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Firmamento: A Multimessenger Astronomy Tool for Citizen and Professional Scientists

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Abstract

Firmamento (https://firmamento.hosting.nyu.edu) is a new-concept, web-based, and mobile-friendly data analysis tool dedicated to multifrequency/multimessenger emitters, as exemplified by blazars. Although initially intended to support a citizen researcher project at New York University–Abu Dhabi, *Firmamento* has evolved to be a valuable tool for professional researchers due to its broad accessibility to classical and contemporary multifrequency open data sets. From this perspective *Firmamento* facilitates the identification of new blazars and other multifrequency emitters in the localization uncertainty regions of sources detected by current and planned observatories such as Fermi-LAT, Swift, eROSITA, CTA, ASTRI Mini-Array, LHAASO, IceCube, KM3Net, SWGO, etc. The multiepoch and multiwavelength data that *Firmamento* retrieves from over 90 remote and local catalogs and databases can be used to characterize the spectral energy distribution and the variability properties of cosmic sources as well as to constrain physical models. *Firmamento* distinguishes itself from other online platforms due to its high specialization, the use of machine learning and other methodologies to characterize the data, and for its commitment to inclusivity. From this particular perspective, its objective is to assist both researchers and citizens interested in science, strengthening a trend that is bound to gain momentum in the coming years as data retrieval facilities improve in power and machine-learning/artificial-intelligence tools become more widely available.

Unified Astronomy Thesaurus concepts: Astronomy software (1855); Astronomy data analysis (1858); Astronomy databases (83)

1. Introduction

The increasing trend in astronomy facilities to provide unrestricted access to their data at some stage, coupled with the push for the adoption of FAIR principles,[13] together with the presence of projects such as the well-established International Virtual Observatory Alliance[14] and many others that have emerged in recent years are significantly expanding the discovery potential in the scientific community. Initiatives of this type include the European Science Cloud (EOSC),[15] the Research Data Alliance (RDA),[16] the Research Infrastructure Cluster (ASTERICS),[17] and Open Universe,[18] among others. In addition, the rapidly increasing number of online data archives, funded by most space agencies and other organizations, provides a wide array of open-access astronomical data. Listing all the currently operating data services would be impractical due to their abundance, a situation that underscores the rapid expansion of the data available and, consequently, the discovery potential. Many of the principles and part of the software outlined in this paper stem from the efforts undertaken over the past few years within the Open Universe initiative (Giommi et al. 2020a). This international collaboration was proposed at the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) in 2016 and has been extensively discussed in various meetings coordinated by the United Nations Office for Outer Space Affairs (UNOOSA).

These positive developments are also creating unprecedented opportunities for individuals with diverse skills to participate in scientific activities and discovery. Along these lines, there are important examples of successful projects involving large numbers of citizen scientists, often without formal scientific training in the field of astronomy. These include Galaxy Zoo,[19]

[13] https://www.go-fair.org/fair-principles
[14] https://ivoa.net
[15] https://www.eosc-portal.eu
[16] https://www.rd-alliance.org
[17] https://www.asterics2020.eu/
[18] https://openuniverse.asi.it
[19] http://zoo1.galaxyzoo.org/

which led to the identification of thousands of galaxies based on their shape, and SETI@home,[20] which involves citizens with Internet-connected computers in the Search for Extraterrestrial Intelligence (SETI). Many scientific papers involving citizen scientists have already appeared in the professional literature demonstrating that untrained individuals can contribute in a significant way to research. Current citizen scientist initiatives are based on scientific projects that are carefully defined by professional scientists, while citizen scientists, often in large numbers, contribute by providing the manpower that is needed to carry out predefined tasks. The rapid proliferation of machine-learning tools and freely accessible artificial-intelligence (AI) services is significantly accelerating the path toward the ultimate objective of enabling normal citizens with an interest in science to autonomously conceive and carry out research projects, one of the long-term goals of the Open Universe initiative.

Despite the positive trend toward unrestricted access to data, challenges still persist as the complete utilization of all available data sets often requires analysis of data from vastly different detectors, each demanding specialized expertize that is nearly impossible to meet. However, the increasing availability of calibrated and science-ready multifrequency data is making multimessenger astronomy accessible to a wider range of researchers and citizen scientists.

This paper introduces *Firmamento*, a new online tool developed to support citizen and professional researchers in the field of blazars and multimessenger research, building upon the experience of the Open Universe initiative. Accessible from a computer, tablet, or mobile phone, this service is a powerful instrument for identifying and studying cosmic sources detected by current and upcoming multimessenger detectors with localization uncertainties ranging from a few arcseconds to several square degrees including, but not limited to, eRosita (Merloni et al. 2020), Swift (Gehrels et al. 2004), Fermi (Atwood et al. 2009), AGILE (Tavani et al. 2009), LHAASO (Cao & Lhaaso Collaboration 2022), CTA (Cherenkov Telescope Array Consortium et al. 2019), ASTRI Mini-Array (Lombardi et al. 2022), IceCubeGen2 (Aartsen et al. 2021), and KM3Net (Benfenati et al. 2023). Due to its user-friendly interface, even individuals without astronomical expertize can utilize *Firmamento*, making it a useful tool also in educational contexts.

2. Multimessenger Astrophysics

In parallel with the achievements of the long-established field of multifrequency astronomy, the recent development of highly advanced observatories capable of detecting other cosmic messengers such as neutrinos,[21] ultra-high-energy cosmic rays,[22] and gravitational waves,[23] paved the way for multimessenger astrophysics. This new development is rapidly widening our knowledge of the Universe through the study of matter and radiation in astrophysical contexts where the gravitational, electromagnetic, strong, and weak forces are at work in an extremely wide range of physical conditions. Neutrinos, in particular, provide a unique observational window on the most extreme astrophysical environments. That is because these weakly interacting particles are stable, can travel cosmological distances, and, unlike photons, can escape from the dense regions where they are produced and can reach Earth unattenuated even at the highest energies.

Despite a flux of neutrinos and high-energy cosmic rays that have been detected (IceCube Collaboration 2013), the nature of the sources that emit these particles largely remains an unresolved issue. Different types of astrophysical sources, located both in our Galaxy and outside, have been proposed to be multimessenger emitters. Among these, the class of blazars appears to be among the most promising.

2.1. Blazars

Blazars are the most powerful persistent sources in the Universe (Urry & Padovani 1995). They are a rare type of highly variable Active Galactic Nuclei (AGNs; Padovani et al. 2017) that emit electromagnetic radiation over the entire energy spectrum, from radio waves to high-energy gamma rays, and are suspected to be the sources of high-energy neutrinos (IceCube Collaboration et al. 2018; Giommi & Padovani 2021). The physical engine that powers these remarkable sources is thought to be a relativistic jet of matter that moves away from the central supermassive black hole in directions that happen to be aligned toward Earth. This very special physical and geometrical condition is what make blazars so peculiar and causes them to be detected at energies where other types of cosmic emitters are not observed, such as in the gamma-ray band where they are by far the most common type of extragalactic sources observed (Bulgarelli et al. 2019; Abdollahi et al. 2020). Despite that, only about 6000 such objects have been so far discovered in the many radio, X-ray, and gamma-ray surveys that have been carried out over the last 40 years (Giommi & Padovani 2021). With the rapidly growing availability of new data, this number is bound to increase significantly very soon. For instance, the ongoing SRG/eRosita X-ray sky survey (Merloni et al. 2020; Brunner et al. 2022) is expected to detect well over 100,000 blazars. The first large catalog from this survey is expected to be published in the coming months. A smaller but still important number of blazars will be detected by upcoming observatories operating in the very high-energy gamma-ray band, such as CTA[24] (Cherenkov Telescope Array Consortium et al. 2019), ASTRI Mini-Array[25] (Scuderi & Astri Project 2023), and SWGO (Engel 2023), as well as by other multimessenger facilities such as KM3NeT[26] (Benfenati et al. 2023), Baikal-GVD[27] (Malyshkin & Baikal-GVD collaboration 2023), and the Pacific Ocean Neutrino Experiment (P-ONE; Agostini et al. 2020). Identifying and characterizing all these sources will be a challenging task. *Firmamento* has the potential to play a significant role in this process, also through citizen scientist and student projects.

