Hands-on Virtual Observatory for High-Energy Astrophysics

Manipulating Fermi, HESS, VLBI and Multi-Wavelength Data

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IVOA Standards and VO Tools

Outline

How This Session Works

- This is a **hands-on session**, not a classical lecture.
- Slides are short instructions and checkpoints.
- Most of the time is for manipulating tools yourself.
- We stop regularly so everyone reaches the same state.

Rule of thumb

5 minutes explanation, then 10–15 minutes practice.

Do not just watch

Open the tools, run the queries, make the plots, and save your intermediate tables.

Hands-on Outcomes

- Load and inspect a HESS source list.
- Overlay HESS positions on a Fermi sky map in Aladin.
- Query Fermi/VLBI catalogues through VizieR, TOPCAT or Python.
- Cross-match HESS and Fermi sources with a justified radius.
- Build a gamma-ray colour-colour plot in TOPCAT.
- Send a selected source to Aladin and inspect its multi-wavelength context.
- Finish with a reproducible notebook-style workflow using `pyVO/ipyaladin` examples.

Tools and Services Introduced

Interactive tools

- **Aladin**: sky visualization, HiPS, overlays, SAMP.
- **TOPCAT**: tables, plots, metadata, TAP, cross-match.
- **STILTS**: command-line TOPCAT-style workflows.
- **Python notebooks**: reproducible VO analysis and embedded Aladin.

VO services and archives

- **CDS Portal, SIMBAD, VizieR, X-Match**: discovery, objects, catalogues and matching.
- **NED**: extragalactic context, AGN, redshifts and SEDs.
- **HEASARC / Fermi**: high-energy mission archives and catalogues.
- **IVOA standards**: TAP, ADQL, VOTable, SAMP, SIA, SSA, MOC.

Installing the Main VO Tools

Desktop / command line

- **Aladin Desktop**: download from CDS; requires Java; launch with `java -jar Aladin.jar`.
- **TOPCAT**: download the Java `.jar`; launch with `java -jar topcat-full.jar`.
- **STILTS**: download the Java `.jar`; launch with `java -jar stilts.jar`.

Browser / Python

- **Python VO**: use an existing Python/Jupyter environment with `pyvo`, `astroquery`, `astropy`, `ipyaladin` if needed.
- **Embedded Python**: open the CDS tutorial notebooks from the link slide.
- **Web services**: SIMBAD, VizieR, NED, HEASARC and Fermi tools run directly in a browser.

Before the practical

Install Java-based tools in advance and keep the link slide open for downloads and tutorials.

Python Environment for VO Workflows

Recommended installation

Use an existing Python environment and install the packages with `pip` or `conda`; do not mix package managers in the same environment.

```
python -m pip install astropy astroquery pyvo ipyaladin \
  jupyterlab notebook ipywidgets pandas numpy matplotlib \
  scipy requests regions mocpy cdshealpix
```

- `astropy`, `regions`, `mocpy`, `cdshealpix`: coordinates, tables, FITS, regions, MOCs and HEALPix.
- `astroquery`, `pyvo`, `requests`: SIMBAD/VizieR queries, TAP/ADQL and web access.
- `ipyaladin`, `jupyterlab`, `notebook`, `ipywidgets`: embedded Aladin and interactive notebooks.
- `pandas`, `numpy`, `scipy`, `matplotlib`: table analysis, statistics and plots.

Suggested Timing

Time	Activity	Deliverable
10 min	VO tools warm-up	Everyone has Aladin and TOPCAT open
15 min	SIMBAD + Aladin	HESS VOTable visible on a Fermi sky map
20 min	TOPCAT + VizieR	Fermi table loaded and columns identified
20 min	Cross-match	HESS–Fermi table saved
20 min	Plots/subsets	Colour-colour diagram with source classes
15 min	PKS 2155-304	Source sent to Aladin; SED context inspected
10 min	Debrief	Query text, tables and figures documented

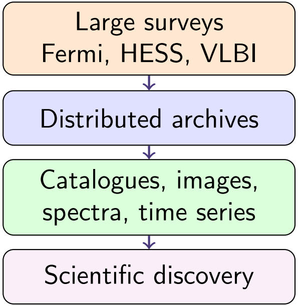
Introduction

VO tools and services in context

Why Do We Need the Virtual Observatory?

Survey	Sources
Fermi 4FGL	>6,600
Pan-STARRS	>3 billion
SDSS	>500 million
2MASS	470 million

- Huge datasets.
- Heterogeneous formats and metadata.
- Distributed archives across institutes and missions.
- Multi-wavelength and time-domain science.

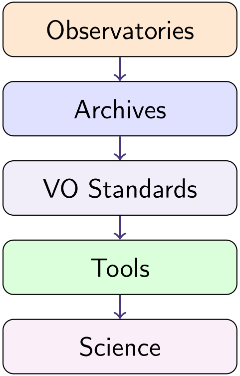


What is the Virtual Observatory?

Definition

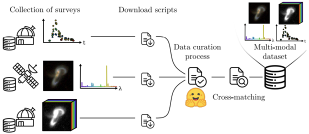
The Virtual Observatory is an international framework that makes astronomical data archives interoperable through shared standards, protocols, and tools.

- A layer connecting data providers and researchers.
- A common language for data discovery and access.
- A practical ecosystem for multi-wavelength science.



The IVOA

- International Virtual Observatory Alliance.
- Coordinates the development of VO standards.
- Ensures that archives, services, and tools can communicate.



Core standards and protocols

TAP, ADQL, VOTable, SAMP, SIA, SSA

VO Scientific Impact

- **HESS**: TeV gamma-ray source catalogues and Galactic-plane surveys.
- **Euclid**: cosmology and galaxy evolution archives.
- **JWST**: high-value imaging and spectroscopy products.
- **Fermi**: gamma-ray catalogues and source identification.
- **eROSITA**: large X-ray source samples.

Scientific value

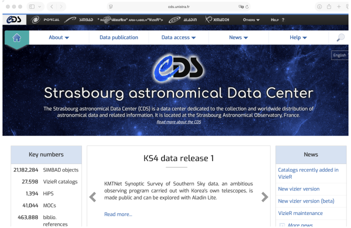
The VO turns separate mission archives into a connected research environment for cross-identification, statistical studies, and multi-wavelength interpretation.

