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

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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 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 VO 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
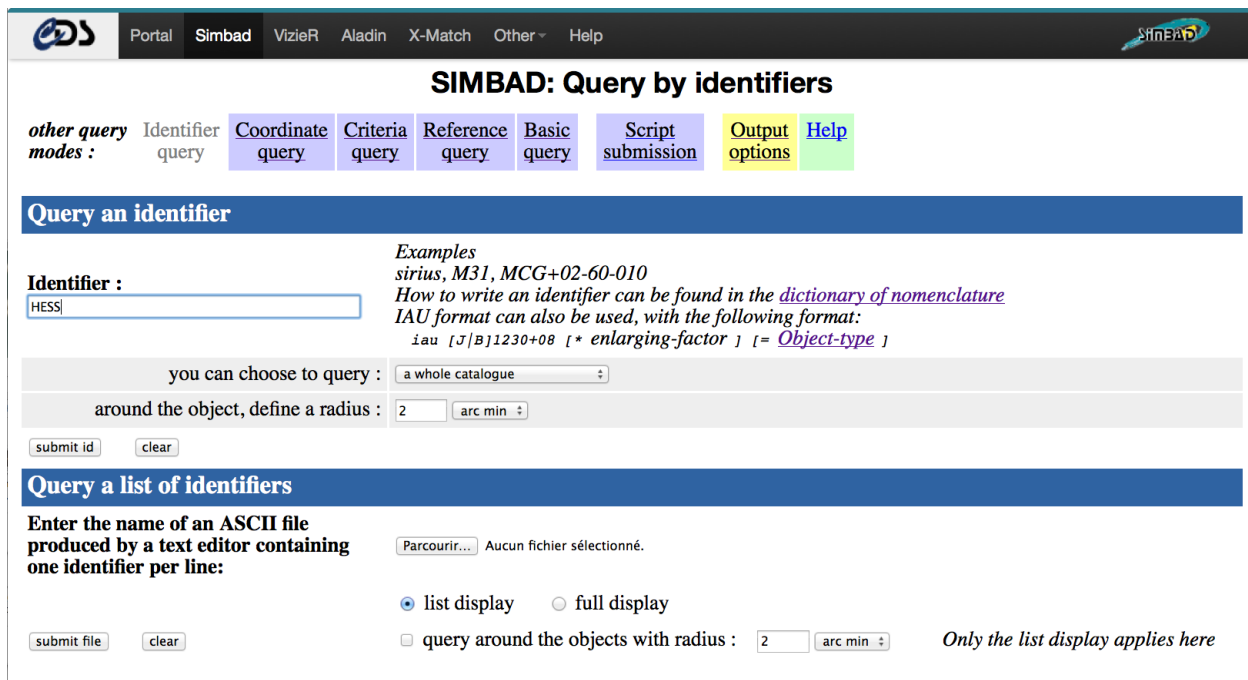rationale of the tutorial

Catalogue of HESS
sources in Simbad

FERMI LAT 3rd
source
catalogue

x-id

61 sources
HESS-FERMI

TeV identified
AGNs

x-id

4 sources
HESS-FERMI AGNs

F4/F3

do AGNs follow a specific trend?

F2/F1

(F1, F2, F3 and F4, being fluxes in the
different energy bands)

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 gamma-rays in the $GeV - TeV$ range. Sources detected by HESS include supernova remnants, wind nebulae pulsar 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.

Figure 1: Simbad interface: selection of HESS catalogue

Save the output as a VOTable file on your disk: at the bottom of the page select the Votable option under "Store this result in Votable, in Ascii, or in the CDS portal".
Alternatively, go to the "output options" of Simbad and save the list as a VOTable file on your disk. Check the "file output" option in order to save this list as a file on your disk. VOTable is the Virtual Observatory format for exchanging tabular data (reload page if it doesn't work).

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.