3. *Firmamento*: A Data Analysis Tool for Blazars Discovery and Multimessenger Research

Firmamento, in its present version (https://firmamento.hosting.nyu.edu), focuses on blazar discovery and on multimessenger astrophysics research. To do so, it provides:

[20] https://setiathome.berkeley.edu/
[21] e.g., https://icecube.wisc.edu
[22] e.g., https://www.auger.org
[23] e.g., https://www.ligo.caltech.edu
[24] https://www.cta-observatory.org
[25] http://astri.me.oa-brera.inaf.it/en/
[26] https://www.km3net.org
[27] https://baikalgvd.jinr.ru

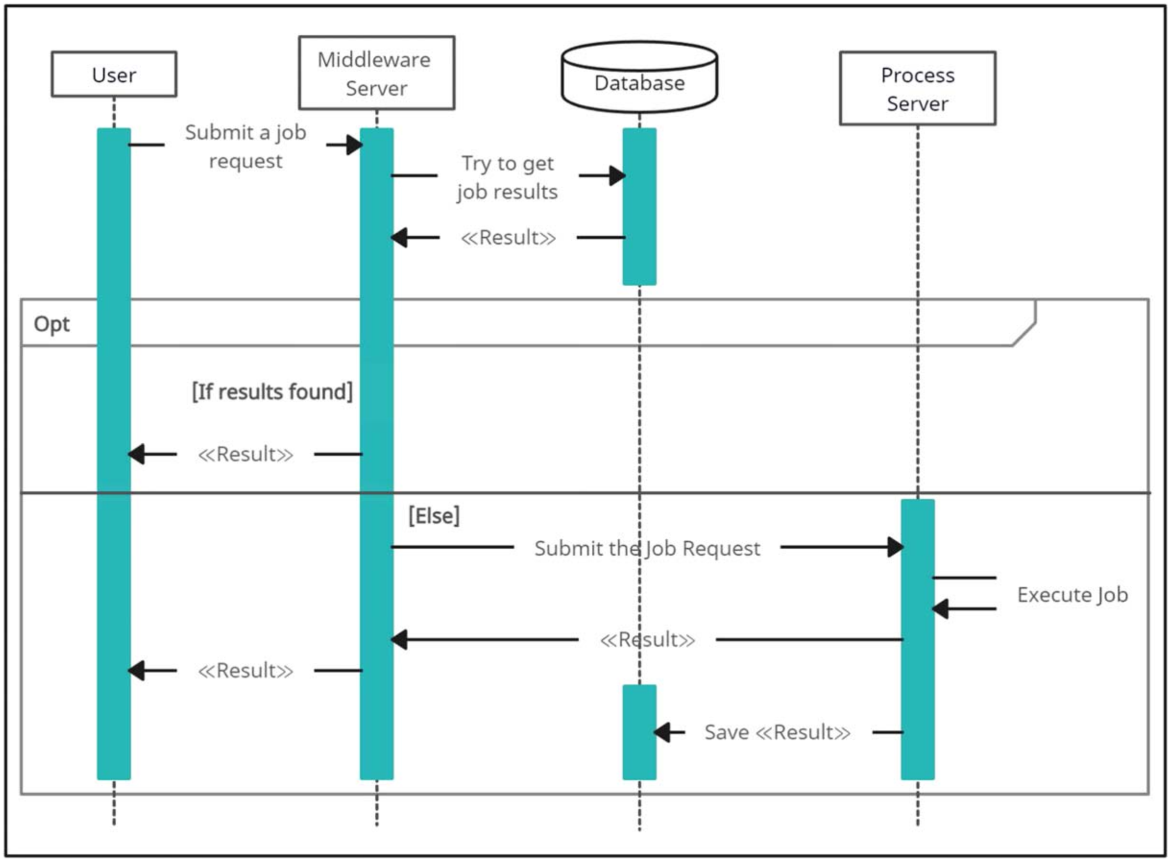

Figure 1. A schematic view of *Firmamento*'s architecture.

1. Localization uncertainty maps useful for the identification of the counterparts of X-ray, gamma-ray, high-energy neutrino, and any other type of astronomical sources with nonnegligible positional errors;
2. Spectral energy distributions (SEDs) obtained via VOU-Blazars (Chang et al. 2020), V2.00, a tool that retrieves, homogenizes, and combines data from over 90 catalogs and spectral databases. SEDs are then generated and plotted after dereddening and converting all measurements to monochromatic $\nu f(\nu)$ fluxes in common units (in frequency and intensity);
3. Access to several classical and recently released astronomical surveys via an adapted version of the Aladin[28] sky visualizer that has been integrated into the *Firmamento* tool. Imaging data in most energy bands of the electromagnetic spectrum, e.g., radio, infrared, optical, UV, X-ray, and gamma rays, are provided;
4. Machine learning and other software suitable for the characterization of blazar broadband spectra;
5. Links to other astronomical sites and space news;
6. Documentation and (video) tutorials.

3.1. Firmamento*'s Architecture*

Figure 1 illustrates the architecture of the *Firmamento* tool, which includes four main components: a front-end web interface, a middleware server, a database, and a processing server. Each component plays a crucial role in the overall functionality of the system. In the following sections, we give a description of each component, as well as of the software running on the server.

3.1.1. The Front-end Web Pages

The front-end website serves as the primary user interface for most online services. In a system such as *Firmamento*, which aims at serving users with varying skill levels, this component is particularly important. Our design follows a minimalist approach with a focus on ease of use. The site includes six main areas that can be accessed from dedicated tabs:

1. Home, which provides an introduction to the site and general information;
2. Data access, where the multimessenger data of astrophysical sources can be requested, retrieved, plotted, and analyzed;
3. Resources, which provides links to a number of external sites about astronomy and space science;
4. Media, where users can browse through media sites about space news, streaming space TVs, the NASA picture of the day, and image galleries.;
5. Tutorials, which provides video tutorials and documentation;
6. Feedback, where users can provide feedback.

From a technical viewpoint the front end of *Firmamento* was built using the React JavaScript framework,[29] taking special care to ensure that it can be easily used on both computers and smart phones.

[28] https://aladin.u-strasbg.fr

[29] https://reactjs.org/

3.1.2. The Middleware Server

The middleware server is hosted on a cloud service provider (presently Heroku but subject to change). It serves as a crucial component in our system, acting as a gateway to the New York University–Abu Dhabi (NYUAD) server and relying on the security measures provided by the cloud service. Its primary functions encompass establishing rate limits, validating user inputs, and implementing safety measures to safeguard the process server at NYUAD against potential cyber threats.

Its operational workflow involves the middleware server conducting preliminary checks in the database when a user requests a new job. If the relevant data are not found, the request is then forwarded to the process server at NYUAD, with the middleware server actively monitoring the process server's status. A noteworthy aspect is the utilization of web sockets for communication, facilitating real-time logs visible on the front end during job execution. This server also serves as a queue manager for incoming jobs, because the current system can only execute a small number of jobs at the one time. Additionally, its role in job distribution contributes to the system's scalability. As the number of process servers increases, the middleware server seamlessly functions as a load balancer, distributing jobs among different process servers, optimizing resource utilization.

3.1.3. The Cloud-based Data Repository

A cloud-based database service (currently firebase and subject to change) is used to store the results of the jobs that have been executed by the process server. This database can only be accessed by the middleware server and the process server. Access from other locations is blocked thus making it secure. Whenever an incoming request comes to the middleware server, the server checks this database to see if the job was previously done, as it has database access rights. In case results for the job are not present, a null value is sent to the middleware server, signaling a need to contact the NYUAD process server.

3.1.4. The Server at NYUAD

The server located at NYUAD is where the requests by the users are directed for appropriate processing when necessary. This crucial component of the *Firmamento* system is a server shared with other NYUAD projects. When a user initiates a new job, the request passes through the middleware component to this server, signaling that the job has not been processed before. Currently, this server can run a maximum of five jobs at the same time, as these may be demanding in terms of available resources. A queue system is therefore established to prioritize jobs on a first-come-first-served basis. During the execution of the job, all the logs are sent to the middleware server through web sockets, thus making it possible for real-time logs. Once a job is executed successfully, results are submitted to the middleware server, which serves the results to the front end. Results include an SED graph, a CSV file including the SED data, two text files, and the output of the *Blast* software. Once the results are available on the middleware server, the user is able to view them on the website. In case of any errors, users are notified on the front end and an error log is kept on the server to be analyzed by the developers for possible recovering actions.

The server at NYUAD is also highly secure, as communication to the server is only possible through the middleware server and the cloud database. Any other attempted connection to the server is blocked by our security system, which was developed in collaboration with the IT team at NYUAD.

3.2. Scientific Software under the Hood

To fulfill its scientific tasks *Firmamento* relies on open-access or internal scientific software that is activated by the users via the front-end module. The following is a brief description of the main components.

1. *VOU-Blazars*

   VOU-Blazars[30] (Chang et al. 2020), a tool developed as part of the Open Universe initiative, is the multi-frequency and multiepoch data retrieval engine of *Firmamento*. This software is used to produce multi-frequency sky maps suitable to locate blazars and blazar candidates in the error regions of X-ray, gamma-ray, high-energy neutrino, and any other sources with a nonnegligible localization uncertainty. VOU-Blazars is also used to build SEDs and light curves.

   Firmamento currently uses VOU-Blazars V2.00, an improved version of the original code that provides access to an expanded list of over 90 catalogs and spectral databases using the protocols defined by the International Virtual Observatory Alliance. Some examples of recently added catalogs are eRosita-eFEDS, NEOWISE, unWISE, PACO, RATAN-600, Gaia, VLASS, RACS, NuSTAR, 4XMM-DR13, and Fermi 4LACDR3 and 4FGL-DR4.

