

1FLAT: a Firmamento-based catalog of AGN in *Fermi*-LAT high Galactic latitude γ -ray sources

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ABSTRACT

We present a systematic reassessment of 5,062 high-Galactic latitude gamma-ray sources from the *Fermi*-LAT 4FGL-DR4 catalog using **Firmamento**, a web-based platform for multi-frequency source discovery and analysis. Our goal is to provide an independent evaluation of LAT γ -ray source associations using alternative spectral and spatial methods that integrate both recent and legacy survey data. The evaluation is further refined through human supervision of SEDs, source morphology, flux variability, and template-based comparisons. **Firmamento** confirms the 4FGL-DR4 and 4LAC-DR3 counterparts or unassociated sources in 4,493 cases (88.8%), demonstrating the robustness of both approaches. Beyond this general agreement, we identify 421 new blazar counterparts among previously unassociated sources, thereby reducing the fraction of unidentified extragalactic *Fermi*-LAT sources from 25% to 17%. In addition, in 64 cases we find alternative blazar associations, while in 49 instances, we do not confirm the 4FGL-DR4 association. For all confirmed blazar counterparts we provide homogeneous estimates of synchrotron peak frequency and peak flux using machine-learning and template-based methods. The results agree with 4LAC-DR3 values in most cases, though significant discrepancies appear for a few dozen sources, often due to improved X-ray coverage. The primary outcome of this work is the 1st **Firmamento** LAT AGN Table (1FLAT), made publicly available through the **Firmamento** platform (<https://firmamento.nyuad.nyu.edu>), where all related multi-wavelength data and images are available. The project involved extensive manual validation and benefited from the active participation of graduate and undergraduate students, highlighting the platform's value for both research and education.

Keywords: Catalogs (205) — Blazars (164) — Astronomy Web Services (1856)

1. INTRODUCTION

A small fraction of active galactic nuclei (AGN) launch powerful relativistic jets that emit radiation across the entire electromagnetic spectrum, making them prominent sources in γ -ray surveys (V. Beckmann & C. Shrader 2012; C. D. Dermer & G. Menon 2009). When these jets are aligned with the observer’s line of sight, the resulting relativistic Doppler boosting amplifies the jet’s luminosity, often outshining other emission components of the AGN and leading to their classification as blazars (P. Padovani et al. 2017). Blazars exhibit a characteristic multi-wavelength emission, with a radio-to- γ -ray Spectral Energy Distribution (SED) that typically shows two broad components (A. Abdo et al. 2010). The low-energy component, spanning from radio to optical frequencies, and sometimes extending to the X-ray band, is attributed to synchrotron radiation from relativistic electrons spiraling in magnetic fields. The high-energy emission (X-rays to gamma-rays) arises from inverse Compton scattering of lower-energy photons or from other non-thermal processes such as hadronic interactions.

Blazars are classified according to the shape of their SEDs, characterized by the location of the synchrotron peak (ν_{peak}), which sheds light on the power budget of the AGN (P. Padovani & P. Giommi 1995; A. Abdo et al. 2010). In this work we classify blazars as Low-Synchrotron Peaked (LSP) if $\nu_{\text{peak}} < 10^{13.5}$ Hz, Intermediate-Synchrotron Peaked (ISP) if $10^{13.5} \leq \nu_{\text{peak}} < 10^{15}$ Hz and High-Synchrotron Peaked (HSP) if $\nu_{\text{peak}} \geq 10^{15}$ Hz.

Large-scale γ -ray surveys conducted by telescopes such as *Fermi*-LAT (hereafter LAT) have resulted in extensive source catalogs, the most recent being the fourth catalog, 4th data release (4FGL-DR4, hereafter 4FGL) (S. Abdollahi et al. 2022; J. Ballet et al. 2023), which builds up from the first release 4FGL-DR1 (S. Abdollahi et al. 2020). The catalog provides extensive information on source detection, including coordinates, significance, spectral fits, etc, and additionally provides proposed counterparts. Such associations are based on unsupervised Bayesian and Likelihood Ratio (LR) statistics algorithms. The Bayesian method is based solely on spatial coincidence between the gamma-ray sources and their potential counterparts, the LR method using their $\log N - \log S$. The probability of association is also estimated using a prior based on the number of emitters in the error circle, and the association is retained if the probability ASSOC_PROB_BAY

is ≥ 0.8 (S. Abdollahi et al. 2022). A large fraction of 4FGL sources were separately further investigated specifically in search for blazar counterparts, making up the dedicated 4LAC-DR3 catalog (M. Ajello et al. 2022) (hereafter 4LAC). The 4FGL catalog contains 7,194 sources, 5,062 of which are located at Galactic latitude $|b| \geq 10^\circ$, while 4LAC reports 3,407 blazars in this region (67% of the 4FGL sources).

Although these catalogs have significantly advanced our understanding of the γ -ray sky, a considerable fraction of sources, approximately 25% in the case of 4FGL, remain unidentified due to the lack of clear counterparts at other wavelengths. Among those, S. Abdollahi et al. (2022) report that it is very likely that those at high Galactic latitudes are likely unassociated blazars. Identifying the nature of these sources is crucial for completing the census of γ -ray emitters and potentially discovering new classes of astrophysical objects.

To address this challenge, we present a systematic reassessment of the AGN counterparts of high-Galactic latitude γ -ray sources in the 4FGL, utilizing *Firmamento* (D. Tripathi et al. 2024) (hereafter *f*), a novel web-based platform specifically developed for the search and identification of multi-frequency counterparts of X-ray and γ -ray sources. *f* employs advanced data-handling capabilities, including machine learning models and specialized data science tools (Y. L. Chang et al. 2020; T. Glauch et al. 2022; P. Giommi et al. 2024a). Our search is primarily spectromorphological. We obtain multi-wavelength data through a survey search (see App. A), compare the spatial morphology and the SED relations to match candidates (D. Tripathi et al. 2024).