Start Aladin and open the server selector ( ). Select the HiPS tab ( ) and load a FERMI allsky survey image from the *Image>Gamma-ray* menu. Choose the 'Fermi Color' line.
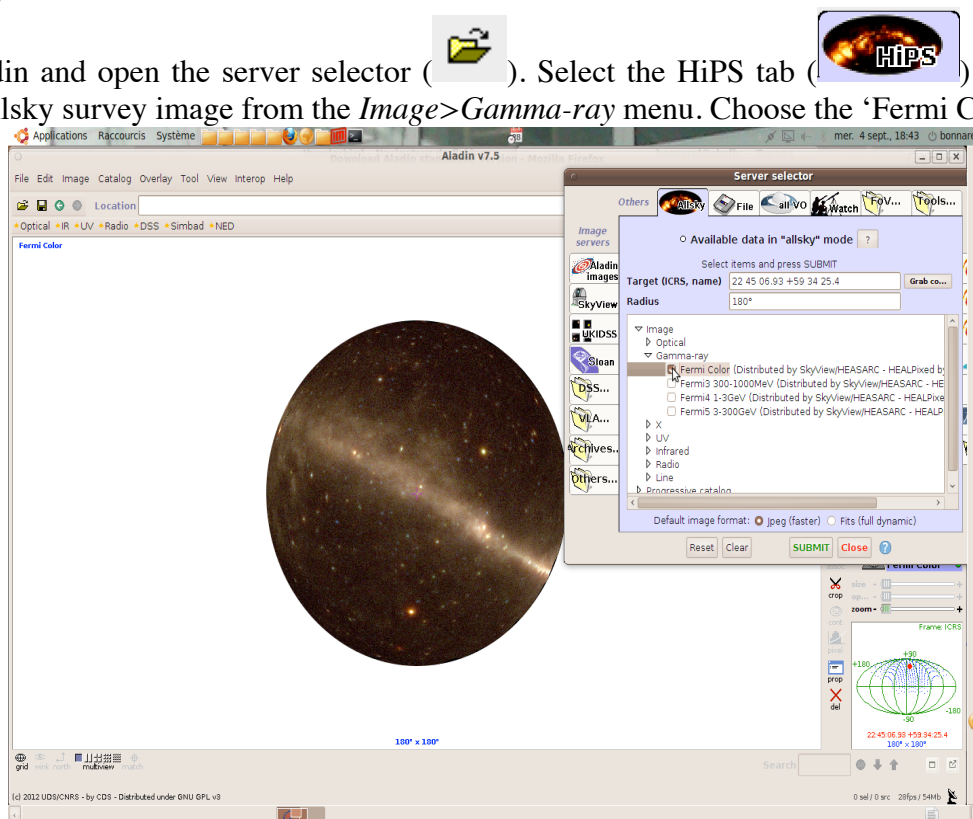

Figure 3: selecting the FERMI color allsky image to display in Aladin

Change the projection to AITOFF (select the "Fermi color" plane in the list of planes on the right

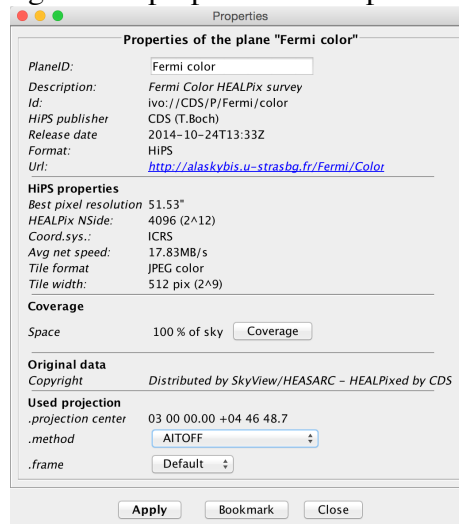of the main Aladin window and go to the properties of the plane -)

Figure 4: 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 - - or drag and drop your VOTable file in the Aladin main window).
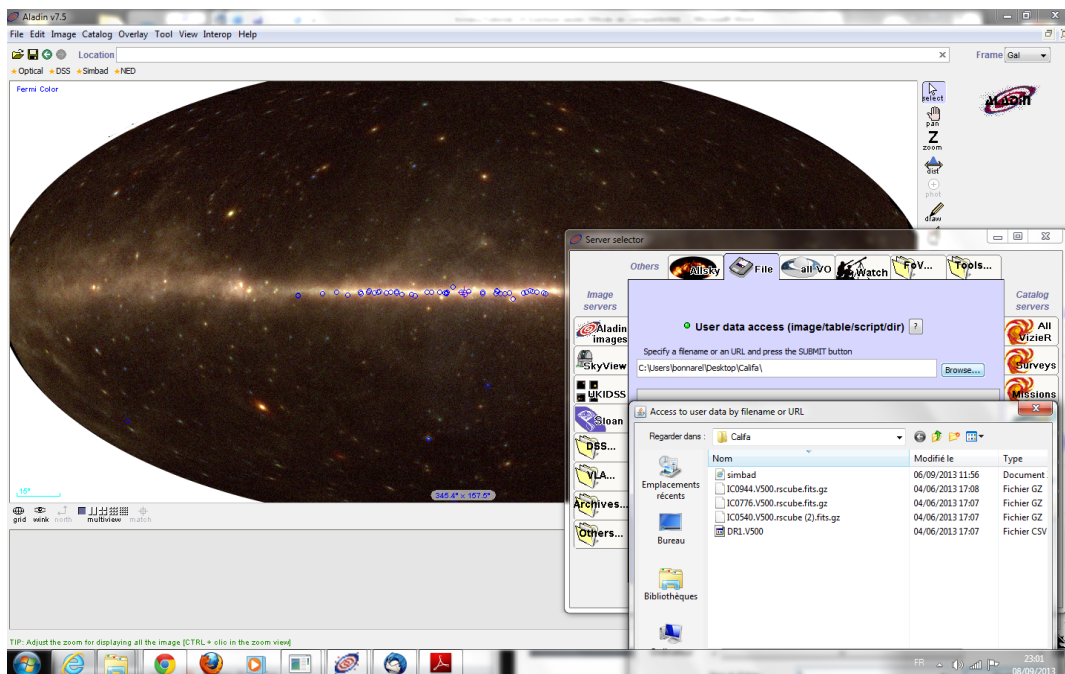These sources get overlaid on the FERMI allsky survey.