   A more complete list of the catalogs and spectral and time-domain databases accessed by this version of VOU-Blazars is given in Table 1.
2. *BLAST*

   BLAST[31] (Glauch et al. 2022) is a machine-learning tool that helps characterizing the SEDs built within *Firmamento* by estimating the position of the peak of the synchrotron emission (usually referred as $\nu_{\rm peak}$), which is an important parameter for physical models and the classification of blazars. The $\nu_{\rm peak}$ values reported in the literature are often estimated manually, and therefore their value can vary depending on the author and the method used. BLAST provides an objective estimation of $\nu_{\rm peak}$ as well as an evaluation of its uncertainty based on the training of the tool with a large number of known blazars with good SEDs and $\nu_{\rm peak}$ estimated by fitting the data to a polynomial function.
3. *W-Peak*

   W-Peak (Giommi et al. 2024) is a blazar SED $\nu_{\rm peak}$ estimator based on the average 4.6–3.5 μ spectral index as determined from WISE and NEOWISE infrared data. The infrared slope, when due to the nonthermal emission from the jet, is linearly related to the average $\nu_{\rm peak}$ of blazars, as shown in Figure 2 where the mean infrared slope is plotted as a function of $\nu_{\rm peak}$ in the subsample of blazars frequently observed by Swift (Giommi et al. 2021) whose IR flux is not due to the host galaxy, the infrared torus, or other components not related to the jet.

[30] https://github.com/ecylchang/VOU_Blazars

[31] https://github.com/tkerscher/blast

Table 1
List of the Main Catalogs and Spectral Databases Queried by VOU-Blazars V2.00 in *Firmamento*

Energy Band	Catalogs/Databases
Radio	NVSS, VLSSR, VLASS-QL, SUMSS, RACS, FIRST, TGSS, LoTSS, PMN, GB6, GB87, North20, WISH, GLEAM, ATPMN, Kühr, VLSS, AT20G, ATPMN, CRATES, RATAN-600, PACO
Microwave/millimeter	ALMA, Planck (PCCS 39, 44, 70, 100, 143, 217, 353, 545, 857)
Infrared	IRAS, AKARI (BSC, PSC) WISE, unWISE, NEOWISE, 2MASS, DENIS, Herschel (SPIRE250, 350, 500, PACS70, ATLAS)
Optical	USNO, HSTGSC, SDSS, PanSTARRS, Gaia, SMARTS
UV	GALEX, Swift-UVOT, XMM-OM
X-ray	Einstein (IPC), IPCSlew, EXOSAT (CMA), ROSAT (WGA, RASS), BeppoSAX, 4XMM-DR13, XMMSL2, Swift (2SXPS), OUSX, XRTSPEC, BMW, BAT105 Chandra (CSC2), NuSTAR (NuBlazars), eROSITA (eFEDS, MAXI-GSC)
Gamma ray	Fermi (2FHL, 3FHL, 4FGL-DR4), 2BIGB, MST12Y, 1FLE, FMONLC, AGILE, VERITAS, MAGIC, HESS
Source catalogs	5BZCat, 3HSP, 4LACDR3, ZWClusters, Abell, MilliQuas Pulsars, CVCat, SNRGREEN, MWSC, MWMC, XRBCAT

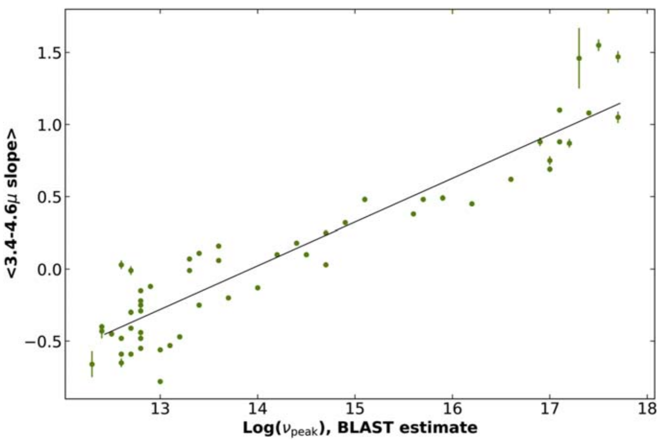

Figure 2. The correlation between the average 3.4–4.6μ spectral slope and $\nu_{\rm peak}$ in the subsample of blazars frequently observed by Swift whose IR emission can be attributed to the jet.

The best fit to the data shown in Figure 2 is

$$\mathrm{Log}(\nu_{\rm peak}) = 3.8 \times \alpha_{(3.4-4.6\mu)} + 13.9. \quad (1)$$

Here, $\alpha_{(3.4-4.6\mu)}$ is the spectral slope between 3.4 and 4.6 μ, calculated in the νf_ν versus ν space, averaged over all the available WISE and NEOWISE flux measurements.

The W-Peak estimation, especially when using NEOWISE data, is based on infrared measurements averaged over a long period of time and it is therefore representative of the mean value of $\nu_{\rm peak}$ of an object and cannot be used to determine the peak value during flaring or low-level states. As part of the process of estimating $\nu_{\rm peak}$, the W-Peak software also generates a table including the results of basic variability statistics and parameters such as variability amplitude, fractional variability, and minimum absolute deviation for NEOWISE data.

4. *Aladin*

Aladin is a widely used powerful visualizer of astronomical images that was developed at CDS (https://aladin.u-strasbg.fr). The specific implementation of Aladin in *Firmamento* provides access to a large selection of high-quality surveys at radio, IR, optical, X-ray, and gamma-ray energies that are useful for blazar identification. Table 2 gives the list of the surveys that are available by default.

Table 2
List of the Main Surveys Accessible via the *Firmamento* Aladin Interface

Energy Band	Survey Name
Radio	NVSS, VLASS (Epochs 1, 2.2, and 3.1), VCSS1, TGSS-ADR, SUMSS, RACS-low, RACS-mid
Infrared	WISE, unWISE, 2MASS, Spitzer, Herschel
Optical	DSS2, PanSTARRS, SDSS, ZTF, DECaLS, BASS, MAMA, SkyMapper, XMM-OM, Swift-UVOT
UV	Galex, Swift-UVOT
Soft X-ray	RASS, Swift-XRT, XMM, Chandra
Hard X-ray	Swift-BAT, MAXI
Gamma ray	Fermi-LAT

3.3. *Tables of Known Blazars, Blazar Candidates, and Other Multiwavelength Emitters*

Firmamento provides access to a catalog of known blazars including over 6400 objects, to tables of blazar candidates compiled in a variety of ways, and to lists of other types of multiwavelength emitters, as described in the following.

1. *The Firmamento reference list of blazars.*

This table combines the objects listed in the 5BZCAT (Massaro et al. 2015) and the 3HSP (Chang et al. 2019) catalogs with the blazars and gamma-ray-detected AGNs of the Fermi 4LACDR3 catalog (Ajello et al. 2022). This reference list is intended to be the starting point of a living blazar catalog that will be periodically updated with newly published blazars and with the blazars that will be discovered with *Firmamento* also via citizen researcher projects at NYUAD.

To facilitate the discovery of new blazars by *Firmamento* users, in particular by citizen scientists or students, the next few tables provide lists of astronomical sources that have been selected with different criteria to match the broadband spectral characteristics of blazars. They are expected to include 10%–20% of real blazars.

(a) *Blazar candidates in the VLBI Radio Fundamental Catalog*. The radio fundamental catalog (RFC)[32] is a compilation of compact radio sources observed using very long baseline interferometry (VLBI) that is statistically complete above a flux density of 150 mJy at 8 GHz. The *Firmamento* table of blazar candidates consists of all the sources in the RFC complete subsample that (a) are positionally coincident with one of the X-ray sources of the RASS, Swift-XRT, XMM, or Chandra catalogs, (b) have a radio to X-ray flux ratio that is within the range observed in blazars, and (c) are not included in our reference list of blazars.

(b) *Blazar candidates in the eRosita eFEDS survey.* The Final Equatorial Depth Survey (eFEDS) is a soft X-ray (0.2–8 keV) survey of 140 square degrees of sky carried out during the performance verification phase of the SGR/eRosita satellite (Predehl et al. 2021). The catalog of detected sources in this region (Brunner et al. 2022) includes 32,684 objects. Our list of eFEDS blazar candidates consists of the subset of eFEDS detections that match the position of a radio source with a flat-spectrum ($\alpha_r > -0.7$) estimated using the 1.4 GHz NVSS and the 3.0 GHz flux densities of the NVSS and the VLSS catalogs.

The list of eRosita blazar candidates will be largely expanded in the near future when the catalogs of eRosita surveys of large parts of the sky will be published.