CDS Strasbourg

VO tools and services in context

CDS Overview

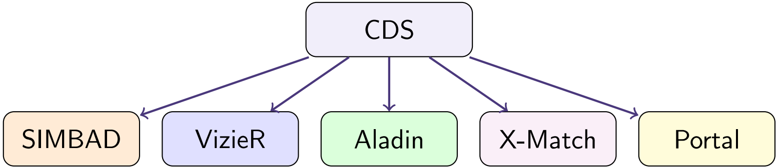
- Centre de Données astronomiques de Strasbourg.
- Founded in 1972.
- Long-term mission: collect, enrich, and distribute astronomical information.
- Major European contributor to the Virtual Observatory.



Mission

Data dissemination, interoperability, curation, and VO services for the international astronomy community.

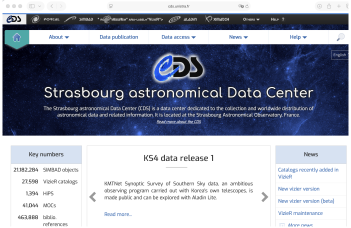
CDS Services



- Object identification, catalogue access, visualization, and cross-matching.
- Services are designed to work together through VO protocols.

CDS Portal

- Global search entry point across CDS resources.
- Useful first step when starting from an object name.
- Example target: **M87**.
- Gives access to publications, catalogues, images, and linked services.

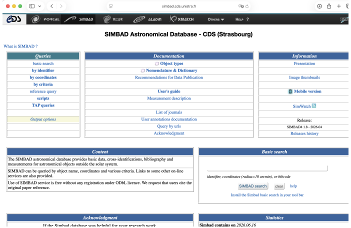


SIMBAD

VO tools and services in context

SIMBAD Introduction

- Reference database for astronomical objects.
- Contains coordinates, object types, bibliography, measurements, and aliases.
- Connects names used in the literature to physical sky positions.

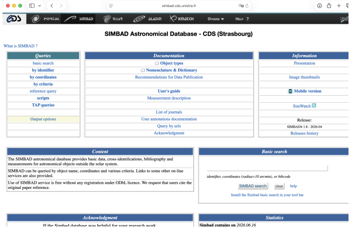


SIMBAD Query Example

Example search

Crab Nebula

- Retrieve coordinates.
- Check object type and classifications.
- Inspect references and measurements.
- Identify aliases and cross-identifications.



SIMBAD Bibliography

- SIMBAD links astronomical objects to publications.
- Bibliographic information connects naturally to NASA ADS.
- Useful for tracing discovery papers, recent observations, and citation context.

Practical use

Before writing a proposal or paper, SIMBAD helps verify what is already known about a source and which references are essential.

Typical Applications of SIMBAD

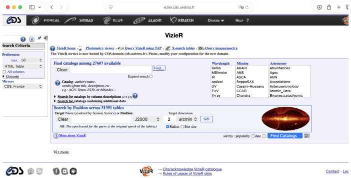
- Prepare an observing run.
- Identify an unknown source in an image or catalogue.
- Verify whether an object is already classified.
- Collect names and aliases used across the literature.
- Retrieve nearby objects for context.

VizieR

VO tools and services in context

VizieR Overview

- Repository of published astronomical catalogues.
- Contains more than 25,000 catalogues.
- Provides metadata, documentation, column descriptions, and query interfaces.
- Major gateway to Fermi, HESS, VLBI, radio, infrared and optical catalogues.

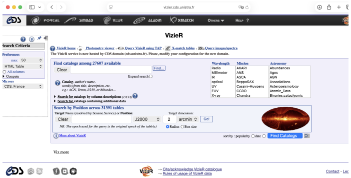


Searching in Vizier

Practical query

Target: M87
Radius: 5 arcmin
Catalogue: VLBI

- Use a cone search around the target coordinates.
- Inspect source density and magnitude limits.
- Export the result for analysis or visualization.



Catalogue Metadata

- Column names and descriptions.
- Units and coordinate systems.
- Data quality flags.
- References and provenance.
- Links to original papers and mission documentation.

Key point

Never analyze a catalogue without reading its metadata and quality flags.

Exporting Data

- CSV for quick inspection.
- FITS for astronomical workflows.
- VOTable for VO interoperability.

Send to

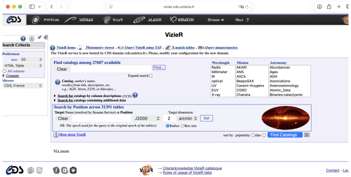
- TOPCAT for analysis.
- Aladin for visualization.
- Python for reproducible scripts.

Aladin

VO tools and services in context

Aladin Overview

- Interactive sky atlas developed by CDS.
- Main visual exploration tool of the VO ecosystem.
- Combines images, catalogues, object databases, and survey layers.
- Supports SAMP communication with TOPCAT and other tools.



Sky Images

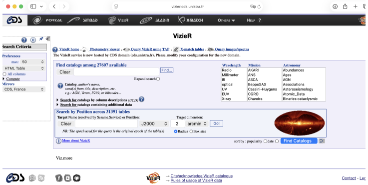
- DSS for optical historical images.
- Pan-STARRS for deep optical imaging.
- 2MASS for near-infrared images.
- WISE for mid-infrared sky maps.

In practice

Load several image layers and compare morphology, depth, and wavelength-dependent emission.

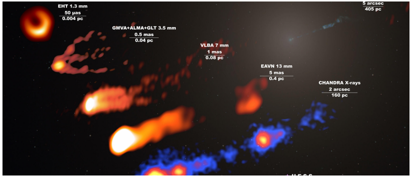
Catalogue Overlay

- Overlay Fermi, HESS or VLBI source positions on images.
- Add SIMBAD object markers.
- Query VizieR catalogues directly in the field of view.
- Check positional associations visually.



Multi-Wavelength Astronomy

- Optical.
- Infrared.
- Radio.
- X-ray.
- Gamma-ray.

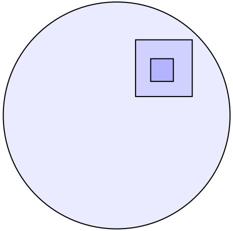


Example

M87 combines stellar light, jet emission, radio structure, X-ray plasma, and high-energy activity.