With respect to 4FGL, we directly access multi-wavelength survey data, rather than source catalogs, including a number of recent surveys that were not available when 4FGL and 4LAC were prepared. Another important difference is that we include source-by-source human validation on the SED as well as the multi-wavelength sky maps to supervise the association. Because of this, an accurate false-positive rate cannot be firmly statistically evaluated, although we discuss the robustness of our results throughout the work. Furthermore, in line with M. Ajello et al. (2022) we compute the synchrotron peak and flux at this frequency and compare these values with those of 4LAC. This massive manual work benefited from the active participation of graduate and undergraduate students through *f*’s user-

friendly interface and commitment to educational engagement.

The structure of this paper is as follows. [Sec. 2](#) provides a concise summary of the features of the *f* platform (presented extensively in ([D. Tripathi et al. 2024](#))) used for this work. [Sec. 3](#) presents the main numerical results of our analysis, discussing both the agreement and discrepancies with previous LAT catalogs and introduce the 1FLAT catalog. In [Sec. 4](#) we study more in depth the properties of our classification, investigating the possible reasons for discrepancies with 4FGL. In [Sec. 5](#) we discuss the educational engagement utilized in this project. Finally, in [Sec. 6](#) we discuss and summarize our findings.

2. METHODOLOGY

2.1. The Firmamento Platform

f is a novel, web-based data analysis platform designed for the discovery and study of multi-frequency and multi-messenger astrophysical sources ([D. Tripathi et al. 2024](#)). It provides a comprehensive suite of tools for exploring sources across the electromagnetic spectrum, integrating extensive multi-band catalogs with advanced data-handling capabilities, including machine learning, through an accessible visual interface ([P. Giommi 2025](#)), and it is conceived for educational engagement. *f* is undergoing constant development to add features, extend investigation to different astrophysical classes of objects, improve performance and appearance. *f* is developed in the framework of the Open Universe initiative — an effort under the auspices of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and implemented by United Nations Office for Outer Space Affairs (UNOOSA) ([P. Giommi et al. 2018](#)).

The Error Region Counterpart Identifier (ERCI), a core component of *f*, is based on an enhanced version of VOU-Blazars ([Y. L. Chang et al. 2020](#)) combined with custom Python scripts. ERCI is designed to identify potential multi-frequency counterparts within the localization regions of X-ray and γ -ray sources. For each 4FGL γ -ray source, within an area about 20% larger than the 95% CL signal containment error region listed [S. Abdollahi et al. \(2022\)](#) catalog, ERCI retrieves multi-frequency survey data and additional information, such as source variability and spatial extension, from about 90 openly-accessible remote and local catalogs, listed in [App. A](#). The retrieved photometric data points are converted to flux densities and to νF_ν values, corrected for absorption within the Galaxy. These data are then combined to construct a full SED, which is displayed on the front-end for user evaluation and is available for down-

load. The source identification algorithm within ERCI exploits gradients in key regions of the SED, and tests for the presence of non-jet-like components (such as accretion disk, dusty torus and host galaxy), as well as source extension at optical and X-ray energies, to assess the consistency with different source types (blazar, other AGN, clusters of galaxies, Galactic sources etc.).

f also incorporates two tools for estimating the synchrotron peak energy ν_{peak} and the flux at the peak $\nu_s F(\nu_s)$ from the SED of candidate blazars: BLAST and W-Peak ([T. Glauch et al. 2022](#); [P. Giommi et al. 2024a](#)). BLAST is a machine-learning-based estimator designed for automated estimation of these parameters directly from the observed SED data points. W-Peak estimates the synchrotron peak frequency and flux by analyzing infrared spectral slopes from WISE and NEOWISE datasets, predictive of blazar jet emission.

Additional tools for investigating source candidates include an Aladin-based multi-wavelength sky map displaying the retrieved catalog data, as well as benchmark SEDs (LSP, ISP, HSP) and host-galaxy or blue-bump templates that can be superimposed on the data for source validation.

2.2. Workflow for 4FGL Sources

We conducted an independent search for blazars among the high-Galactic-latitude ($|b| > 10^\circ$) γ -ray sources of the LAT 4FGL catalog ([S. Abdollahi et al. 2022](#)), with a starting dataset of 5,062 sources. We prepared an ASCII file with 4FGL Source name `SourceName`, Right Ascension, Declination `RAJ2000`, `DEJ2000`, Long and Short radii of error ellipse at 95% confidence `Conf_95_SemiMajor`, `Conf_95_SemiMinor`, Position angle (eastward) of the long axis from celestial North `Conf_95_PosAng` and the Name of identified or likely associated source name and class `ASSOC1`, `CLASS` along with its position `RA_Counterpart`, `DEC_Counterpart`. From the 4LAC catalog we took the `ASSOC1`, `CLASS1` fields. We also annotated the 4FGL association probabilities `ASSOC_PROB_BAY`, `ASSOC_PROB_LR`. We remark that we did not consider the 4FGL secondary association `ASSOC2`, `CLASS2` because no position is given. However, we took note of those secondary association for discussion of some specific cases. This type of information was entered into *f*, which features a special mode for user-input table-data. We run the ERCI tool on all sources one by one. ERCI can provide none, single or multiple candidate counterparts. Whenever ERCI identified one or more candidates, we verified the validity of each potential counterpart based on its multi-frequency morphological properties (via the Aladin skymaps) and

its SED. Particular attention was given to the SED to ensure the synchrotron peak was consistent with the γ -ray intensity and spectral slope reported in 4FGL. Cases with multiple plausible candidates were resolved by selecting the counterpart with the most compelling SED. While specific quantitative thresholds for all parameters are complex and depend on the multi-dimensional parameter space explored by ERCI, the final selection of counterparts involved a careful visual inspection of the SEDs by experienced users and, in many cases, by undergraduate and graduate students under expert supervision (see Sec. 5). The synchrotron peak position estimated by BLAST and W-Peak (T. Glauch et al. 2022; P. Giommi et al. 2024a) provided additional validation of the blazar nature of the counterparts.

The coincidence with the proposed 4FGL or¹² 4LAC candidates were also finally scrutinized based on the position (and naming) of the proposed association. The step-by-step procedure is reported in App. B.