Figure 5: 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-correlate and combine sources from two catalogues and to work with the combined set of properties of all objects. The cross-correlation 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 third Fermi-LAT catalogue (3FGL) all identified Fermi sources after 4 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 then 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 6: 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*.
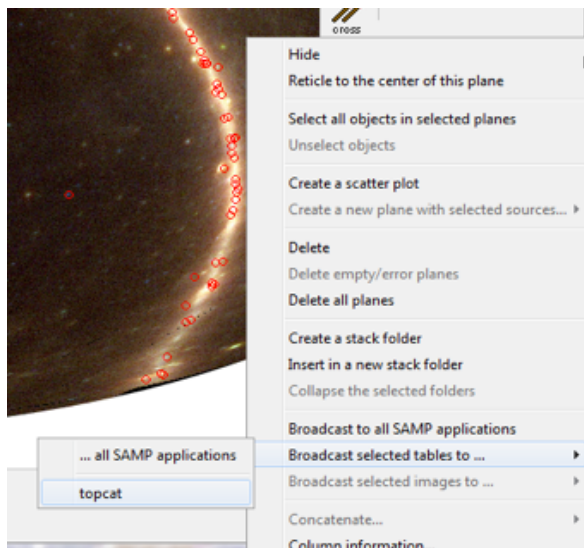

Figure 7: how to broadcast a table from Aladin to TOPCAT

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 8: displaying the informations on the HESS table from Simbad in TOPCAT

In TOPCAT, load the FERMI LAT 3rd source catalogue (3FGL) from VizieR with all rows and all columns selected:

- click on [icon] to get different ways to open new tables. Use the [icon] button to open the VizieR Catalogue Service window.
- Select *All Rows* in the Row selection and *all* in the column selection
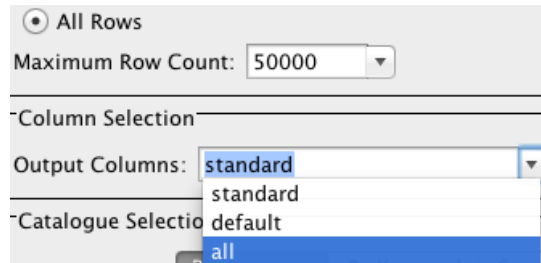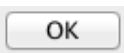
Figure 9: all column selection in the VizieR query from TOPCAT

- select catalogues [By Keyword] and type "3FGL" in the *Keywords window,* then search catalogues.

- select the Fermi LAT third source catalogue (3FGL) and press [OK]
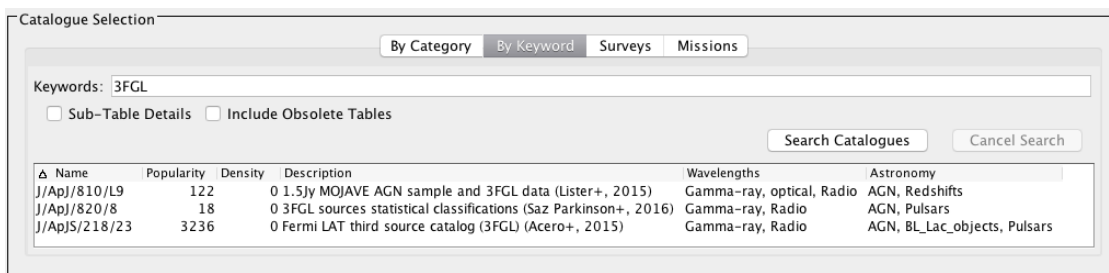
Figure 10: selecting the 3FGL catalogue from VizieR in TOPCAT