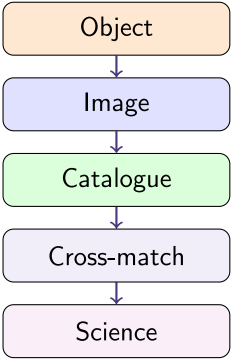
HiPS Surveys

- HiPS means Hierarchical Progressive Surveys.
- Enables smooth all-sky browsing and progressive zooming.
- Efficient for very large surveys.
- Allows fast comparison of all-sky maps and deep fields.



all-sky $\rightarrow$ zoom $\rightarrow$ tiles

Aladin Live Workflow



Hands-on Session 1

Focus

Aladin warm-up: open the sky viewer, load a target and check SAMP readiness.

Hands-on 1: Aladin Warm-Up

1. Open Aladin Desktop.
2. Search for **M87**.
3. Switch between DSS, Pan-STARRS, 2MASS and a Fermi HiPS map.
4. Change the coordinate grid and zoom level.
5. Add one catalogue layer from VizieR around the field.

Time box

12 minutes hands-on.

Checkpoint

You should have at least two image layers and one catalogue overlay in the stack.

Aladin Desktop: Practical Setup

- Aladin Desktop is the full-featured Java application.
- It can load local files, URLs, HiPS surveys, catalogues and MOC maps.
- The interface is organized around the command bar, the stack, the sky view and the data-discovery tree.
- Allocate enough memory when manipulating large sky maps or many layers.

Command-line launch

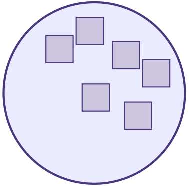
```
java -Xmx3g -jar Aladin.jar
```

Best use

Use Aladin Desktop for live multimessenger exercises rather than only the web view.

MOC Maps in Aladin

- **MOC** means Multi-Order Coverage map.
- It encodes complex sky regions using HEALPix cells at multiple resolutions.
- It is compact and efficient for irregular regions such as gravitational-wave localizations.
- Aladin can display, compare and manipulate MOC layers directly.



irregular sky region

Aladin for Gravitational-Wave Follow-Up

1. Get a public skymap URL from **GraceDB** or a **GCN** notice.
2. Load the `*.multiorder.fits` URL into the Aladin command bar.
3. Display the probability skymap as a layer in the stack.
4. Generate credible regions from the probability map, e.g. 50% and 90%.
5. Overlay candidate transients, galaxies, reference images and survey footprints.

Where to get the FITS file

Example public superevent: **S231015by**:
`https://gracedb.ligo.org/superevents/S231015by/`
Open its GraceDB file list and copy `bayestar.multiorder.fits,1`. For an always-available class test, use:
`https://emfollow.docs.ligo.org/userguide/_static/bayestar.multiorder.fits`

Important

Do not type the template URL directly: replace `<SID>` with a real superevent ID, or better, copy the exact `Sky Map` / `SKYMAP_FITS_URL` link from the GraceDB or GCN page.

Creating Credible Regions in Aladin

- Select the loaded probability skymap.
- Use **Coverage** → **Generate a spatial MOC based on** → **current probability skymap**.
- Enter a probability threshold, e.g. 0.5 or 0.9.
- Inspect the MOC area in square degrees and as a sky fraction.
- Adjust colors and transparency from layer properties.

Interpretation caution

A 90% credible region is a probability contour, not a guaranteed counterpart position.

Useful overlays

Galaxies, transient candidates, neutrino regions, GRB localizations and telescope pointings.

Aladin Script: Mark a Candidate Event

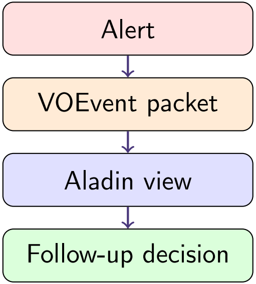
Example: add a transient marker

```
draw rgb(255,255,255) \
  tag(15:51:54.201 +30:54:08.67,
      "AT2025ulz",100,30,circle,22)
```

- The command bar can execute Aladin script commands.
- Markers help compare candidates with GW credible regions.
- Scripts make a live demonstration reproducible.

VOEvent: Alerts as Interoperable Events

- **VOEvent** is an IVOA standard for describing transient astronomical events.
- It packages who reported the event, what was observed, where and when it happened, and why it may be scientifically relevant.
- It is designed for rapid alert distribution and machine-readable follow-up.
- It complements visual tools such as Aladin by carrying event metadata and coordinates.



Aladin + MOC + VOEvent Workflow

1. Receive or read an alert notice, e.g. GCN or VOEvent.
2. Load the event coordinates and metadata.
3. Load the GW probability skymap in Aladin.
4. Generate 50% and 90% MOC credible regions.
5. Overlay candidates, catalogues and telescope footprints.
6. Prioritize targets for follow-up observations.

Key message

VOEvent describes the transient; MOC describes the sky region; Aladin connects both visually.

Hands-on Session 2

Focus

Aladin multimessenger workflow: load a MOC map and overlay candidate sources.

Hands-on 2: MOC and Candidate Overlay

1. Load a probability skymap or use the instructor-provided example.
2. Generate 50% and 90% credible-region MOCs.
3. Change colors/transparency so both regions remain visible.
4. Add one candidate position or catalogue overlay.
5. Write down the MOC area in square degrees.

Discussion question

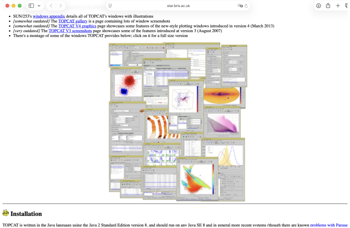
How does the follow-up strategy change when the 90% region is large, fragmented, or close to the Galactic plane?

TOPCAT

VO tools and services in context

TOPCAT Introduction

- Desktop tool for catalogue analysis.
- Handles large tables interactively.
- Provides plots, selections, statistics, joins, and cross-matches.
- One of the most widely used VO tools in daily research.



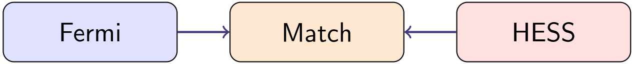
Importing Data

- Direct import from VizieR.
- Receive tables from Aladin through SAMP.
- Load local CSV, FITS, or VOTable files.
- Query remote TAP services.

Good practice

Keep a record of the catalogue version, query radius, selected columns, and quality cuts.