2.3. The Role of Flux Variability

While the ERCI tool retrieves variability flags from the catalogs that include such information, a detailed quantitative analysis of variability was not the primary driver for counterpart associations. Multi-wavelength variability was in some cases considered as an additional factor in the evaluation of the counterpart selection process. For example large variability in the optical or in the infrared band, e.g. from the Zwicky Transient Facility (ZTF, F. J. Masci et al. 2019) or from NEOWISE (A. Mainzer et al. 2014) data, which is retrievable directly from f , was used as a confirmation of the blazar nature of a potential counterpart. Cases exhibiting extreme variability in certain bands were also noted and considered in the overall assessment of the counterpart's nature. Future work may involve a more systematic and quantitative analysis of multi-wavelength variability data to further refine the counterpart associations and blazar classifications.

3. RESULTS

3.1. Numerical Overview

The results of the search for counterparts to the 5,062 4FGL γ -ray sources above the Galactic plane ($|b| > 10^\circ$) with f , are discussed below and are summarized in Tab. 1.

¹² There were cases in which LAT sources were associated to blazars in both 4FGL and 4LAC but some only in 4FGL and not in 4LAC and vice-versa. We required a blazar classification in either of the two catalogs.

Cases where f and 4FGL/4LAC agree	Nr.	%
$\triangleright f$ finds same blazar automatically	3,380	66.8
$\triangleright f$ finds same blazar supervised	76	1.5
$\triangleright f$ finds same galaxy/radiogalaxy	20	0.4
$\triangleright f$ finds same pulsar or galactic source	163	3.2
$\triangleright f$ confirms unassociated	854	16.9
Total agree	4,493	88.8
Cases where f and 4FGL/4LAC disagree	Nr.	%
$\triangleright f$ finds a new blazar in previously unassociated source	421	8.3
$\triangleright f$ finds alternative blazar	64	1.3
$\triangleright f$ does not find any association	49	1.0
$\triangleright f$ does not confirm the association	16	0.3
$\triangleright f$ finds a galaxy instead	18	0.4
$\triangleright f$ finds a galactic object instead	1	0.0
Total disagree	569	11.2

Table 1. Summary of the classification of 4FGL/4LAC sources made with f . Percentages are calculated with respect to the total number of 4FGL sources, excluding those associated with Galactic sources in the catalog. The upper block lists the cases where there is agreement with 4FGL, while the lower block gives the cases where there are disagreements.

We found that f agrees with the 4FGL or 4LAC counterparts in 88.8% of cases (4,493 sources). Of these, 3,380 (66.8%) are blazars confirmed in an automatic way, and 76 (1.5%) only after supervision¹³, for a total of 3,456 blazars. We also confirm the non-existence of a plausible candidate in 854 (16.9%) of the cases. The remainder are extragalactic objects (20, 0.4%, e.g. misaligned jetted and non-jetted AGNs, or near-by galaxies) and Galactic sources (163, 3.2%, e.g. pulsars, supernova remnants, etc.).

f is in disagreement with 4FGL or 4LAC for 569 (11.2%) γ -ray sources. Among these, the largest population is that of new blazar associations discovered with f , which amounts to 421 (8.3%) objects. In 64 cases (1.4%) we instead find a different, and more plausible, blazar counterpart. In 49 cases (1.0%) we cannot confirm a candidate that instead is claimed by 4FGL. In 16 cases (0.3%), although we observe the presence of a possible counterpart, its nature cannot be confirmed with high confidence. Finally, f finds different counter-

¹³ This latter minority is related to the fact that f algorithm does not provide an association in case optical data are missing or on the contrary too numerous. Very likely the LAT spatial association with radio sources overcome this problem and find valid candidate in these cases. We are investigating an improvement of our algorithm to address this issue for future release

parts for 19 (0.4%) sources, including 18 galaxies and 1 Galactic object. In the following sections, we discuss individual cases, focusing on blazars, the class of sources most relevant to this work.

3.2. Agreement between *Firmamento* and 4FGL

We focus here on the 4,493 (88.8%) sources for which there is an agreement between f and 4FGL.

3.2.1. Confirmed blazars

4FGL classifies 3,508 sources (CLASS1) as blazars, differentiating between **b11**, **bcu**, **fsrq** with 47 sources classified **rdg** as well as few less populated classes. 4LAC instead counts 3,383 sources that are also listed in 4FGL. Of these 1,191 are **bcus**. Consider that the 4LAC catalog has 3,407 sources in total, 24 of which are not included in 4FGL (listed in App. C), and are not considered in this work.

Our results agree on the association of blazars with 4FGL sources in 3,456 cases. In 98.5% of the cases this is achieved automatically by f . In the remaining 1.5% of the cases (76) sources, f did not find the rightful counterpart nor proposed an alternative valid counterpart. This is due to the fact that ERCI tends to give low probability of associations when optical data are either very poor or subject to source confusion. We are currently working on improving this part of the algorithm recognizing that it applies too strict criteria although only for a small minority.

An example of agreement is shown in Fig. 1 for the case of 4FGL J2221.8+3358. In the figure, the error region of the γ -ray source is shown as a purple ellipse and the 4LAC refined candidate position as a yellow circle. The f blazar candidate, which is usually unique, coincides with the 4LAC candidate. The SED of this blazar shows the multi-wavelength spectrum and the position of the synchrotron peak. It is interesting to notice that 213 sources classified as blazars in 4FGL (5.9%) were not reported in the 4LAC catalog and vice-versa 5 sources classified as blazar in 4LAC were not similarly classified in 4FGL.

In Tab. 2 we report the blazar classification obtained with f for three CLASS values: **b11**, **fsrq**, **bcu**. One can see that more than half of the 4FGL **b11** are HSPs, almost all the FSRQs are LSPs while we find that half of the 4FGL **bcus** are LSPs. We did not report the statistics for the 4FGL blazars with different classification as their contribution is minor.

The estimation of the synchrotron peak, not present in 4FGL, is instead provided in 4LAC. We report the comparison of our classification with that of 4LAC in Sec. 4.2 over our entire blazar sample.