(c) *Blazar candidates among the Swift-XRT serendipitous sources.* The Neil Gehrels Swift observatory (Gehrels et al. 2004) has been observing the X-ray sky since 2004. A recent analysis of entire Swift X-Ray Telescope (XRT) archive led to the creation of a catalog of ∼150,000 soft X-ray sources, many of which are not associated with known astronomical objects. The *Firmamento* table of Swift-XRT blazars candidates consists of the subset of still-unidentified X-ray detections that match the position of a radio source. To limit the table to a manageable size and to increase the fraction of real blazars that could be detected in high-energy surveys (that is, blazars with large $\nu_{\rm peak}$) we chose to select sources with a (0.5–10 keV) X-ray to radio flux ratio larger than 5×10^{-11} erg cm^{-2} s^{-1} Jy^{-1}. These selection criteria may change in the future to provide larger samples.

(d) *Blazar candidates in Fermi-LAT unidentified gamma-ray sources.* Most of the counterparts of the Fermi-LAT gamma-ray sources located away from the Galactic plane are identified with blazars. However, a significant fraction still remains unidentified, although it is likely that a good percentage of these still-unassociated sources will eventually be identified with blazars. The list of still-unassociated Fermi-LAT sources provided in *Firmamento* consists of all sources in the 4FGL-DR4 catalog (Abdollahi et al. 2022) located at Galactic latitudes $|b| > 10°$ and is expected to include several gamma-ray emitting blazars that could be discovered and characterized by *Firmamento* users.

(e) *Blazars and blazar candidates in the error regions of IceCube neutrino tracks.* The detection of a flow of high-energy astrophysical neutrinos by the IceCube South Pole observatory[33] opened a new window on the Universe (IceCube Collaboration 2013). A number of papers reported evidence that blazars are likely responsible for generating at least a fraction of the astrophysical neutrino flux that has been detected by IceCube (IceCube Collaboration et al. 2018; Giommi & Padovani 2021; Sahakyan et al. 2023, and references therein).

Over the last decade the IceCube team published a number of high-energy neutrino tracks as alerts communicated via GCNs immediately after their detections. These events have a good probability of being of astrophysical origin and have relatively small uncertainty regions (≈1°–4° in size), although still significantly larger than those of electromagnetic sources. Very recently the IceCube collaboration published a new list of likely astrophysical neutrino track-like events detected between 2011 and the end of 2020 (Abbasi et al. 2023). The table provided in *Firmamento* lists all the 274 tracks of the Abbasi et al. (2023) catalog, as well all the neutrino tracks published via the GCN channel from 2021 to the time of writing. The *Firmamento* list currently includes over 330 events and will be kept up to date, adding new events shortly after they are announced.

2. *User-provided lists of blazar candidates. Firmamento* users can provide their own list of sources by uploading a simple comma-separated-values (csv) file, which must include the source name, R.A. and dec. (in degrees), and (optionally) parameters defining the search radius around the source and the parameters of the uncertainty region, which is assumed to be of an elliptical shape. A comment field can also be added. The following is an example of the required format:

```
Name,ra,dec,fov,major,minor,angle,
comment
sourc-
e1,127.51611,1.57949,0.3,0.2,0.15,40.0,
comment for source 1
source2,139.48841,-
1.54498,0.4,0.2,0.2,0.0, comment for source 2
...
other sources details with the same format
```

Here, "fov, major, minor, angle" are the size of the area including the uncertainty region and the parameters of the ellipse (in units of arcminutes and degrees). If the file only includes the fields "name, ra and dec;" that is, if "fov," "major," "minor" and "angle" are missing, then *Firmamento* assumes that the position of the source has no uncertainty and it will only generate the SED using the multifrequency data that match the specified position.

3. *Other catalogs and tables of multifrequency emitters. Firmamento* also provides tables and catalogs of known astronomical sources of a variety of types.

[32] http://astrogeo.org/rfc/

[33] https://icecube.wisc.edu/

Table 3
An Extract from the Preliminary LSSUM Catalog of Blazar Candidates Obtained with *Firmamento*

Fermi-LAT ID	R.A.	Decl.	LSSUM ID	R.A.	Decl.	z	$\log_{10}\nu_{\rm peak}$
4FGL J0000.7+2530	0.188	25.515	LSSUM J000027.9+252805	0.11633	25.4680	0.49	16.6 ± 0.5
4FGL J0026.1−0732	6.540	−7.543	LSSUM J002611.6−073115	6.54842	−7.52097	…	16.9 ± 0.4
4FGL J0045.8−1324	11.472	−13.403	LSSUM J004602.8−132422	11.51154	−13.4060	…	15.6 ± 0.6
4FGL J0055.7+4507	13.940	45.124	LSSUM J005542.7+450701	13.92792	45.11706	…	15.8 ± 0.5
…							
4FGL J1628.2+4642	247.063	46.715	LSSUM J162755+464249	246.98105	46.71342	0.2135	15.8 ± 0.4
4FGL J1658.5+4315	254.646	43.254	LSSUM J165831.5+431615	254.63126	43.27085	0.63 (phot)	16.0 ± 0.5
4FGL J1706.4+6428	256.606	64.475	LSSUM J170623.3+642725	256.59688	64.45706	0.27 (phot)	15.9 ± 0.7
4FGL J1727.1+5955	261.776	59.926	LSSUM J172640.4+595549	261.66833	59.93036	featureless	16.1 ± 0.4
…							

Note. In the redshift column, "phot" means the redshift is taken from SDSS17 or NED and not from the galaxy spectra, while "featureless" is in case there are no optical lines.

(a) Catalogs of high-energy sources (e.g., blazars in the TevCat, the Fermi 4FGL-DR4 , and the 2Agile catalogs).
(b) Selected tables of nonblazar multifrequency sources. These are tables of astronomical objects that are in general not related to blazars but that are nevertheless useful for general or educational purposes in the context of multimessenger astrophysics.

4. Firmamento for Citizen Scientists and Students

4.1. *The NYUAD Citizen Researches Initiative and* Firmamento

Citizen Researcher at the New York University–Abu Dhabi[34] is a research public participation initiative developed by NYUAD that encourages members of the public in the UAE and elsewhere to participate and contribute to research in science, engineering, social sciences, arts, and humanities. The NYUAD Citizen Researcher initiative is a program that embodies the ethos of Citizen Science, a global movement where public involvement in scientific research goes beyond mere participation to encompass education, contribution, and collaboration. Unlike the conventional understanding of citizen science, which may simply involve data collection by the public, Citizen Researcher integrates participants into the heart of the research process. This program aims not just at assisting with data collection but at fostering a deep educational experience where participants develop research skills, engage in analysis, and contribute meaningfully to the outcomes of research projects across a wide spectrum of disciplines. Most importantly, Citizen Researcher removes the barrier that research can only be done by professionals and in professional settings. Based on best practices from the field of Public Participation in Scientific Research, Citizen Researcher projects at NYUAD are designed to ensure that public participants can clearly and easily take part and have a meaningful learning experience in which they can make an impact on critical research that has local and global significance. Citizen Researcher projects such as *Firmamento* transcend traditional public participation by not only providing tools and training for tasks such as the astronomical sources validation process but also by leveraging the public's contribution in the context of high-level research, utilizing sophisticated methods such as machine learning to enrich the data collected by participants. This innovative approach contributes to democratizing the research process, enabling anyone with interest and dedication to actively partake in research. Through this initiative, NYUAD makes citizen science a deeply immersive and educational experience that accelerates research outcomes and broadens the impact of academic studies by tapping into the collective effort and wisdom of the community.

4.2. *A Catalog of New Blazar Candidates with* Firmamento *by High School Students*

In 2022, four students from the Liceo Scientifico Statale Ugo Morin high school in Venice, Italy, participated in a citizen science program within the framework of the Italian MIUR PCTO program, which translates to "Paths for cross-disciplinary skills and orientation." The program aims at making students acquire skills outside the standard educational program. Within this agreement, the students invested around 40 hours each on a program with the Department of Physics and Astronomy of the University of Padova under the supervision of researchers. For this work the students started with Fermi-LAT data (Atwood et al. 2009). In the 4FGL catalog (DR3; Abdollahi et al. 2020) there are 6658 sources, out of which several hundreds are blazars. Out of all the unassociated sources in this catalog, a selection was done based on spectral hardness and distance from the Galactic plane. The students were given a list of 198 unidentified LAT sources as input selected by spectral hardness and location. Their goal was to find counterparts at other wavelengths and eventually propose an identification.

The first step was to verify whether these sources had counterparts in any other wavelength. This check was performed with *Firmamento*, inserting the coordinates of the region and of the parameters of the uncertainty area. In a second step, the students verified each single candidate association one by one. This was done by inserting the candidate coordinates again in *Firmamento* and evaluating the sky map in the optical spectrum in the direction of the candidate. In a third step, the students generated the SED. As a result, 54 new blazar candidates were found, characterized by the synchrotron peak with the BLAST code (Glauch et al. 2022) and by redshift, where it exists (Fronte et al. 2023). The candidates were labeled with the LLSUM acronym following the name of the high school. An extract of the candidate table is shown in Table 3.