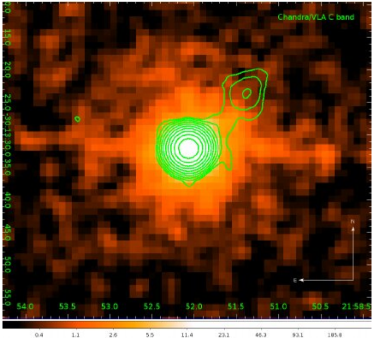
Cross-Matching



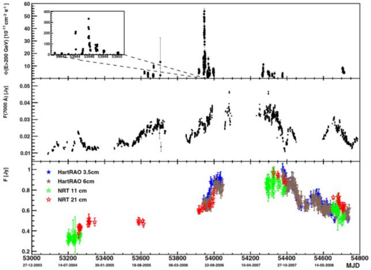
- Positional matching with configurable radius.
- One-to-one, best-match, or all-match strategies.
- Essential for multi-wavelength source association.

PKS 2155-304: Image, Light Curve and SED

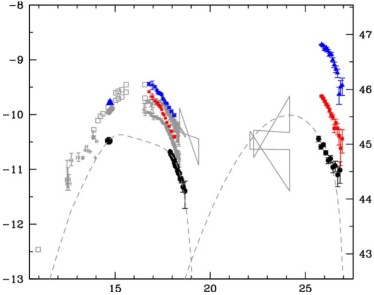
Image



Light curve



Spectral Energy Distribution



Multi-wavelength view

PKS 2155-304 illustrates how VO workflows connect imaging, variability and spectral energy distribution information for a high-energy blazar.

- Send tables and selections between applications.
- Select sources in TOPCAT and see them on the sky in Aladin.
- Combine quantitative and visual analysis.

Hands-on Session 3

Focus

TOPCAT workflow: load tables, inspect metadata and prepare for cross-matching.

Hands-on 3: TOPCAT Basics

1. Load `hess-simbad.vot` or the instructor-provided HESS table.
2. Open column metadata and identify RA/Dec or Galactic coordinate columns.
3. Load the instructor-provided Fermi table or query it from VizieR.
4. Make a quick sky plot for each table and verify that coordinates are interpreted correctly.
5. Rename tables clearly and note the table names used for matching.

Time box

15 minutes hands-on.

Checkpoint

Two renamed tables are loaded in TOPCAT, with coordinate columns identified and visible in sky plots.

STILTS

VO tools and services in context

Why Use STILTS?

- STILTS is the command-line companion to TOPCAT.
- It applies the same table logic without a graphical interface.
- It is useful for large, repeated, or scripted workflows.
- Typical operations: inspect, filter, join, cross-match, plot and convert tables.

TOPCAT → STILTS

Explore interactively in TOPCAT, then reproduce the final operations with STILTS commands.

Practical value

Every command becomes part of a reproducible analysis recipe.

STILTS Warm-Up Commands

```
java -jar stilts.jar calc 'sqrt(2)'

java -jar stilts.jar tpipe \
  in=fermi.vot \
  cmd='keepcols "Source_Name RAJ2000 DEJ2000 CLASS1"' \
  out=fermi_small.vot
```

- `calc` is a quick calculator for expressions.
- `tpipe` reads a table, applies processing commands, and writes a new table.
- `keepcols` keeps only useful columns before sharing or matching data.

STILTS Example: M87 VLBI Catalogue

```
java -jar stilts.jar tcopy \
  in='https://vizier.cds.unistra.fr/viz-bin/votable?-source=J/ApJ/807/150' \
  ifmt=votable out=m87_vlbi.vot ofmt=votable

java -jar stilts.jar tpipe \
  in=m87_vlbi.vot cmd='meta' cmd='head 10'
```

- This uses the VizieR catalogue `J/ApJ/807/150`: 230 GHz VLBI observations of M87.
- `tcopy` downloads the VOTable and writes a local file for TOPCAT or later STILTS steps.
- `tpipe` can inspect metadata and preview rows before doing analysis.

Exercise

Open `m87_vlbi.vot` in TOPCAT and compare the table metadata with the paper description.

STILTS Example: Cross-Match Two Tables

```
java -jar stilts.jar tmatch2 \
  in1=fermi_small.vot ifmt1=votable values1='RAJ2000 DEJ2000' \
  in2=hess_sources.vot ifmt2=votable values2='ra dec' \
  matcher=sky params=1.0 join=1and2 find=best \
  out=hess_fermi_match.vot ofmt=votable
```

- `tmatch2` reproduces a TOPCAT two-table sky match on the command line.
- `matcher=sky` uses celestial coordinates; `params=1.0` is a 1 arcsec radius.
- For gamma-ray catalogues, adapt the radius to the source localization uncertainty.

STILTS Example: Reproducible Plot

```
java -jar stilts.jar plot2plane \
  in=fermi_small.vot \
  x='F2/F1' y='F4/F3' xlog=true ylog=true \
  layer1=mark color1=blue \
  out=fermi_colours.png
```

- STILTS can generate publication or report figures from the same tables used in TOPCAT.
- Axis expressions can reuse TOPCAT-style column names and arithmetic.
- Keep the command next to the figure so the plot can be regenerated later.

Workflow pattern

TOPCAT for exploration; STILTS for scripted repetition; Python for extended analysis.

CDS X-Match

VO tools and services in context

X-Match

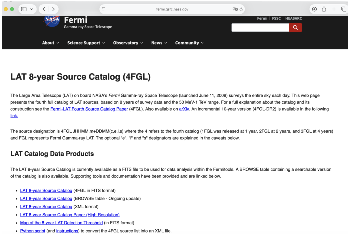
- CDS service for massive catalogue cross-matching.
- Designed for millions of objects.
- Avoids downloading very large catalogues locally.
- Supports matching user tables against major public catalogues.

When to use it

Use X-Match when interactive desktop matching becomes too slow or too memory-intensive.

Practical Example: HESS $\leftrightarrow$ Fermi

- Start from a Fermi LAT source list.
- Search for possible HESS or VLBI/radio counterparts.
- Inspect positional uncertainty and source density.
- Follow candidates in SIMBAD, Aladin, TOPCAT, and NED.

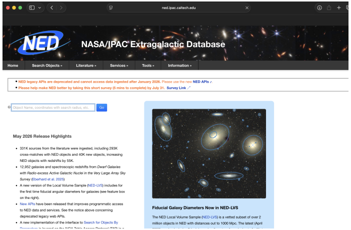


NED

VO tools and services in context

NED Overview

- NASA/IPAC Extragalactic Database.
- Specialized in galaxies, AGN, quasars, and extragalactic systems.
- Provides redshifts, photometry, SEDs, object classifications, and references.