Three different tables from the 3FGL catalogue are then loaded in the TOPCAT main window:
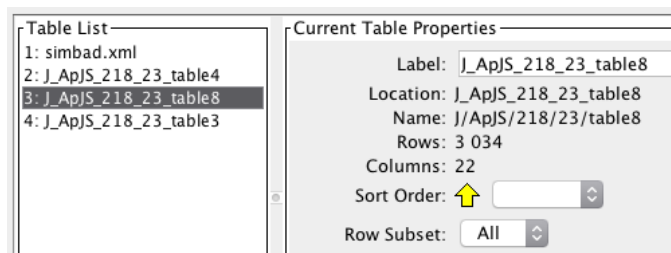
Figure 11: the different 3FGL tables loaded in TOPCAT

Information on each table is obtained with the button [icon]. Doing so, we learn that the first table (J_ApJS_218_23_table4) contains the 3FGL catalogue with the former Fermi/LAT associations (0/1/2FGL catalogues), the second one (J_ApJS_218_23_table8) contains the spectral information of the sources while the last one contains the definition of the analysis flags.

As we are interested in the coordinates and the spectral informations, we need to cross match the first two tables:

     - TOPCAT offers a cross match tool with the button.
     - select the *exact value* algorithm, matched value column "3FGL".
     - select J_ApJS_218_23_table4 (=position information) as the first table.
     - select J_ApJS_218_23_table8 (=spectral information) as the second table.
     - and *Go*

We obtain a new catalogue containing the 2954[1] sources of the 3FGL catalogue with both the coordinates and the spectral informations. The catalogue is named ''match(2,3)''. It can be renamed (e.g. "3FGL") in the *Label* field in the *Current Table Properties*.

We will now make a cross-identification of the two catalogues (HESS sources from Simbad and 3FGL sources):

     - select the 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). Note that the 1.0 degrees correspond to the limit of the search rather than an error.
     - select 3FGL as the first table
   - select simbad.xml (=HESS sources) as the second table
     - and *Go*

We obtain a new catalogue containing the 59 best-match sources observed with both HESS and FERMI. This catalogue is named "match(5,1)" 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 3*LAC* catalogue (Ackermann et al. 2015) 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 3LAC catalogue (Ackermann+2015) from VizieR (same steps as above) in order to get the table 10 (J_ApJ_810_14_table10) - 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 3FGL identification. To do so, open the x-match tool again and select

select the HESS-FERMI (x-matched catalogue) as Table 1 and the TeV selected AGNs as the second table. In each case, select the 3*FGL* (note the name might have changed to 3FGL_1) identification column as the "Matched Value Column" and press *Go*.
We find 5 sources that fulfill these criteria (TeV selected AGNs observed with HESS and FERMI). Rename the new table accordingly (e.g. "HESS-FERMI AGNs").

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[1] Sources detected in confused regions, labelled as 'c-sources', are not included in this final sample.

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 3FGL 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 Fermi/LAT classification) observed by HESS and FERMI
- Supernova Remnants (according to the Simbad data base) observed by HESS and FERMI

To do so, select the third LAT catalogue and click on the plane plotting window □ and write "F2/F1" for the X Axis, "F4/F3" for the Y Axis. Put both axis on log scale by selecting 'X log' and 'Y log' in the ▦ Axes options at the bottom left of the window.
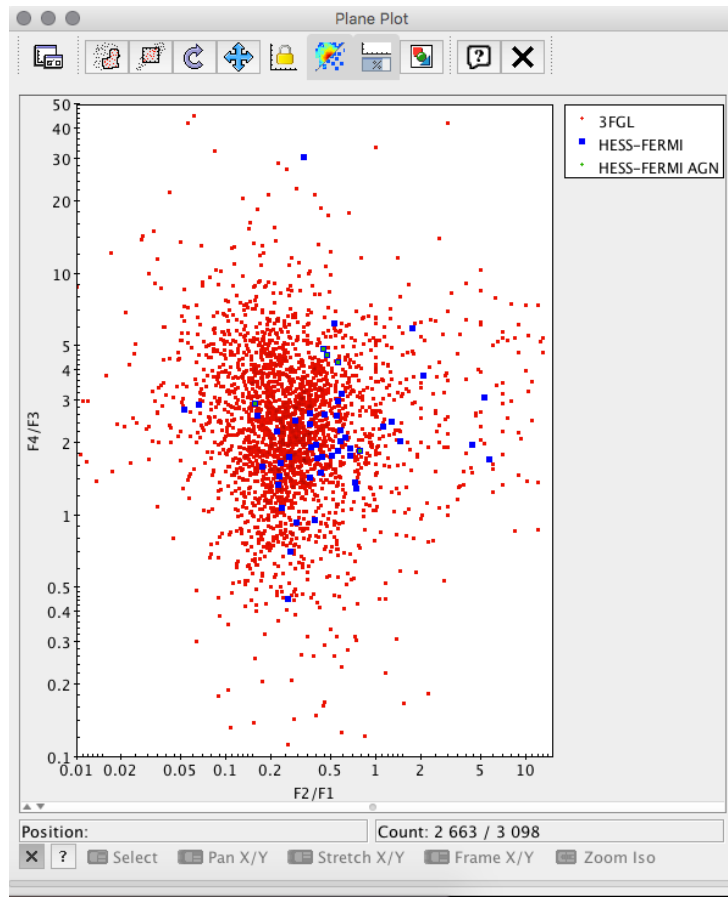
Figure 12: color-color diagram of all FERMI sources in TOPCAT