[34] https://citizenresearcher.hosting.nyu.edu/

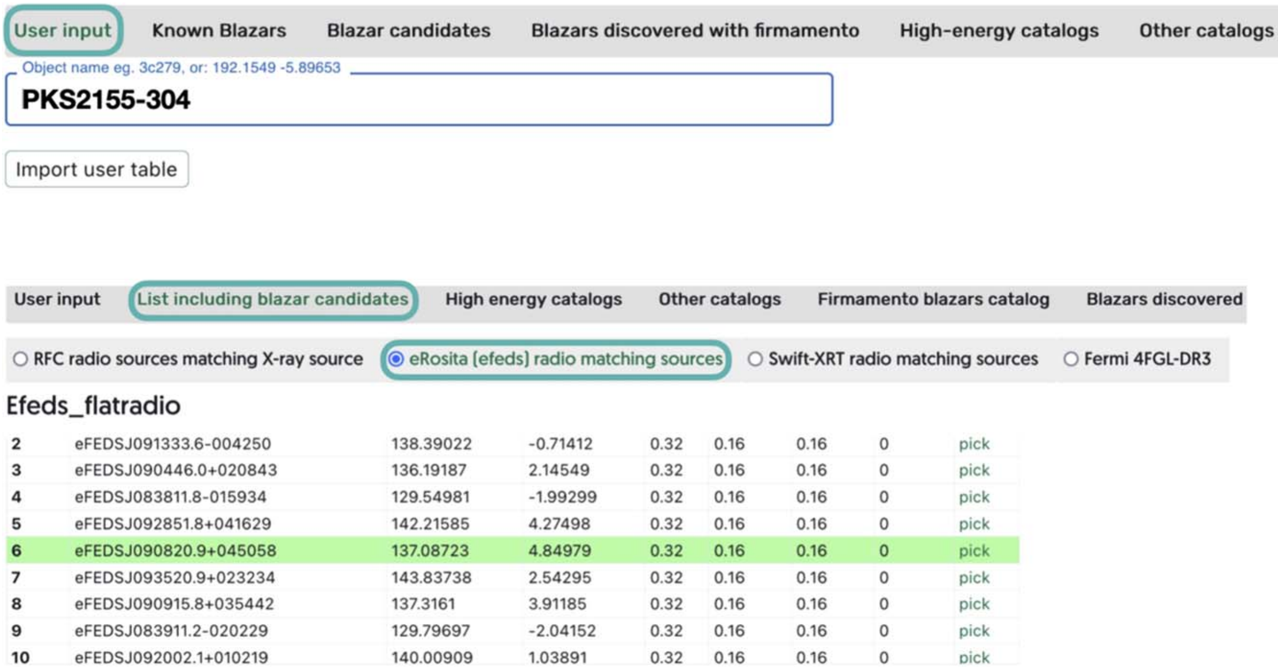

Figure 3. The name or the position of an astronomical source, or of a localization error to be processed by *Firmamento* can be provided by specifying a source name or a set of R.A., decl. coordinates, or selecting one entry from a list uploaded by the user (top), or by choosing an entry from one of the lists provided, e.g., the table of eROSITA detections from the eFEDS survey matching flat-spectrum radio sources, as in the lower part of the figure.

Plans to reevaluate the targets by relaxing the criteria on the number of `Fermi`-LAT unassociated objects in the sample are being carried out as a follow-up project. Discussion about possible follow-up observations in the optical (to estimate redshift) and in the X-rays and gamma rays (to validate the inverse Compton peak) are ongoing. The four involved students remarked (Fronte et al. 2023):

> *"This PCTO experience has been a fundamental opportunity to grow as persons, it gave us the possibility to see the research environment in close contact and to understand what working at a University really means. Thanks to this occasion we now know that we would like to have a career as researchers someday."*

We plan some follow-up initiatives, such as submitting proposals for observations of sources with no redshift, and propose similar undertakings to other students, both in Italy and at NYUAD.

5. *Firmamento* for Astro and Particle Physicists

In the following we give some examples of possible uses of *Firmamento* in the framework of contemporary astro-particle research.

Firmamento provides multifrequency data of astronomical objects whose common names or positions are entered by the users (as do most web services providing astronomical data) or are included in lists assembled in various ways, e.g., from radio catalogs, X-ray and gamma-ray detections or high-energy neutrinos, as described above. Figure 3 shows the part of *Firmamento* where the user directly inputs the name of a source (top) or chooses one object from the table of eRosita sources (bottom).

5.1. The SED of a Well-known and Often-observed Object: BL Lacertae

In this example, we consider the SED of BL Lacertae (also known as BL Lac), the prototype of the class of blazars. This object has been observed with many ground-based and space observatories many times over the years. Figure 4 shows the SED generated with *Firmamento*. Note the very large density of data available in most energy bands and, in particular, in the X-ray region where the many spectral measurements from the systematic analysis of Swift (Giommi et al. 2021) and NuSTAR (Middei et al. 2022) blazars observations are plotted. All SED data points, inclusive of observation time and corresponding bibliographic references, can be downloaded in different formats with a simple click, as shown in the figure. These data can be selected by the user for specific needs, e.g., fitting a model during a particular intensity state or time interval. In the future *Firmamento* will provide tools to access the data for specified time intervals or according to other selection criteria.

5.2. Locating Blazars Candidates in Unidentified FERMI 4FGLDR3 Gamma-Ray Sources

Here, we show how *Firmamento* can be useful to identify blazars in the error ellipses of Fermi-LAT sources. Figure 5 shows the case of the gamma-ray source 4FGL J1747.8-0316, one of those listed in the table of Fermi unidentified sources (upper left); the error ellipse of this source generated with *Firmamento* is shown in the upper right part of the figure. The orange symbol is a candidate blazar selected by VOU-Blazars considering X-ray and radio matching sources. The bottom part of Figure 5 shows the SED of the candidate (left) and the error circles chart shown with Aladin using the PanSTARRS survey (image background) overlaid with the uncertainty region of the X-ray data (blue circle) and the radio measurement (red circle).

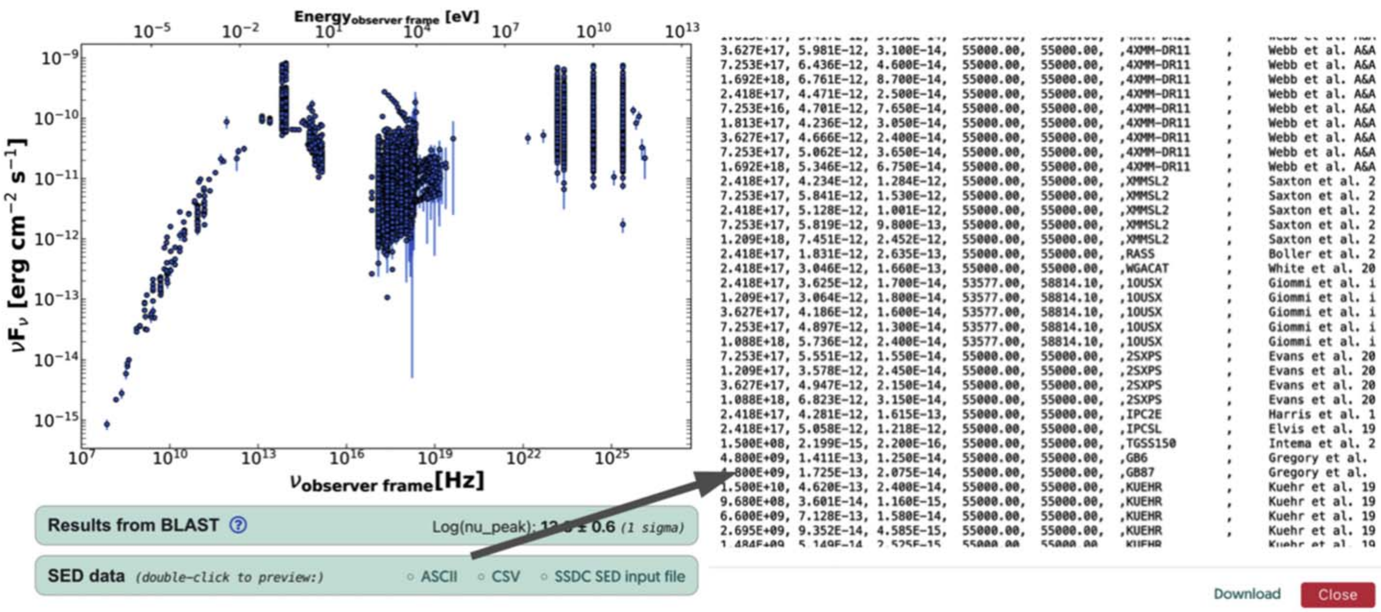

Figure 4. The SED of the well-known source named BL Lacertae, the archetype of the class of blazars. The right side shows part of the corresponding data file, which can be downloaded by clicking next to the chosen format.