Galaxy Example: M87

- Retrieve redshift and distance information.
- Inspect photometry and spectral energy distribution data.
- Check object classifications and environment.
- Follow references for observations across wavelengths.

Why M87?

M87 is a rich example: nearby giant elliptical galaxy, relativistic jet, radio source, X-ray source, and Event Horizon Telescope target.

SIMBAD vs NED

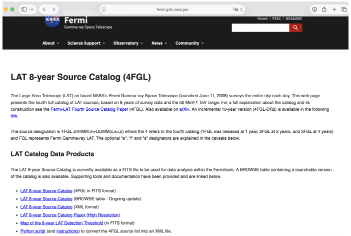
	SIMBAD	**NED**
Scope	All astronomical object types	Extragalactic objects
Best for	Identification, aliases, bibliography	Galaxies, AGN, redshifts, SEDs
Typical target	Stars, nebulae, compact objects, galaxies	Galaxies, quasars, clusters, AGN
Complementarity	Broad object database	Deep extragalactic context

High-Energy Archives

VO tools and services in context

Fermi LAT

- Gamma-ray survey of the sky.
- Source catalogues such as 4FGL.
- Important for AGN, pulsars, supernova remnants, binaries, and transients.
- Counterpart identification requires multi-wavelength data.



HEASARC

- High Energy Astrophysics Science Archive Research Center.
- Provides access to many space-mission archives.
- Examples: Chandra, XMM-Newton, Swift, NICER.
- Contains observations, catalogues, and mission-specific tools.

VO connection

High-energy catalogues can be combined with optical, infrared, and radio data through VO tools and services.

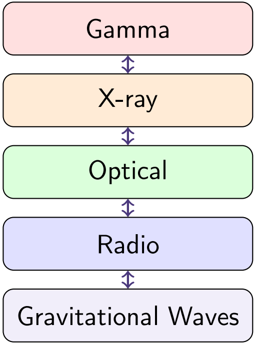
eROSITA

- Modern X-ray survey mission.
- Produces large samples of clusters, AGN, stars, and compact objects.
- Strong scientific potential when combined with Fermi, HESS, VLBI, optical surveys, and infrared catalogues.

Science challenge

Large X-ray catalogues require robust counterpart identification and careful treatment of positional uncertainties.

Multi-Messenger Context



VO role

The VO provides the data-discovery and interoperability layer needed to connect electromagnetic and multi-messenger information.

Complete Scientific Workflow

VO tools and services in context

Case Study: Identifying a Fermi Source

- Start with a Fermi LAT source and its uncertainty region.
- Search for known objects in SIMBAD.
- Visualize the field in Aladin.
- Load HESS, VLBI/radio and infrared catalogues.
- Cross-match candidates in TOPCAT or CDS X-Match.
- Check extragalactic candidates in NED.

Full Workflow

Fermi → SIMBAD → Aladin → VLBI / Radio → TOPCAT → NED → Publication

Reproducible Science: VO + Python

- `astroquery`: query astronomical databases.
- `pyvo`: access VO services programmatically.
- `astropy`: tables, coordinates, FITS, units.

Recommended workflow

Explore interactively with Aladin and TOPCAT, then reproduce the final query and analysis in Python.

Python and the Virtual Observatory

VO tools and services in context

Why Use VO Tools from Python?

- Modern astronomical analyses are increasingly performed in Jupyter notebooks.
- Python is widely used for data reduction, catalogue analysis, visualization and machine learning.
- VO standards can be accessed directly from reproducible scripts.
- Interactive exploration can be connected to final scientific analysis.

Main packages

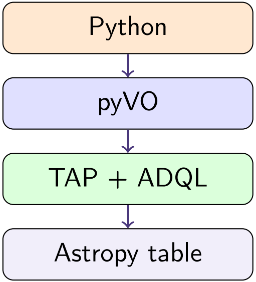
- `astropy`: tables, coordinates, units.
- `astroquery`: archive-specific queries.
- `pyvo`: generic VO protocols.
- `ipyaladin`: Aladin inside notebooks.

What is pyVO?

Definition

pyvo is a Python package for discovering and accessing Virtual Observatory services using IVOA standards.

- Access TAP services and run ADQL queries.
- Discover VO resources through registries.
- Retrieve tables as Astropy-compatible data structures.
- Use the same standards as TOPCAT and Aladin, but in scripts.



pyVO: Query a TAP Service

```
import pyvo as vo

service = vo.dal.TAPService("https://dc.g-vo.org/tap")

query = """
SELECT TOP 20 Source_Name, RAJ2000, DEJ2000, Conf_95_SemiMajor
FROM "fermi"."lat4gl"
WHERE CLASS1 = 'bll'
"""

result = service.search(query)
table = result.to_table()
```

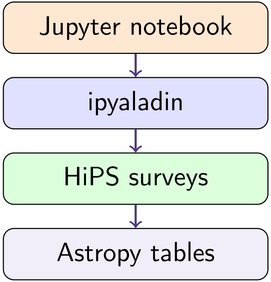
- The ADQL query is executed remotely.
- The result is converted into an Astropy table.
- The workflow is fully reproducible in a notebook or script.

What is ipyaladin?

Definition

`ipyaladin` is a Jupyter widget developed by CDS that embeds the Aladin Sky Atlas directly inside a Python notebook.

- Interactive sky visualization.
- Access to HiPS surveys.
- Display of catalogues and user tables.
- Integration with Astropy tables.
- Reproducible visual exploration in notebooks.



ipyaladin: Basic Viewer

Python

```python
from ipyaladin import Aladin

aladin = Aladin(
    target="M87",
    survey="CDS/P/PanSTARRS/DR1/color-z-zg-g",
    fov=0.2
)

aladin
```

- The target name is resolved by the notebook widget.
- The survey can be changed programmatically.
- The same cell documents the visualization choices.

Changing HiPS Surveys in ipyaladin

```
aladin.survey = "P/DSS2/color"
aladin.survey = "CDS/P/PanSTARRS/DR1/color-z-zg-g"
aladin.survey = "P/2MASS/color"
aladin.survey = "CDS/P/Fermi/color"
```

- HiPS surveys allow fast multi-wavelength browsing.
- The same target can be inspected in optical, infrared or gamma rays.
- Survey names should be checked in Aladin or the HiPS list before the live session.