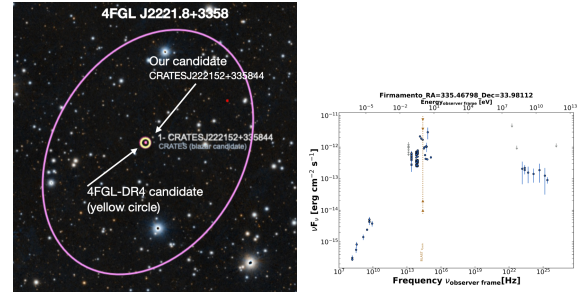


Figure 1. The most common situation exemplified by the case of 4FGL J2221.8+3358 where f and 4FGL/4LAC identify the same γ -ray blazar. Left: f proposes a single counterpart coincident with the 4LAC counterpart (yellow circle). The purple ellipse in the figure represents the 4FGL error region. Right: The SED of CRATES J222152+3335844, the counterpart of 4FGL J2221.8+3358.

$\downarrow$ 4FGL $f \rightarrow$	LSP	ISP	HSP
4FGL b11 (1407)	304 (22%)	335 (24%)	768 (55%)
4FGL fsrq (783)	763 (97%)	12 (2%)	8 (1%)
4FGL bcu (1318)	739 (56%)	202 (15%)	377 (29%)
TOT (3508)	1806 (52%)	549 (16%)	1153 (33%)

Table 2. Distribution of the f classification of the 4FGL CLASS: **b11**, **fsrq**, **bcu** blazars also identified by f .

3.2.2. Confirmed missing counterparts

For 854 4FGL sources (16.9%), we concur with 4FGL on the absence of a plausible AGN counterpart. This is partly due to the lack of availability of multi-wavelength data at least in one of the bands that characterize a blazar (e.g. X-ray or optical/infrared). In such cases, the f algorithm does not reach the threshold for plausible counterpart proposal and return a null association. We remark that if future data will be added, the same algorithm could be run again to re-evaluate the association. We remark that among these entries, 14 sources have a non-empty 4FGL_CLASS2, with the following classifications: **agn**: 8, **unk**: 5, **nlsy1**: 1.

3.2.3. Confirmed non-blazar counterparts

We confirm 20 radio galaxies in the sample, associated to extended or double-lobed radio emission, 163 Galactic sources out of which 152 are pulsars. The confirmation is based on both a morphological multi-wavelength visual check with Aladin as well as via SED inspection. We do not investigate further the properties of these non-blazars objects.

3.3. Disagreements between *Firmamento* and 4FGL

We focus here on the 569 (11.2%) sources for which there is a disagreement between f and 4FGL.

3.4. New Blazar Associations

Most of the disagreements (74%) come from the identification of 421 new associations with blazars in previously unassociated sources. These new findings result from the inclusion of recent multi-wavelength catalogs, the use of independent association algorithms based on multi-wavelength data and not solely on spatial position, and from the visual scrutiny of the SED. An example of a new association is shown in Fig. 2 for the case of 4FGLJ0122.4+1034. The candidate association lies at the border of the 4FGL error region. No other counterparts are found by f . The SED clearly reveals the blazar nature of this source. In other cases where multiple associations are proposed from f each candidate is visually scrutinized. Only in case a single blazar is found, then the association is marked as clear, otherwise as uncertain. This procedure is discussed in Sec. 3.7.

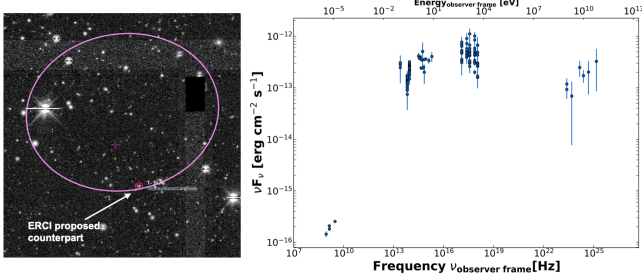


Figure 2. Example of identification of a previously unassociated source (4FGLJ0122.4+1034). Left: the 4FGLJ0122.4+1034 elliptical error region and f 's counterpart. Right: the SED of f 's candidate (1FLAT J012223.6+103213).

When comparing with 4FGL we found that a number of these counterparts were classified with $\text{ASSOC_PROB_BAY} < 0.85$ and $\text{ASSOC_PROB_LR} = 0$. For this reason they did not receive a primary association ASSOC1 , the 4FGL class designation for associated source, but 21 of them received as 4FGL.CLASS2 association, with the following distribution: **agn** (19), **sey** (1), **unk** (1). Interestingly, the source significance **Signif_Avg** distribution for these sources mimics that of the large sample, as shown in Fig. 3. We checked that 12 out of them coincides with f association. For these ASSOC_PROB_BAY ranges from 0.12 to 0.79 while $\text{ASSOC_PROB_LR} = 0$ for all of them. The classification types of the newly discovered blazars are reported in Tab. 3. One can see that the largest fractions are HSP.

A skymap displaying the new f associations (yellow stars), and 4FGL confirmed associations (gray points) is shown in Fig. 4. The sky distributions of the two datasets are similar.

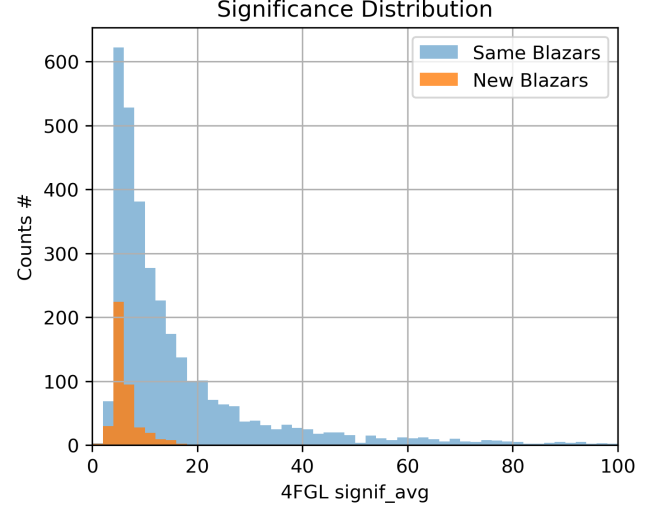


Figure 3. Distribution of the 4FGL **signif_avg** significance parameter for the confirmed blazars and the newly discovered.

$f \rightarrow$	LSP	ISP	HSP
New blazar (421)	130 (31%)	96 (23%)	195 (46%)
Different blazar (64)	17 (27%)	8 (12%)	39 (61%)

Table 3. f classification of the 4FGL unassociated and those for which we find a different blazar.