Add a new dataset to this plot by clicking on [icon]. Select the HESS-FERMI x-matched catalogue. Select again the F2/F1 and F4/F3 for the X and Y axis. The resulting plot shows that the "GeV colors" F4/F3 and the "sub-GeV colors" F2/F1 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, ... Note that the customizing window can be separated from the plot by clicking on [icon]. Names of the different subsamples can be changed in the "Subset tab" of each plot dataset.
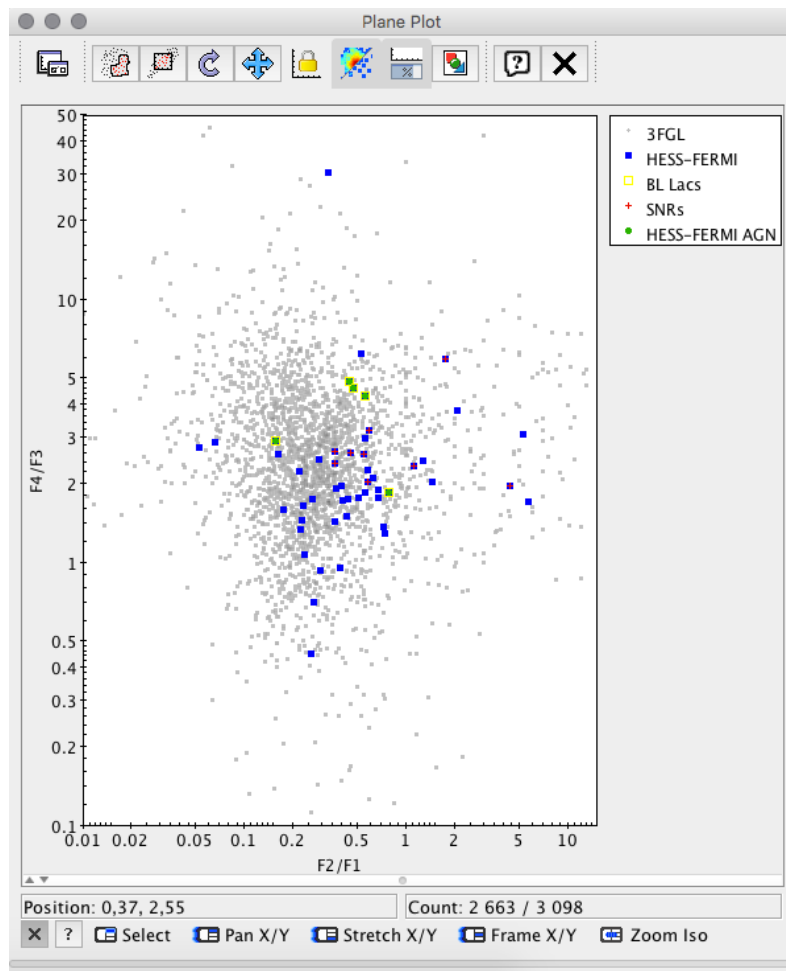
Figure 13: color-color diagram of FERMI sources, HESS-FERMI sources or AGNs only

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 (BL Lac) objects in the 3FGL catalogue.