M87: Use VLBI

```
from astroquery.vizier import Vizier

vizier = Vizier(columns=["**"], row_limit=200)

# First discover suitable M87/VLBI catalogues.
catalogues = Vizier.find_catalogs("M87 VLBI")

# Then query a selected VLBI/radio catalogue.
vlbi_tables = vizier.query_object(
    "M87",
    radius="5m",
    catalog="J/ApJS/230/7"
)
```

- Use `find_catalogs` before the live session to confirm the best VLBI catalogue.
- Inspect returned table metadata before overlaying the result.
- If no VLBI table is returned, switch to a radio catalogue such as NVSS.

Overlay a VLBI Table in ipyaladin

```
from ipyaladin import Aladin

aladin = Aladin(target="M87", fov=0.2)
aladin.survey = "CDS/P/PanSTARRS/DR1/color-z-zg-g"

if len(vlbi_tables) > 0:
    aladin.add_table(vlbi_tables[0])
else:
    radio = vizier.query_object("M87", radius="5m",
                                catalog="VIII/65/nvss")
    aladin.add_table(radio[0])

aladin
```

- Query with astroquery; visualize with ipyaladin.
- Keep the table for later analysis.
- Discuss offsets, resolution and counterpart identification.

Hands-on Session 4

Focus

Python notebook checkpoint: reproduce VO queries and embedded Aladin views.

Hands-on 4: Notebook Checkpoint

1. Open the prepared notebook or create a new one.
2. Import `Vizier` and `Aladin`.
3. Query a VLBI/radio catalogue around **M87**.
4. Display the field with `ipyaladin`.
5. Overlay the returned table.

Deliverable

A notebook cell showing M87 with a radio/VLBI catalogue overlay and the query radius used.

If a package is missing

Do not debug alone for more than two minutes: use the instructor environment or pair with a neighbour.

Python VO Workflow for the Practical

Scientific question

↓

Registry / VizieR / TAP

↓

astroquery or pyVO

↓

Astropy table

↓

ipyaladin overlay

↓

Analysis + figure

Key message

Use Aladin/TOPCAT to explore quickly, then preserve the final query and visualization in Python.

Hands-on: Using ADQL

VO tools and services in context

What is ADQL?

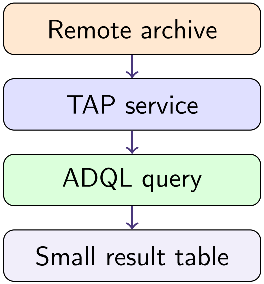
- **ADQL** means Astronomical Data Query Language.
- It is the VO query language used with TAP services.
- It is close to SQL, with astronomy-specific sky geometry.
- It lets researchers query large remote catalogues without downloading everything.

What is ADQL

ADQL is the common language used to ask different VO archives the same kind of scientific question.

Why Use ADQL in Astronomy?

- Modern catalogues are too large to download first.
- Many archives expose tables through standardized TAP services.
- The server can filter, join, count and compute before returning data.
- Queries can be saved, shared and rerun for reproducibility.



ADQL in TOPCAT: First Contact

1. Start TOPCAT.
2. Open **VO** → **Table Access Protocol**.
3. Search the Registry for a TAP service, for example **GAVO DC TAP**.
4. Select a service and inspect its table metadata.
5. Run a very small test query before doing science.

Important habit

Before writing a query, read the table descriptions, column names, units and quality flags.

Hands-on Session 5

Focus

ADQL warm-up: query a TAP service from TOPCAT and understand query patterns.

Hands-on 5: ADQL Warm-Up

1. Open TOPCAT's TAP client from **VO** → **Table Access Protocol**.
2. Choose a known service, e.g. VizieR TAP, or a high-energy TAP service provided by the instructor.
3. Inspect table metadata before writing a query.
4. Run a minimal `SELECT TOP 10 * FROM <table>` query.
5. Replace `*` with two or three column names and rerun.
6. Save the final ADQL text with the result table.

Time box

12 minutes hands-on.

Checkpoint

You should have one small ADQL result table, plus the exact service name, table name and query text saved.

A Minimal ADQL Query

```
SELECT TOP 10 Source_Name, RAJ2000, DEJ2000, CLASS1
FROM "fermi"."lat4gl"
WHERE CLASS1 = 'bll'
ORDER BY Source_Name
```

- `SELECT`: choose the columns or expressions to return.
- `TOP`: limit the number of rows for fast tests.
- `FROM`: choose the catalogue table.
- `WHERE`: filter rows on the server side.
- `ORDER BY`: sort results, but use it only when needed.

Derived Columns and Missing Values

```
SELECT TOP 20
  Source_Name,
  Flux1000,
  Unc_Flux1000,
  Unc_Flux1000/Flux1000 AS rel_flux_error
FROM "fermi"."lat4gl"
WHERE Flux1000 IS NOT NULL
ORDER BY rel_flux_error
```

- ADQL can compute new columns directly on the server.
- `AS` gives a readable name to a computed quantity.
- `NULL` means missing data; it is not zero.
- Use `IS NULL` or `IS NOT NULL` explicitly.

ADQL Geometry: Query a Sky Region

```
SELECT TOP 100 Source_Name, RAJ2000, DEJ2000, CLASS1
FROM "fermi"."lat4gl"
WHERE 1 = CONTAINS(
  POINT(RAJ2000, DEJ2000),
  CIRCLE(187.7059, 12.3911, 5./60.)
)
```

- `POINT` represents a sky position.
- `CIRCLE` defines a cone-search region.
- `CONTAINS` tests whether a source lies inside the region.
- In this common pattern, angles are in degrees.

ADQL Cross-Match with JOIN

```
SELECT TOP 500
  f.Source_Name, f.RAJ2000, f.DEJ2000,
  h.main_id, h.ra, h.dec
FROM "fermi"."lat4gl" AS f
JOIN hess.sources AS h
ON 1 = CONTAINS(
  POINT(f.RAJ2000, f.DEJ2000),
  CIRCLE(h.ra, h.dec, 1.0)
)
```

- `JOIN` combines two tables.
- The geometry condition performs a positional cross-match.
- The match radius must reflect gamma-ray localization uncertainty and source density.

ADQL Good Practices

- Start with `TOP` and a few columns.
- Avoid `SELECT *` for large tables.
- Filter on indexed columns when possible.
- Use asynchronous TAP jobs for long queries.
- Save the final query with the result table.