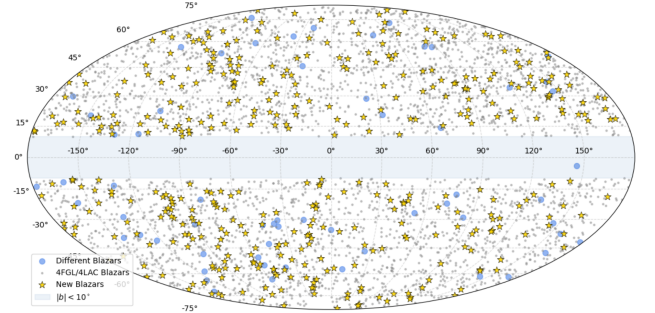


Figure 4. Skymap of 4FGL/4LAC sources (light gray) along with the 421 new blazars discovered (yellow stars symbols) and the sources assigned a different association (light blue circles).

3.5. Alternative Associations

We identified 64 cases (1.3% of the sample) where a blazar, different from the one associated in the 4FGL/4LAC catalogs, can be more confidently associated with a γ -ray source. An example is the case of 4FGL J0212.2-2259, shown in Fig. 5, where the 4FGL proposed counterpart has an SED with strong radio emission but no detectable infrared or optical flux. In contrast, the counterpart proposed by f , 3HSP J021205.7-255758, is an HSP with a well-defined SED

that closely matches the flat γ -ray spectral data from LAT.

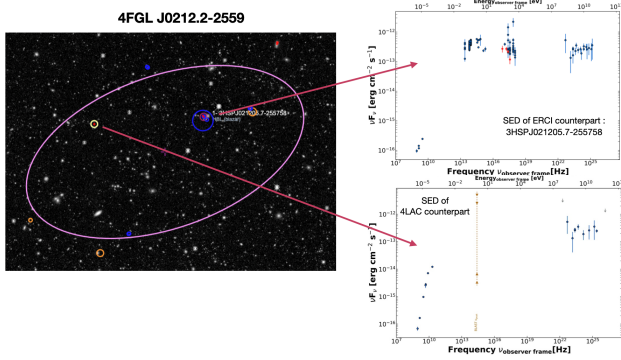


Figure 5. Example of a 4FGL proposed counterpart that is not confirmed by f , which proposed a second blazar. The 4FGL counterpart (lower SED on the right) has a strong radio but no infrared, optical or X-ray flux, the SED of the 3HSPJ021205.7-255758, the f counterpart, clearly fits well with that of an HSP counterpart.

Of these sources, in 4FGL, 47 were classified as `bcu`, 12 a `b11`, 4 as `fsrq` and 1 as `rdg`. A possible reason for this different association may be related to the fact that 4FGL uses catalog association within a spatial range, while f uses data correlation and assisted validation. The f classification of the differently associated blazars is reported in Tab. 3. Also in this case the majority of the sources are HSPs.

3.6. Non-Confirmation of 4FGL/4LAC Associations

In 49 other cases (1.0%), the 4FGL or 4LAC counterparts are considered unreliable, and ERCI did not find alternative counterparts within the error region. These source were mostly `bcus` in 4FGL_CLASS1.

3.7. Uncertain classification

We identified 16 4FGL sources with possible counterparts, but owing to limited data or uncertain SED shapes, we feel that their associations are not sufficiently secure. Most of these were again classified as `bcus` in 4FGL_CLASS1.

3.8. The 1FLAT catalog

Our findings are compiled in a catalog called 1FLAT (first Firmamento LAT AGN Table). The catalog is primarily focused on blazars, although we report some additional results to enable interested scientist to further explore our work. We instead do not list Galactic objects or non-active galaxies. In summary the 1FLAT includes:

- **Blazars:** 3,456 blazars found by f in agreement with 4FGL; 421 new f blazar associations; 64

blazars for which f finds a different blazar candidate than 4FGL

- **Uncertain:** 16 sources for which f finds an uncertain association
- **Unassociated:** 854 γ -ray sources for which both f and 4FGL do not find an association and 49 sources for which f does not find a valid association whereas 4FGL does
- **Radio galaxies:** 20 galaxies found by f in agreement with 4FGL and 18 galaxies for which f finds a different blazar candidate than 4FGL

For all f sources we report the 4FGL name, the sky coordinates RAJ2000, DEJ2000, the counterpart class CLASS, the synchrotron peak frequency and flux, `nu_syn`, `nuFnu_syn` as well as a tag field TAG that reports our internal flags reflecting the level of agreement with 4FGL.

In 1FLAT we also report basic information from 4FGL and 4LAC. For 4FGL we report the provenance fields: the name of identified or likely associated primary source ASSOC1, the class designation for associated primary source CLASS1, and corresponding secondary association ASSOC2, CLASS2, the source significance in σ units over the 50 MeV to 1 TeV band Signif.Avg, the photon index when fitting with Power Law PL_Index, the Energy flux from 100 MeV to 100 GeV obtained by spectral fitting Energy_Flux100, the Fractional variability Frac_Variability, the Probability of association according to the Bayesian method ASSOC_PROB_BAY, and the Probability of association according to the likelihood-ratio method ASSOC_PROB_LR. For 4LAC we report the provenance fields ASSOC1, CLASS, the Synchrotron-peak frequency in the observer frame `nu_syn` and the νf_ν at synchrotron-peak frequency `nuFnu_syn`.

We format 1FLAT as a FITS file. The detailed description of the FITS file is reported in App. D. A simplified version of the catalog is also available from Firmamento, which gives simple access to all the multi-frequency data and images.

3.9. Comparison with Other Association Methods

The identification of 421 new blazar associations among previously unassociated γ -ray sources represents one of the major outcomes of this work. In addition, we associate 64 sources with counterparts that differ from those reported in 4FGL, highlighting important differences with respect to the 4FGL catalog results. In the following, we briefly compare our f -based technique with the Bayesian and Likelihood Ratio methods adopted by the LAT collaboration.