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:
`Class == "SNR" || Class == "snr"`
in the row subset window, we see that this subset contains 9 objets 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 in the 3FGL catalogue with the algebraic expression:
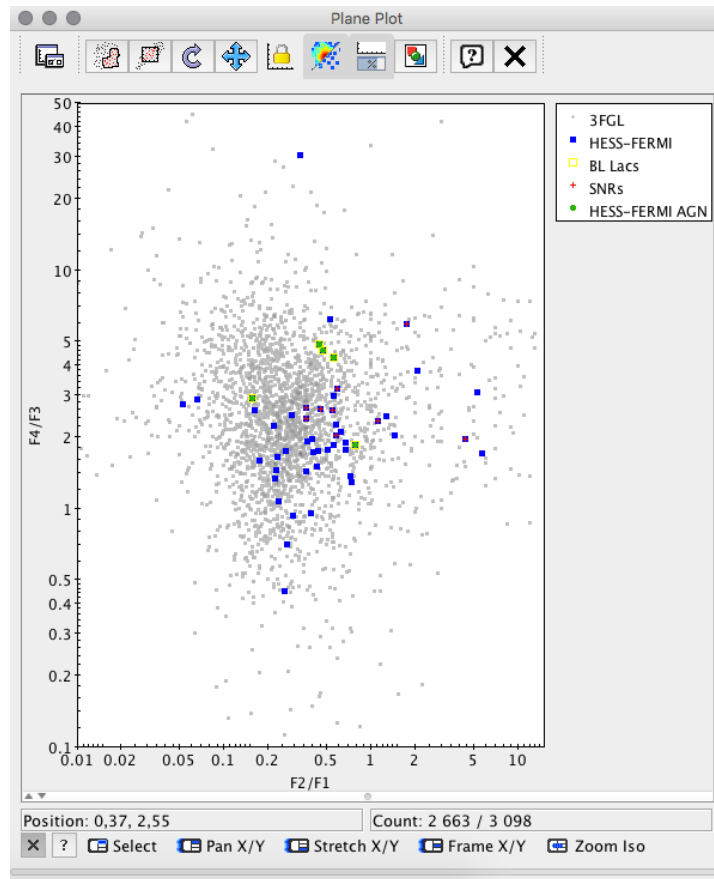`Class == "BLL" || Class ==  "bll"`

Figure 14: same as Fig. 13, but additional subset of sources have been tagged and overlaid with different symbols

These 5 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 5 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)
- In the 'Form' tab of the plot, select the new subsets that you want to display
- again, you can change the size, color, shape of the symbols and change the labels

A word of caution in this context: the number of sources identified as BL Lac or SNRs in the literature for the HESS-FERMI sources is very small at the moment (5 and 9 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 5 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.
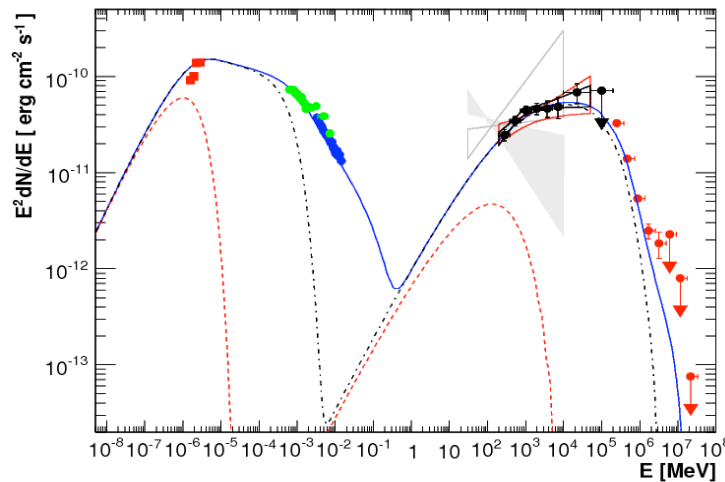

Figure 15: Broad-band spectrum reaching from the radio to the high-energy band
(H.E.S.S., Fermi-LAT collaborations, ApJ 696, L150)

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 ![icon]. The table is now loaded in Aladin.
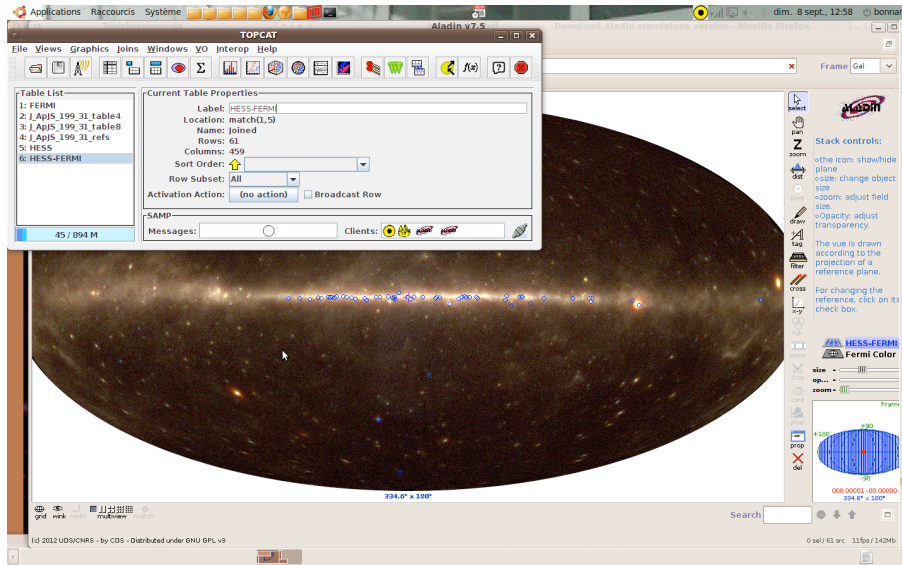
Figure 16: broadcasting the HESS-FERMI x-matched catalogue from TOPCAT to Aladin