Reproducibility checklist

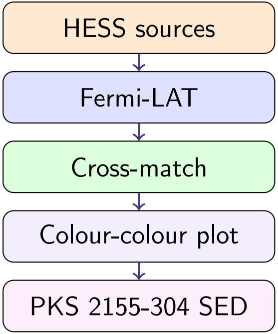
Record the TAP service, table name, ADQL query, catalogue version, units, match radius and quality cuts.

Hands-on Practical: High-Energy VO

VO tools and services in context

Practical Goal and Scientific Question

- Use VO tools for high-energy, multi-wavelength data mining.
- Start from HESS gamma-ray sources.
- Cross-identify them with Fermi-LAT catalogues.
- Inspect source classes and flux-ratio trends.
- Finish with a multi-wavelength view of PKS 2155-304.



Reference Tutorial for This Practical

Source workflow

The hands-on block follows **tutorial-highenergy_2016Nov.pdf**: *Multi-instrument, multi-wavelength study of high energy sources with the Virtual Observatory*.

- Retrieve HESS sources from SIMBAD and save them as VOTable.
- Overlay HESS positions on a Fermi all-sky image in Aladin.
- Use TOPCAT and VizieR to load the Fermi-LAT 3FGL catalogue tables.
- Cross-match HESS and Fermi sources, then identify TeV-selected AGNs from 3LAC.
- Build the Fermi flux-ratio diagram `F4/F3` versus `F2/F1`.
- Finish with PKS 2155-304 in Aladin, SPECFIND and VizieR photometry.

Practical Map: Tools and Data Products

Step	Tool	Output
1	SIMBAD	HESS source list as VOTable
2	Aladin	HESS positions over Fermi all-sky image
3	TOPCAT + VizieR	Combined 3FGL position + spectral table
4	TOPCAT cross-match	HESS–Fermi and TeV-selected AGN tables
5	TOPCAT plots	Fermi flux-ratio diagrams and subsets
6	Aladin + SAMP + VizieR	PKS 2155-304 sky context and SED

Work Mode for the Practical

- Work in pairs if possible.
- One person drives; one person checks metadata and notes decisions.
- Swap roles after the cross-match step.
- Ask for help when blocked for more than two minutes.

What to save

`hess-simbad.vot`, combined **3FGL**, **HESS–Fermi**, **HESS–Fermi AGNs**, plot export, and notes on matching radius.

Hands-on Session 6A

Focus

Data discovery and visualization: retrieve HESS sources and overlay them on Fermi context maps.

Step 1: Retrieve HESS Sources from SIMBAD

1. Open SIMBAD and choose the **query by catalogue** mode.
2. Select the HESS catalogue using the **whole catalogue** option.
3. Inspect the returned source list and check that coordinates are present.
4. In output options, choose **VOTable** and enable **file output**.
5. Save the file as `hess-simbad.vot` for Aladin and TOPCAT.

Checkpoint

A local `hess-simbad.vot` file containing the SIMBAD HESS source list.

Time box

10 minutes.

Common issue

If the browser displays the VOTable instead of saving it, use the output options and enable file output.

Step 2: Overlay HESS Sources on the Fermi Sky

1. Start Aladin Desktop and keep SAMP enabled.
2. Open the server selector, choose the **HiPS** tab, and search for **Fermi**.
3. Load a Fermi all-sky gamma-ray color image.
4. Switch the view to **Aitoff** projection.
5. Use **Galactic** coordinates.
6. Load `hess-simbad.vot` from the File tab or drag it into Aladin.

What to observe

The HESS positions should appear over the Fermi all-sky map, revealing the Galactic plane concentration and extragalactic outliers.

Time box

12 minutes.

Step 3: Build the Fermi 3FGL Working Table

- Start TOPCAT and load `hess-simbad.vot` or receive it from Aladin via SAMP.
- Open **VO** → **VizieR Catalogue Service**.
- Search for **3FGL** and select the Fermi-LAT third source catalogue.
- Request **all rows** and **all columns**; load the catalogue tables.
- Exact-match the main position/association table with the spectral table using column `3FGL`.
- Rename the joined result **3FGL**.

Checkpoint

The working **3FGL** table has 2954 rows and contains coordinates, `Class`, and fluxes `F1`–`F5`.

Hands-on Session 6B

Focus

Association building: cross-match HESS and Fermi catalogues, then isolate TeV AGN candidates.

Step 4: Cross-Match HESS and Fermi Sources

1. Open TOPCAT's pair cross-match tool.
2. Choose sky-position matching and verify the RA/Dec columns for both tables.
3. Use the combined **3FGL** table as Table 1.
4. Use the HESS/SIMBAD table as Table 2.
5. Use a 1 degree maximum separation and keep the best match per source.
6. Rename the result **HESS–Fermi** and check the match count.

Interpretation caution

A large search radius helps with gamma-ray positional uncertainty, but it can also create ambiguous associations.

Time box

15 minutes, including discussion of radius choice; the tutorial result is about 59 matches.

Step 5: Select TeV AGN Counterparts

- Query VizieR from TOPCAT for the **3LAC** catalogue **Ackermann+2015**.
- Load the table of Fermi AGN previously detected at TeV energies.
- Rename that table **TeV selected AGNs**.
- Cross-match **TeV selected AGNs** with **HESS–Fermi**.
- Use exact-value matching on the `3FGL` identifier; if TOPCAT renamed it, use `3FGL_1`.
- Rename the result **HESS–Fermi AGNs** and keep it for plotting.

Checkpoint

Participants should now have a **HESS–Fermi AGNs** table; the tutorial result contains 5 sources.

Time box

10 minutes.

Hands-on Session 6C

Focus

Population analysis: build gamma-ray colour-colour diagrams and source-class subsets.

Step 6: Build a Gamma-Ray Colour-Colour Diagram

- In TOPCAT, open a **Plane Plot** for the **3FGL** table.
- X axis: `F2/F1`.
- Y axis: `F4/F3`.
- Enable logarithmic scale on both axes.
- Add datasets for **HESS–Fermi** and **HESS–Fermi AGNs** with different symbols/colors.
- Save or export the plot before changing subsets.

Physical idea

Flux ratios act like high-energy colours and can reveal whether selected populations occupy different regions of parameter space.

Time box

15 minutes: plot, change axes to log scale, and save/export the figure.