The 4LAC and f methods are fundamentally different and depend on markedly different amounts of information. As detailed in Sec. 2.1, the algorithm implemented in f combines very large amount of multi-frequency data with information on source variability and spatial extension. f determines whether a given error region includes one or more sources that are likely to be blazars or other types of multi-frequency emitters through a two-step process: first it analyzes the shape of the broadband SED of all radio and X-ray sources in the requested area, constructed from approximately 50 catalogs and survey data; then, it builds a more detailed SED from approximately 90 catalogs and spectral databases (see App. A), which is visually inspected by our team to confirm or reject the candidate(s). This final human intervention will eventually be replaced by a machine learning tool trained on the results of this and similar works.

The 4FGL Bayesian and likelihood ratio methods, by contrast, rely solely on single catalogs of previously known sources—namely blazars or flat-spectrum radio sources in the Bayesian case, and radio or X-ray survey catalogs in the likelihood ratio case.

Fig. 5 exemplifies the different outcomes that can result from the application of the 4FGL and f methods. The 4FGL proposed counterpart (yellow circle and lower SED) was selected both with the Bayesian and the Likelihood ratio methods with association probability of 0.99 and 0.89, respectively. In contrast, the f method ignores the 4FGL candidate and selects instead the source named 3HSPJ021205.7-255758, which has a better overall SED. There are also cases where the 4FGL methods select reasonable candidates, whereas the f method fails to identify any. This typically occurs when the candidate is a relatively strong radio source whose SED is of the LSP type, with a very faint optical counterpart and no available X-ray data. This situation often occurs in regions of the sky where eROSITA survey data are not yet available.

Since the publication of the first LAT catalogs, a number of independent teams have also devised alternative methods to aid in the identification of unassociated γ -ray sources. Some of these approaches use machine learning techniques that rely solely on γ -ray data (D. Salvetti et al. 2017), while others combine γ -ray and X-ray data (A. Kaur et al. 2019).

To support the identification process, R. D’Abrusco et al. (2019) selected a large sample of blazar candidates based on radio data and infrared colors, while Y.-L. Chang et al. (2019) compiled a sample of high-energy-peaked blazars, many of which were expected to be detected by LAT and are indeed listed among the confirmed and newly identified blazars in the 1FLAT catalog.

More recent works have focused on the selection of samples of blazars that are detected in the very-high-energy (VHE) band (e.g. B. Arsioli et al. 2025; A. Neronov & D. Semikoz 2025). A detailed comparison between our work and these efforts — some of which are considered in the 4FGL-DR4 and 4LAC-DR3 papers — is beyond the scope of this study.

4. ANALYSIS AND DISCUSSION

The main result of this work is the discovery of 421 new blazar identifications in the 4FGL catalog. In the following we characterize this population properties.

4.1. γ -ray flux

In Fig. 6 we show the distribution of γ -ray fluxes as reported in 4FGL, `Energy_Flux100` field, for the confirmed blazars, the newly discovered and those for which we have a different classification. The confirmed blazars have a wide distribution of fluxes, reaching values as high as 10^{-9} erg cm $^{-2}$ s $^{-1}$. The newly discovered blazars and the different associations are instead less bright, with maximum flux of the order of 10^{-11} erg cm $^{-2}$ s $^{-1}$. This distribution likely reflects that these are fainter blazars and are therefore more difficult to detect and reliably associate.

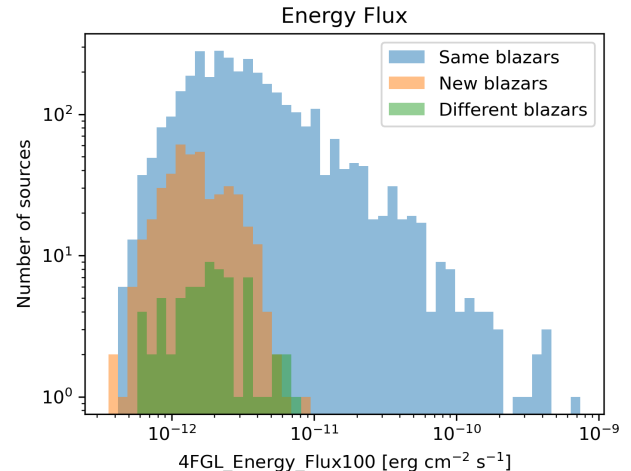


Figure 6. The distribution of the flux `Energy_Flux100` for the same, different and new blazars.

4.2. Synchrotron peak frequency and blazar classes

In this work we classify blazars as LSP if $\nu_{\text{peak}} < 10^{13.5}$ Hz, ISP if $10^{13.5} \leq \nu_{\text{peak}} < 10^{15}$ Hz and HSP if $\nu_{\text{peak}} \geq 10^{15}$ Hz (P. Giommi & P. Padovani 2021). This is slightly different from the 4LAC catalog, which uses 10^{14} Hz to separate LSP/ISP. As mentioned, we esti-

mate the synchrotron peak with two independent algorithms, **BLAST** (T. Glauch et al. 2022) and **wpeak** (P. Giommi et al. 2024a). While **BLAST** always returns an estimation of ν_{peak} , **wpeak** only provides an estimate if the flux from the host galaxy is negligible. This happens roughly half of the cases. The two estimations are consistent and compatible, with null mean difference and 5% RMSD, which suggests that the two methods are robust and their estimations accurate.

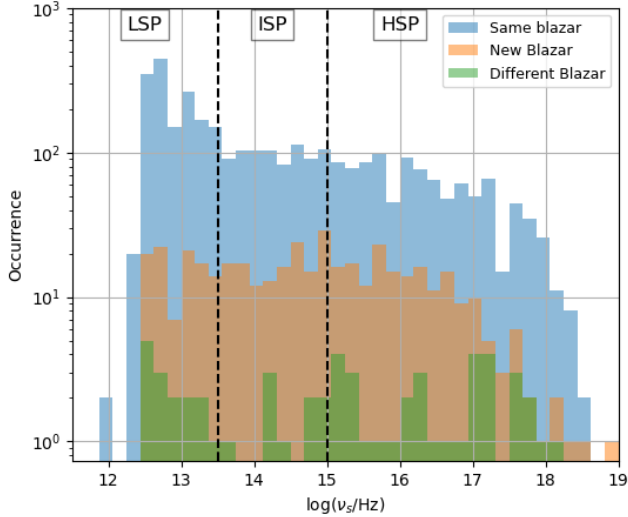


Figure 7. The distribution of the synchrotron peak frequency in the sample. Altogether, we show a total blazar population of 1,696 (43.0%) LSP, 925 (23.5%) ISP and 1,322 (33.5%) HSP.