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).
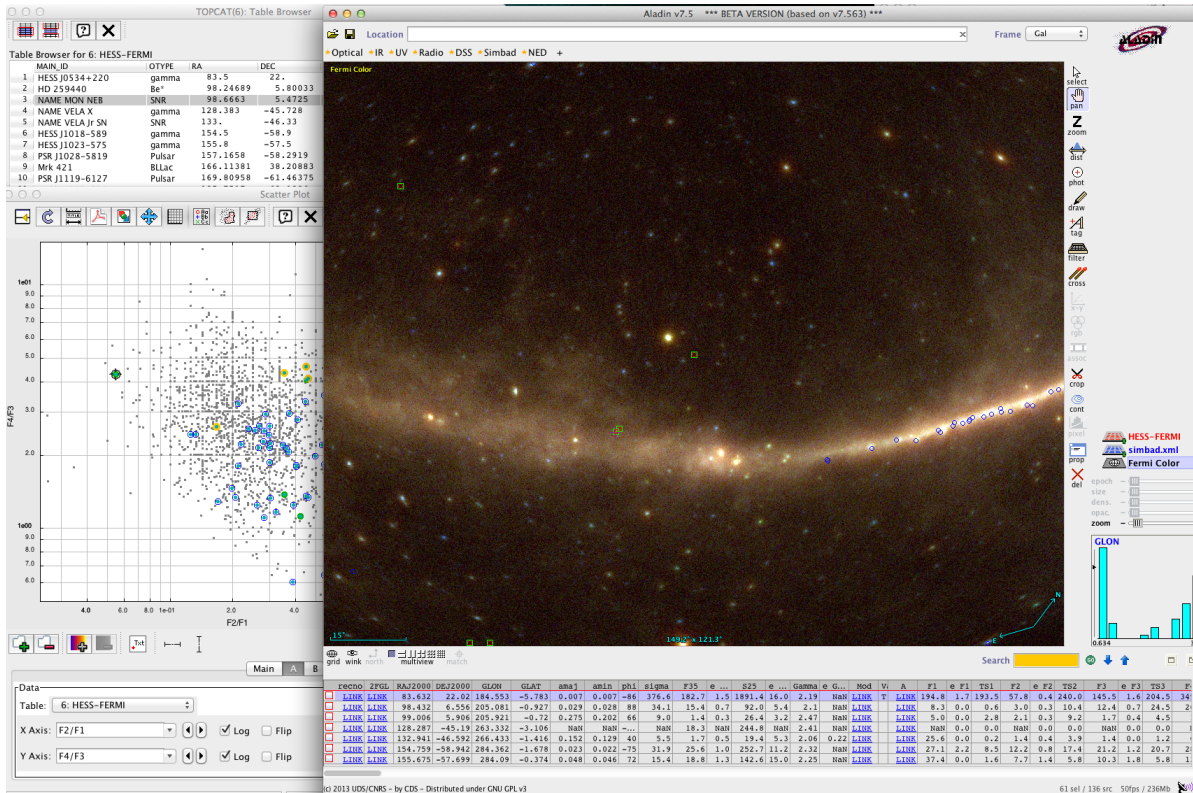

Figure 17: interaction between the Aladin and TOPCAT tools when selecting a source

In Aladin, type "PKS 2155-304" in the location box of the main window. This source, PKS 2155-304, 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.