Step 7: Create Source-Class Subsets

- In TOPCAT, select the **HESS–Fermi** table.
- Open the row-subset window and inspect the exact class-column name.
- Define an SNR subset using `Class == "SNR" || Class == "snr"`.
- Define a BL Lac subset using `Class == "BLL" || Class == "bll"`.
- Add these subsets to the HESS–Fermi layer in the colour-colour diagram.
- If the column was renamed during matching, adapt `Class` to the visible column name.

Checkpoint

The colour-colour diagram should show at least two highlighted source-class subsets.

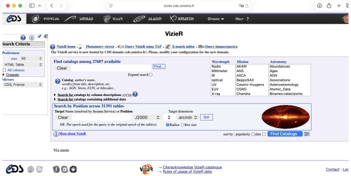
Hands-on Session 6D

Focus

Source interpretation: focus on PKS 2155-304 and inspect broad-band context.

Step 8: Focus on PKS 2155-304

- In TOPCAT, enable SAMP and check that Aladin is connected.
- Broadcast the **HESS–Fermi** table to Aladin.
- Enable **broadcast row** in TOPCAT.
- In Aladin, search for **PKS 2155-304**.
- Select PKS 2155-304 in Aladin or TOPCAT and check linked highlighting.



Checkpoint

Selecting PKS 2155-304 in TOPCAT should identify the same sky position in Aladin.

Step 9: Search Radio SED with SPECFIND

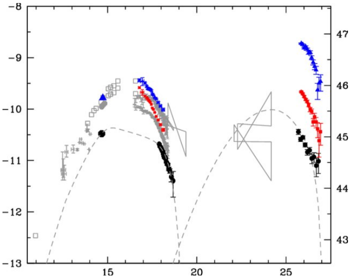
- In Aladin, open the VizieR query panel centered on PKS 2155-304.
- Search for **SPECFIND**.
- Select catalogue **VIII/85A/spectra** and overlay the result.
- Select the SPECFIND record corresponding to PKS 2155-304.
- Open the associated radio SED view.

Learning point

The VO does not only retrieve positions; it also links catalogue records to derived products such as spectral energy distributions.

Step 10: Broad-Band Photometry with VizieR

1. Open the VizieR photometry/SED service.
2. Query around **PKS 2155-304**.
3. Use a search radius of **20 arcsec**.
4. Inspect photometric points by wavelength and catalogue.
5. Toggle catalogues or individual records to identify inconsistent points.
6. Save a screenshot or export of the final SED view.



Practical Debrief: What You Produced

- A HESS source table exported from SIMBAD.
- A Fermi catalogue loaded through TOPCAT/VizieR.
- A HESS–Fermi cross-match table with a documented radius.
- A gamma-ray colour-colour diagram with source-class subsets.
- A PKS 2155-304 multi-wavelength view in Aladin/VizieR.
- Notes on ambiguous matches, small samples and next analysis steps.

Conclusion

VO tools and services in context

Summary

Key Message

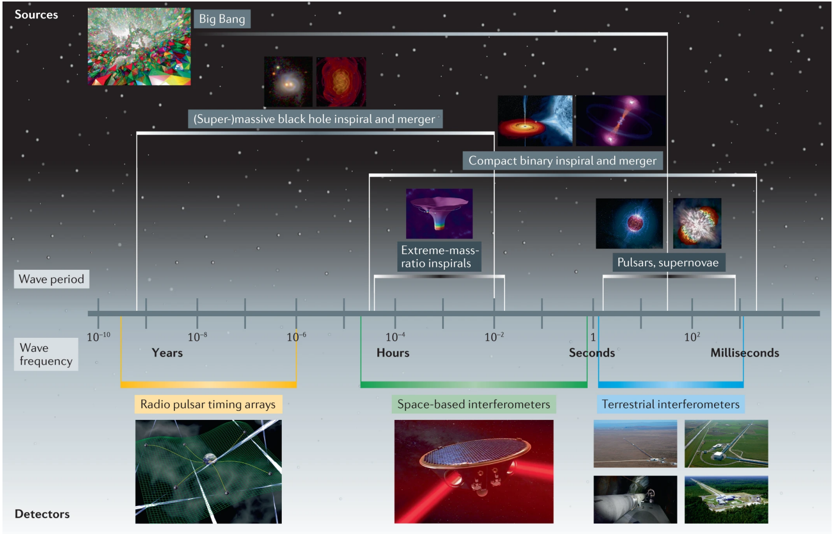
The Virtual Observatory is indispensable for efficient, interoperable, and multi-wavelength astronomy.

- CDS is a central hub of the VO ecosystem.
- SIMBAD and NED identify and contextualize objects.
- VizieR provides catalogue access and metadata.
- Aladin and TOPCAT are the main daily tools for visualization and analysis.
- VO standards make distributed archives work together.

Useful Links

Service	URL
CDS Strasbourg	https://cds.unistra.fr
SIMBAD	https://simbad.cds.unistra.fr
VizieR	https://vizier.cds.unistra.fr
Aladin Sky Atlas	https://aladin.cds.unistra.fr
TOPCAT	https://www.star.bristol.ac.uk/~mbt/topcat
STILTS	https://www.star.bris.ac.uk/mbt/stilts/
Python embedded tutorials	https://cds-astro.github.io/tutorials/intro.html
NED	https://ned.ipac.caltech.edu
HEASARC	https://heasarc.gsfc.nasa.gov
Fermi Science Support Center	https://fermi.gsfc.nasa.gov
IVOA	https://www.ivoa.net
TP ADQL Hendrik	https://share.obspm.fr/s/e9yyJw8BrWe4zKy
TP High-Energy 2016	https://share.obspm.fr/s/ATojeqJqzesBZG4

Questions


Sources
Big Bang
(Super-)massive black hole inspiral and merger
Compact binary inspiral and merger
Extreme-mass-ratio inspirals
Pulsars, supernovae
Wave period
Wave frequency
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
Years
Hours
Seconds
Milliseconds
Radio pulsar timing arrays
Space-based interferometers
Terrestrial interferometers
Detectors

Suggested 10-Minute Live Demonstration

1. Search for **M87** in SIMBAD.
2. Open the field in Aladin.
3. Load a Fermi HiPS image or Fermi-LAT catalogue layer.
4. Send the selected catalogue table to TOPCAT.
5. Build a quick sky plot or flux-ratio plot.
6. Search **M87** in NED.
7. Inspect the Fermi-LAT source field and note possible counterparts.