The distribution of synchrotron peak frequencies in the 1FLAT catalog is plotted in Fig. 7 for the newly discovered blazar, those with alternative associations, and for the confirmed blazars. The overall distribution shows LSPs as the most common type, consistent with the LAT team catalogs, see Tab. 4 for details.

Table 4. Classification summary for blazars. "Same" are those that both 4FGL and f find. "New" are those found only in f . "Different" are the alternative blazar f finds with respect to 4FGL.

	Same	New	Different	All
LSP	1824 – 52.8%	130 – 30.9%	17 – 26.6%	50.0%
ISP	560 – 16.2%	96 – 22.8%	8 – 12.5%	16.8%
HSP	1072 – 31.0%	195 – 46.3%	39 – 60.9%	33.1%
Tot	3456	421	64	3941

The newly associated blazars exhibit a greater prevalence of ISPs and HSPs compared to the general population. This is very likely due to the fact that HSPs are typically found with low significance in 4FGL due to the position of the high-energy SED bump that is located at higher energies and to a low value of the Compton dominance, i.e. the ratio between the high energy and synchrotron peak. The mean values of 4FGL_ASSOC_PROB_BAY for the three blazar classes are 0.78, 0.82, and 0.92 for HSP, ISP, and LSP, respectively. On average, LSPs have the highest association probability, with a tighter spread, while HSPs have the lowest mean and the widest range.

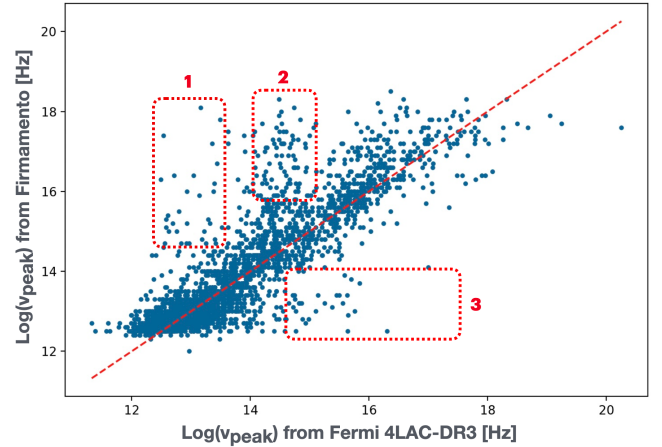


Figure 8. The $\text{Log}(\nu_{\text{peak}})$ from the LAT 4LAC catalog is plotted against the $\text{Log}(\nu_{\text{peak}})$ estimated with **BLAST** within f . The diagonal red dashed line represents equal values. The two estimates generally agree within less than one decade, however there are also large differences, highlighted by the dotted box areas labeled 1, 2 and 3 (see text for details).

Fig. 8 compares 1FLAT $\text{Log}(\nu_{\text{peak}})$ values with those estimated in the 4LAC catalog, for blazars where this parameter could be estimated in both datasets; the red diagonal line indicates equal values. The two independent estimations generally cluster around the red line, with some scatter, likely due to differences in the SED datasets available in f compared to those used in 4LAC, as well as the different estimation methods. In f , the estimation method is homogeneous, relying on a machine learning approach or a tool based on an algorithm, and thus largely independent of human intervention. We note that in Fig. 8 there are also regions, highlighted by the dotted rectangles labeled 1, 2, and 3, where significant disagreement between 4LAC and f is observed. We examined the cases where **BLAST** estimated a much larger ν_{peak} value compared to 4LAC (areas labeled 1 and 2). In all instances, the higher ν_{peak} values were

attributed to the availability of high-quality X-ray measurements, which may not have been available when the 4LAC catalog was compiled. The limited X-ray data available to 4LAC and the potential misinterpretation of X-ray data as the end of the synchrotron component, rather than as IC emission in f could explain the discrepancies observed in the area labeled 3.

4.3. Spectral properties

To further compare the sample of new associations with the confirmed associations in 4FGL, we plot in Fig. 9 the histogram of γ -ray spectral indices for the HSP and LSP blazar subsamples. The histograms show both the large sample of confirmed blazars and the newly discovered blazars, along with some relevant statistics. The distributions of γ -ray spectral indices of the new blazars appear similar to that of the confirmed blazars. Therefore we conclude that our new associations are an extension of the same type of blazars found in 4FGL rather than a new population with peculiar properties.

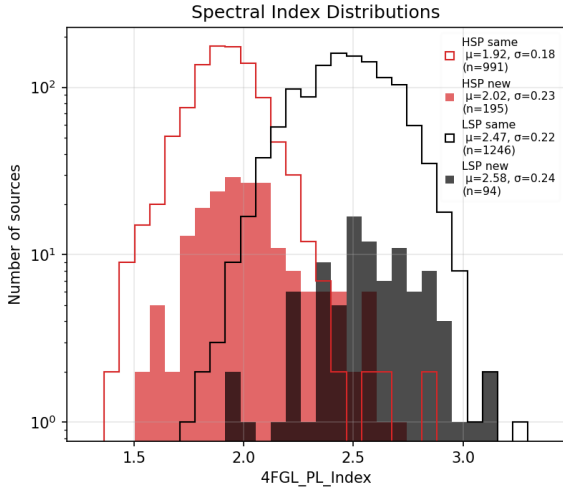


Figure 9. The distribution of 4LAC γ -ray spectral slopes in the subsamples of LSP and HSP blazars, including both confirmed and newly associated sources. Since nearly all newly associated blazars have a lower γ -ray flux than the confirmed blazars, we restrict the comparison to sources with $\text{Energy_Flux100} < 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, for consistency.

Fig. 10 shows the 4FGL photon index versus the 4FGL γ -ray flux for the confirmed, new and differently associated blazars. Again, the new population of blazars overlaps well with the general population, in the lower flux range.