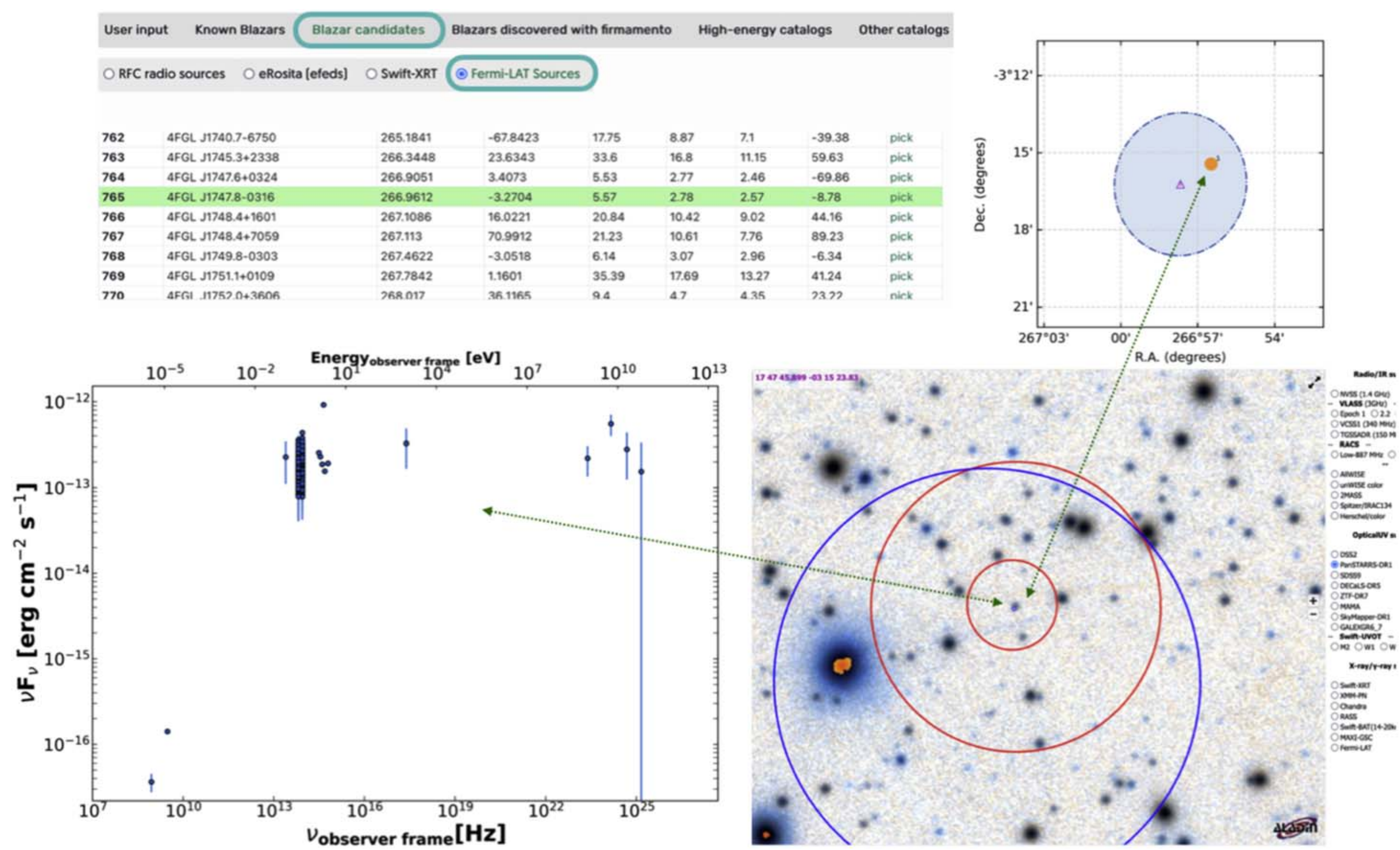

Figure 5. Example of a possible identification of a blazar counterpart in the error ellipse of a still-unidentified gamma-ray source. Top left: the user selects a source from the list of unidentified Fermi 4FGLDR3 detections. Top right: the 4FGLDR3 localization error ellipse of the chosen source with a possible blazar counterpart appearing as an orange symbol. Lower left: the SED of the blazar candidate. Lower right: the error regions of cataloged radio and X-ray sources (red and blue circles) matching the position of the candidate blazar are superposed to the image from an optical survey chosen in the *Firmamento* Aladin interface.

5.3. The Localization Error of IceCube200107A and the Blazar 3HSP J095507.1+355100

The blazar 3HSP J095507.1+355100 has been reported as the possible counterpart of the high-energy neutrino IceCube200107A (Giommi et al. 2020c). The left side of Figure 6 shows the 90% localization error of IceCube200107A (light-blue inner area), which includes several candidate blazars, as generated by *Firmamento* via VOU-Blazars. Only

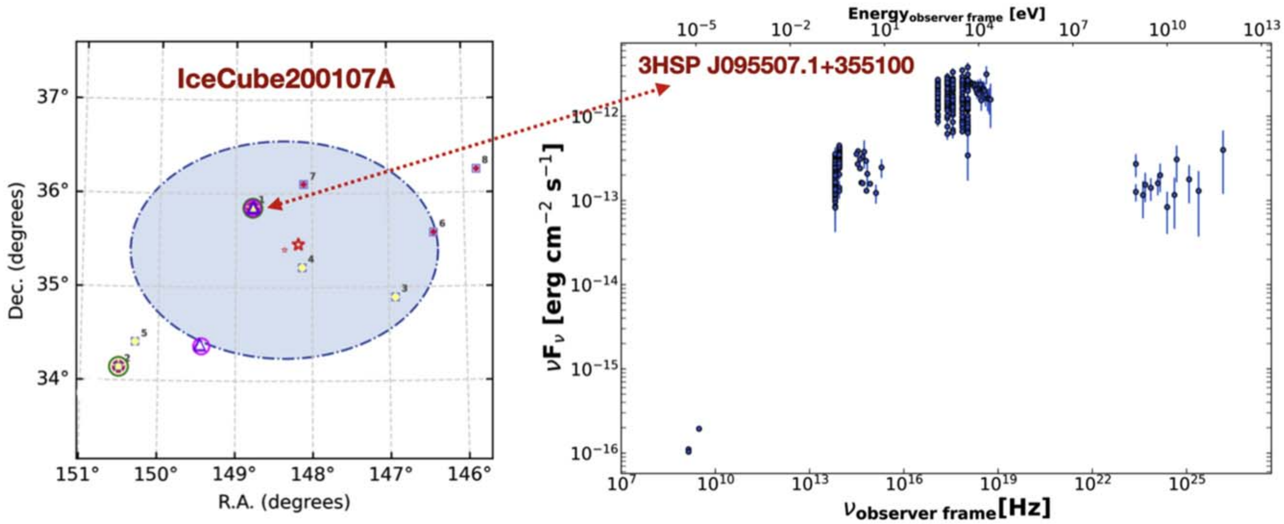

Figure 6. The 90% localization uncertainty of the IceCube neutrino track IceCube200107A and the SED of the possible electromagnetic counterpart 3HSP J095507.1+355100. See text for details.

