	329.716941	-30.225596	I/297/out	181.75e+3	1.65e+4	52.4e-3		2MASS:H
<input checked="" type="checkbox"/>	NOMAD1==0597-1038713	329.716941	-30.225596	I/297/out	241.96e+3	1.24e+4	43.5e-3		2MASS:J
<input checked="" type="checkbox"/>	I/312/sample								
<input checked="" type="checkbox"/>	PPMX==215852.0-301332	329.716939	-30.225597	I/312/sample	138.55e+3	2.16e+4	58.8e-3	1.2e-3	2MASS:Ks
<input checked="" type="checkbox"/>	PPMX==215852.0-301332	329.716939	-30.225597	I/312/sample	181.75e+3	1.65e+4	52.4e-3	1.3e-3	2MASS:H
<input checked="" type="checkbox"/>	PPMX==215852.0-301332	329.716939	-30.225597	I/312/sample	241.96e+3	1.24e+4	43.5e-3	1.1e-3	2MASS:J
<input checked="" type="checkbox"/>	I/317/sample								

Showing 1 to 97 of 97 entries

Figure 26: display of the catalogues and individual photometric records found in VizieR for PKS 2155-304

Catalogues and/or individual records/data points can be selected or unselected, i.e. displayed or not on the plots. Conversely, selecting a point in the plot region selects the corresponding record at the bottom.

Except for a few data points, we observe that many photometric records exist in the VizieR database that are consistent with a general spectral shape for PKS 2155-304 and could thus be interested to study further the multi-wavelengths spectral energy distribution of this source.

Note that the radius search of this tool is limited to 20" for technical reasons for the moment. Due to this limitation, this tool is appropriate only for observations for which the resolution is lower or equal to 20". While this may not apply to some sub-mm or high energy observations, it is however a very powerful tool to search for photometric information on your favorite source in the optical, the infrared or the radio domain.