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, verify that your query is centered on PKS 2155-304 and that the query radius is not too large (14' by default) and *SUBMIT*.
- Select the SPECFIND catalog (VIII/85A/spectra), it gets overlaid on the images in the main Aladin window.
- Unselect or delete the "VIII/85A/waste" plane
- 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 vizualise the SED found for this source
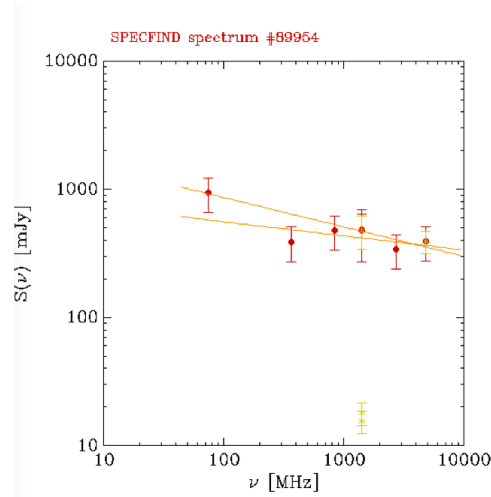
Figure 18: SPECFIND SED for object PKS 2155-304

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

VizieR has 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 the VizieR webpage (http://vizier.u-strasbg.fr/) using the button [Photometry] or directly at http://vizier.u-strasbg.fr/vizier/sed/

Figure 19: the VizieR photometry tool is available as a link in the VizieR webpage

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

Figure 20: 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.
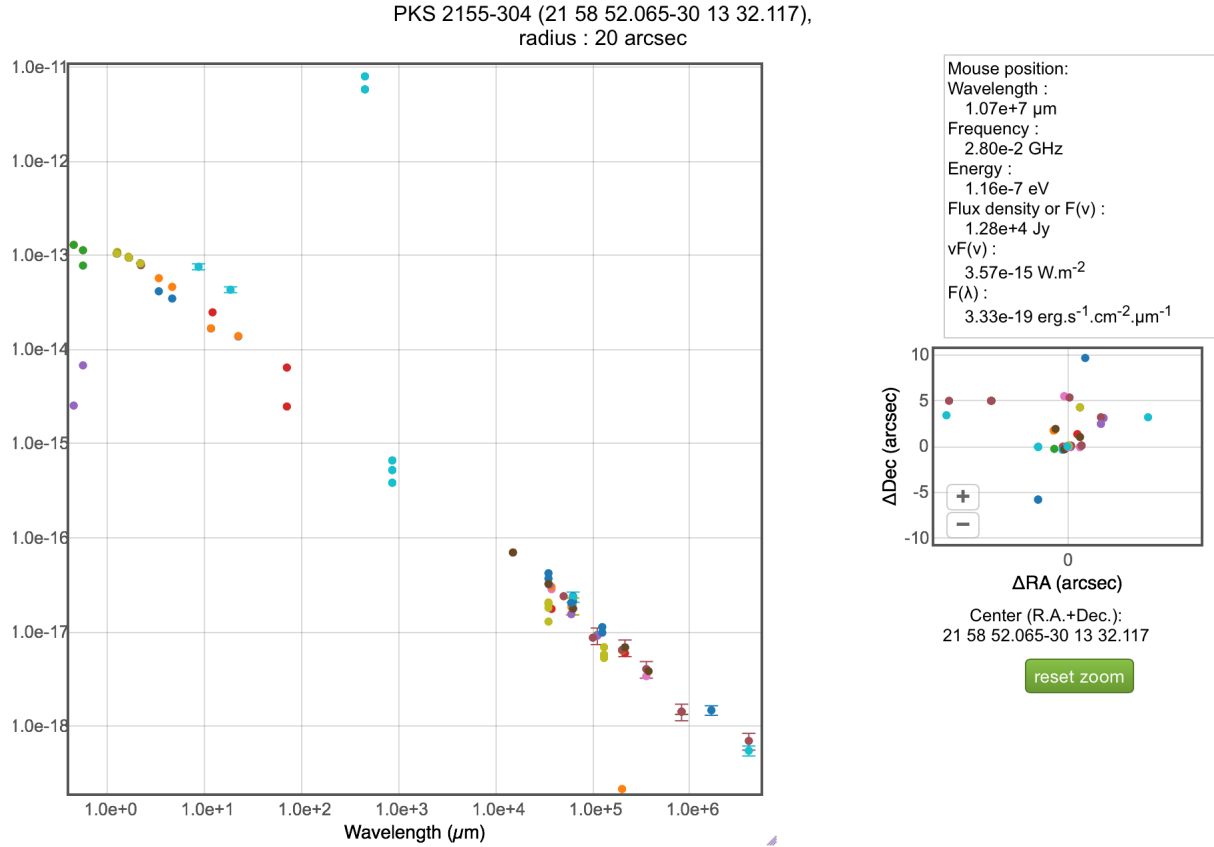
Figure 21: display of the photometric data points from VizieR catalogues found for PKS 2155-304

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:

Figure 22: 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 interesting to study further the multi-wavelengths spectral energy distribution of this source.

Note that the radius search of this tool is limited to 30" 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 30". 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.