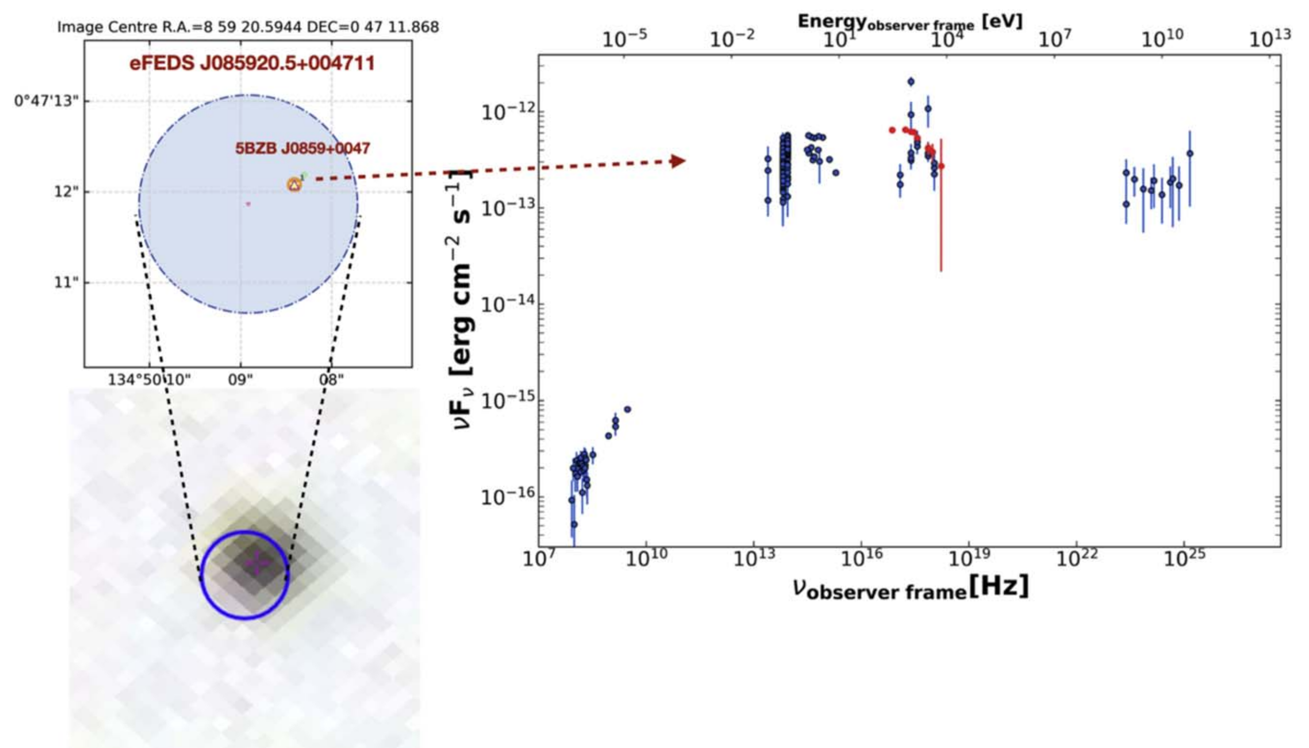

Figure 7. Top left: the error circle of the source eFEDS J085920.5+004711 including the blazar 5BZB J0859+0047. On the lower left is shown the very small error circle overlaid to the Sloan Digital Sky Survey optical image of this part of the sky. Right: the SED of the Blazar 5BZB J0859+0047 = eFEDS J085920.5+004711 generated with *Firmamento*. The red points are from the eRosita eFEDS survey.

one of these sources, 3HSP J095507.1+355100, is also a gamma-ray source, as marked by the open purple triangle. Its SED is shown on the right side of the figure. For more details on this case and about the association of IceCube astrophysical neutrinos and blazars in general, see Giommi et al. (2020b, 2020c) and Padovani et al. (2018).

5.4. The eRosita-eFEDS Sample of X-Ray Sources with Radio Counterparts

Firmamento provides several lists of sources with associated positional uncertainties that potentially include blazars. As an example, we mention here a sample of X-ray sources that are positionally consistent with radio sources and have been detected in the eRosita Final Equatorial Depth Survey (eFEDS; Brunner et al. 2022), a data set covering 140 square degrees of sky that was made publically available shortly after the launch of the mission. A specific case illustrating the detection of a blazar in eRosita data is shown in Figure 7, where the X-ray error region of the source eFEDS J085920.5+004711, which includes the blazar 5BZBJ0859+0047, as well as the corresponding SED, are shown. The eRosita X-ray data points, converted to $\nu f(\nu)$ units from the integrated fluxes reported in

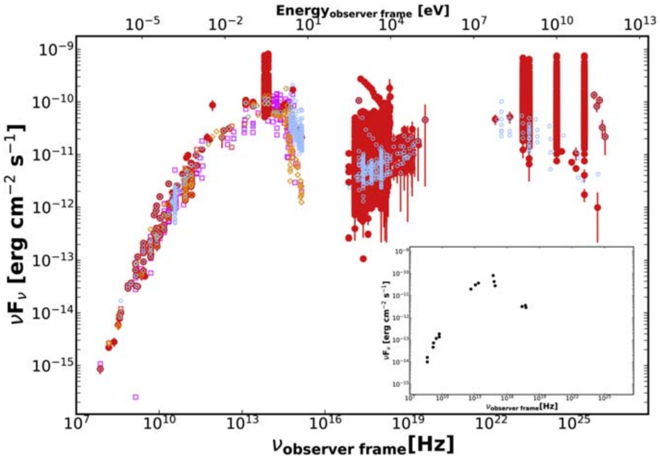

Figure 8. A comparison of the SED of the prototype blazar source BL Lacertae obtained with *Firmamento* and other online SED tools. *Firmamento* data is shown as filled red points, SSDC SED builder as open light-blue circles, NED as magenta open squares, and Vizier as orange open diamonds. The SED in the inset, adapted from Giommi et al. (1995), illustrates the amount of multifrequency data available from public sites in the mid 1990s.

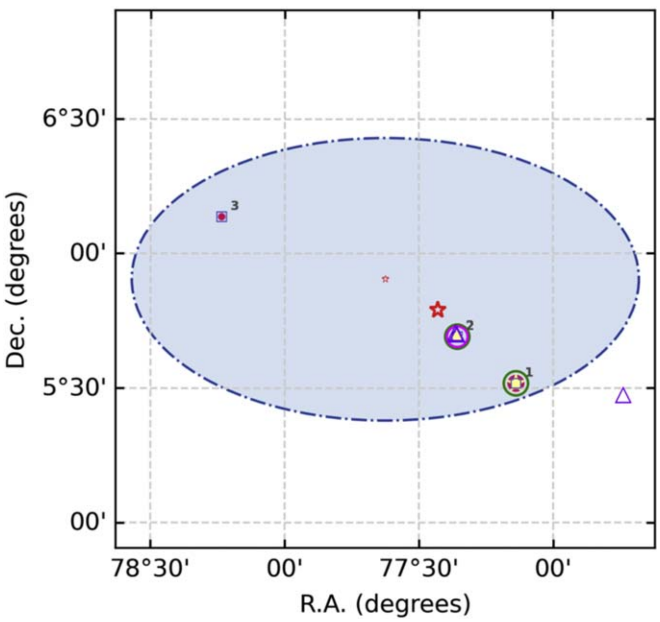

Figure 9. The blue ellipse plotted in this figure illustrates the localization error region of IceCube170922. The only known source detected in gamma rays inside this area (identified by the number 2) is the blazar TXS0506+056, which has been associated with the IceCube neutrino.

the catalog, appear as red symbols. Additional samples of eRosita sources will be provided shortly after these will be released by the eRosita teams.

6. Scientific Validation and Comparison with Other Platforms

As mentioned in the Introduction, for several years now a number of official archives have provided access to astronomical data generated by scientific satellites and ground-based observatories funded by agencies around the world, serving the international astronomical community. Alongside these institutional services a wealth of other websites offer public data and tools to the general astronomical community in many ways. *Firmamento* was conceived to follow a somewhat different concept and therefore distinguishes itself from other online platforms for several notable reasons:

1. Specialization: *Firmamento* is a scientific topic-oriented tool with a current clear specialization in the field of blazars and multimessenger emitters. It places a strong emphasis on addressing contemporary scientific challenges, such as spectral and time-domain detailed studies and the identification of new blazars and other multifrequency emitters in the error regions of high-energy sources, including in X-rays, gamma rays, and astrophysical neutrinos.
2. Comprehensive data: The platform offers a comprehensive range of products in the energy, time, and imaging domains. These include well-populated SEDs, time-domain data in several energy bands (e.g., IR, optical, X-ray, and gamma ray), error regions maps with candidate counterparts, visualization of multiwavelength surveys, lists of candidate blazars, catalogs of high-energy sources, etc.
3. Value-added information and data characterization: By incorporating value-added information generated through machine learning and other techniques, *Firmamento* seeks to help characterize the data retrieved and therefore enhance the quality and depth of the services it provides. Examples are outputs of the BLAST and W-Peak tools that estimate of the position and intensity of the synchrotron peak of the SED, two important observational parameters in contemporary blazar research.
4. Inclusivity: Building on the principles of the Open Universe initiative, one of *Firmamento*'s core objectives is to provide quality services that cater not only to professional scientists but also to citizen scientists and the educational sector. This inclusive approach ensures that its resources are accessible and beneficial to a broader audience.

To scientifically validate *Firmamento* and assess its effectiveness, in the following we compare some of the data products generated using *Firmamento* with those produced by other online platforms or have been published in the scientific literature.

Figure 8 presents a comparison of the SED for the Blazar BL Lacertae built using *Firmamento* with those produced using other SED analysis tools accessible online. *Firmamento* data points are shown as filled red circles, while those from the SSDC SED builder[35] appear as overlaid open light-blue circles, those from NED[36] as magenta open squares, and those from the Vizier photometry viewer[37] as orange open diamonds. Note the large overlap and agreement among all the data sets in the region 10^8 Hz to $\sim 3 \times 10^{14}$ Hz. At higher frequencies, up to a few times 10^{15} Hz, the NED and Vizier points are systematically lower than those of *Firmamento* and of SSDC. That is because NED and Vizier provide flux values "as observed" without any correction to compensate for absorption in our Galaxy. These points should be corrected before they can be compared to theoretical emission models. The much larger amount of *Firmamento* data points in the X-ray bands is due to the inclusion of the spectral data from many Swift and

[35] https://tools.ssdc.asi.it/SED
[36] https://ned.ipac.caltech.edu
[37] http://vizier.cds.unistra.fr/vizier/sed/

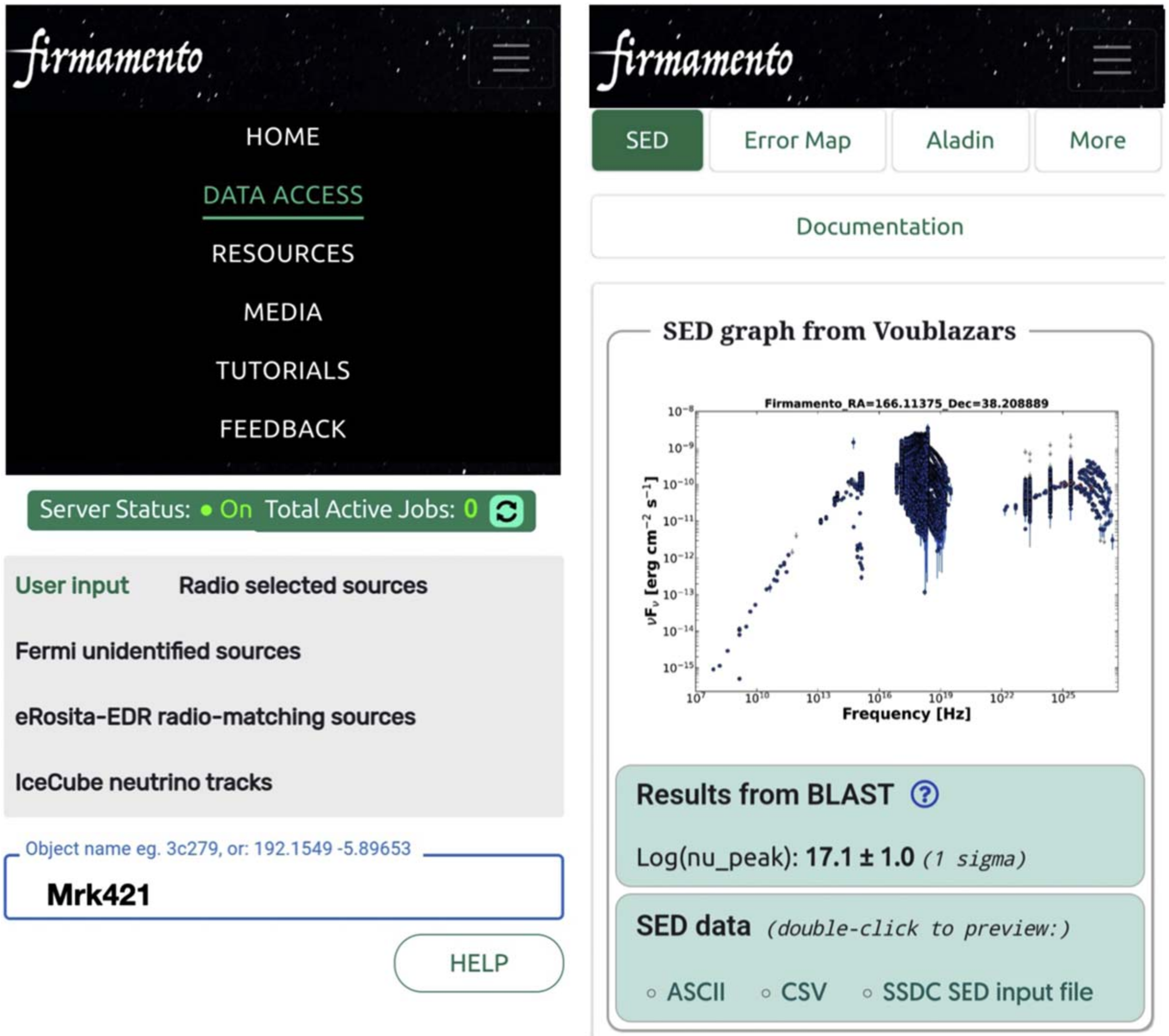

Figure 10. Screenshots of *Firmamento* running on a mobile phone. Left: the input area, where the user can enter a source name or choose from a list of radio, X-ray, gamma-ray, or IceCube neutrino detections. The right part shows the SED of the blazar MRK421, together with the estimation of $\nu_{\rm peak}$ from BLAST and the option to download the SED data in different formats.

NuSTAR observations that have been analyzed and made publically available in the framework of the Open Universe initiative (Giommi et al. 2021; Middei et al. 2022). In the inset of Figure 8, we showcase an early SED of the same blazar, as initially presented by Giommi et al. (1995) in the mid 1990s using data from the European Space Information System (Giommi & Ansari 1994), one of the first online sites to serve multifrequency data at a time when multiwavelength astrophysics was still in its early stages. The large disparity in data abundance (18 versus approximately 17,700 flux measurements) and the large variability observed reflects both the recent exponential growth in available astronomical data and the close interconnection between multifrequency and time-domain astronomy.

One of the most distinctive features of *Firmamento* is its ability to facilitate the identification of blazars in the localization uncertainty regions of high-energy sources. To use a well-known case to compare the maps generated by *Firmamento* with those that appeared in the literature, Figure 9 shows the error region of the famous astrophysical neutrino IceCube170922, which has been associated the blazar TXS0506+056. This figure is very similar and can be directly compared with, e.g., Figure 2 of IceCube Collaboration et al. (2018) and Figure 1 of Padovani et al. (2018), the papers that identified TXS0506+056 as the first neutrino source.

7. A Mobile-friendly Tool

In an effort to offer a good degree of flexibility and usability by the widest possible range of users with different skills and preferences, including the participants of the citizen researcher project at NYUAD, *Firmamento* has been designed to be both mobile and computer friendly.

To illustrate how *Firmamento* can be used on a smartphone, Figure 10 shows two screenshots corresponding to a request for the SED of a well-known blazar. On the left side the user, after choosing the "Data Access" option, types the name of the requested source (Mrk421) in the input area, and then clicks on the "Run" button. The right side shows the result with a picture of the requested SED generated using VOU-Blazars, the result from the BLAST tool, and various options to continue, including the option to download the SED data in different formats.

8. Conclusions and Future Perspectives

We presented *Firmamento*, a web-based and mobile-friendly tool dedicated to blazars and multifrequency/multimessenger emitters, in general. Since many aspects of modern astrophysics rely on multifrequency data, this new facility has the potential to become a valuable service supporting a broad range of topics in contemporary astronomy. *Firmamento* has been designed to assist both professional and citizen scientists, with the goal of increasing the discovery power in the scientific community and of offering new opportunities for people with different skills to contribute to scientific advancement. We will use *Firmamento* to support citizen researcher projects and we hope this system will be used in the scientific community. *Firmamento* can be accessed from all devices including mobile phones, thus providing effortless access to a vast pool of science-ready, high-quality data and efficient tools for handling multifrequency data. *Firmamento* also employs advanced algorithms and machine-learning tools to assist professional scientists in a novel way and makes astrophysical research more accessible to a wide range of individuals with varying levels of expertize. This approach is expected to become widely adopted in the coming years as artificial-intelligence technologies are integrated into online scientific services.

Along with these expectations, future versions of *Firmamento* will expand its capabilities in different directions, starting with increasing the amount of data available by providing interfaces to other similar websites, e.g., NED, Zwicky Transient Facility (ZTF),[38] Vizier, etc. From the data analysis viewpoint, we plan to offer more support to time-domain analysis, which at the moment is limited to the timing parameters provided by the W-Peak tool in the infrared band. To expand the potential for the discovery of new blazars, we will define lists of candidate blazars in the eROSITA all-sky surveys, which are expected to include several thousand new BL Lacs and FSRQs that could be discovered by *Firmamento* users, hopefully with a good participation of citizen scientists and students. In an effort to broaden support for multifrequency emitters of all types, we plan to include methods to identify radio-quiet extragalactic sources, such as normal AGNs and X-ray emitting stars, and to incorporate catalogs of Galactic sources. Subsequently, we aim to introduce algorithms suitable for discovering new Galactic sources based on their specific multifrequency emission. Finally, to expand the involvement, to increase the analysis capability, and to stimulate the capacity to conceive and perform independent scientific projects by citizen scientists and to better serve the education sector, we will interface *Firmamento* with artificial-intelligence tools, starting with ChatGPT or similar tools. These language generation tools undoubtedly have significant potential to enhance *Firmamento*'s services, beginning with a more comprehensive presentation of the results. Predicting the exact direction of the application of these methods is challenging; therefore, we plan to start gradually by training these tools with scientific papers related to the data provided by *Firmamento*. This approach will enable the tools to assist users, especially citizen scientists, in answering questions and understanding the physical models used to interpret the data.

[38] https://www.ztf.caltech.edu/

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Software: VOU-Blazars (Chang et al. 2020), Aladin (Boch & Fernique 2014), BLAST (Glauch et al. 2022).

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