5. EDUCATIONAL ENGAGEMENT

The f platform was designed with a strong commitment to inclusivity and educational engagement, align-

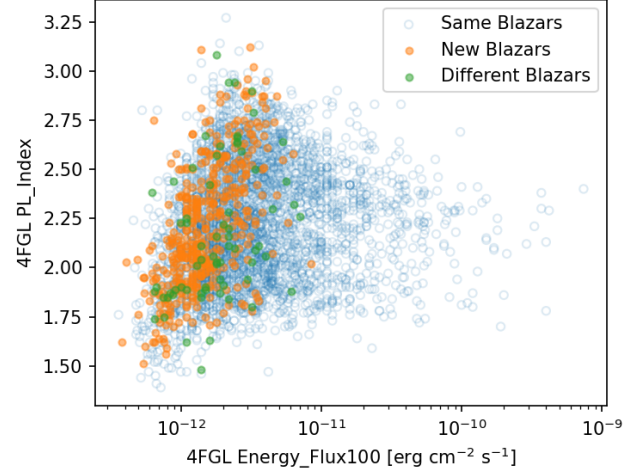


Figure 10. The power-law photon index from the 4FGL catalog is plotted against the γ -ray flux, for the cases of the confirmed associations, newly identified blazars, and with different associations. The new and different identifications are spread over the spectral index but are largely confined to γ -ray fluxes lower than $\approx 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$.

ing with the principles of the Open Universe (OU) initiative (P. Giommi et al. 2018). This commitment facilitated the active participation of both graduate and undergraduate students in the 1FLAT project. These students, some with limited or no prior experience in blazar research, played a relevant role in the analysis of LAT γ -ray sources.

The activity started with a preliminary project within the Italian Ministry of Education PCTO program¹⁴. Undergraduate students participated in the research through a series of online sessions led by experts in the field, spanning approximately six months. These sessions focused on training them in the functionalities of the f platform and the procedures for blazar discovery. This training finished with the discovery of an initial sample of 54 potential blazars among a subset of 4FGL sources. This was presented in conferences and international gatherings, and received significant media coverage and recognition, and obtained a prize in the FAST 2023 contest¹⁵. Ultimately it resulted in the peer-reviewed proceedings L. Fronte et al. (2023). f received important upgrades after that experience to

¹⁴ https://www.istruzione.it/pon/avviso_pcto.html

¹⁵ See e.g. NYUAD Citizen Researcher (2023), <https://www.instagram.com/reel/Cq-X1XaAuQY>; Firmamento Workshop (2023), <https://nyuad.nyu.edu/en/events/2023/april/firmamento-workshop.html>; La Nuova Venezia (2022), <https://l.infn.it/1bo>; INFN News (2023), <https://l.infn.it/1bn>.

improve the algorithm and the usage. We have cross-checked that now 45 out of 54 new blazars proposed in (L. Fronte et al. 2023) are also found in this work, while 9 are confirmed without associations: 4FGL J0152.9-1109, J0944.6+5729, J1409.8+7921, J1504.6+4343, J1519.7+6727, J1658.5+4315, J1706.4+6428, J2030.3-5038, J2237.8+2430, due to **Firmamento** improvement.

The process of identifying blazar in this work was extended to multiple participants, including the students that were in the pilot project. About half of the authors of this manuscript are undergraduate and they scrutinized about 38% of the sources. The classifications made by the participants were subsequently reviewed by experts in the field to ensure the accuracy and reliability of the results. This was done at random on sources that the students classified with certainty, while it was done systematically on the sources that the students labeled for further checks. These were typically sources with multiple proposed counterparts.

6. DISCUSSION AND CONCLUSIONS

In this study, we have presented the 1FLAT, an independently derived catalog of blazar counterparts of high-Galactic latitude γ -ray sources in the LAT 4FGL catalog, constructed using the *f* web-based platform. Our results showed a high level of agreement (over 88%) with the associations reported in the 4FGL and 4LAC catalogs, but also significant differences. A key finding of this work is the identification of 421 new credible blazar associations for previously unassociated γ -ray sources in the 4FGL catalog. This significantly reduces the fraction of unidentified high-Galactic latitude LAT sources from approximately 25% to 17%. We also identified 64 alternative blazar counterparts and found 49 cases where the 4FGL/4LAC association was not confirmed.

The 1FLAT catalog, with its refined and expanded list of AGN counterparts of LAT γ -ray sources, has several important astrophysical implications. The increased number of identified blazars, particularly HSPs and ISPs among the previously unassociated sources, contributes to a more complete understanding of the γ -ray emitting blazar population. The detailed SED information and synchrotron peak parameter estimates provided in the catalog are valuable for detailed population studies and help modeling the physical processes within relativistic jets.

However, the methodology employed in this work also has limitations. While *f* leverages a vast amount of multi-frequency data and sophisticated tools, the identification of counterparts may still be challenging in large error regions, crowded fields, or when multi-wavelength data are sparse or of poor quality. Also, the reliance

on visual inspection of SEDs, while allowing for expert judgment, can introduce a degree of subjectivity.

Potential biases in the new associations should also be considered. For instance, if our method is more sensitive to blazars with specific multi-wavelength properties, this could lead to a biased representation of the overall unassociated source population.

Future studies could address these limitations and further enhance the 1FLAT catalog. Incorporating quantitative variability measures in a more systematic way could improve the robustness of the process. In addition, developing more sophisticated machine-learning techniques for automated SED classification and counterpart association would further enhance its efficiency. The upcoming release of the full eROSITA X-ray survey data is expected to significantly aid in identifying counterparts for currently unassociated γ -ray sources, providing an opportunity to further validate and expand the 1FLAT catalog.

Finally, we note that a systematic analysis of redshift distributions was not attempted in this work, as reliable spectroscopic information is only available for a subset of the sources. Since the main focus here is on counterpart associations, we defer a comprehensive redshift study to a future dedicated publication.

In summary, the 1FLAT catalog, available online through the *f* platform, provides a complementary and independently derived list of AGN associated with LAT γ -ray sources. It is intended as a useful reference for very-high-energy γ -ray observations, multi-wavelength campaigns, and studies of γ -ray-emitting AGN, particularly in view of the significant number of new associations presented here.

DATA AVAILABILITY

All the data used in this paper is public and available via the *f* and other platforms.

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REFERENCES

- Abdo, A., Ackermann, M., Agudo, I., et al. 2010, *ApJ*, 716, 30, doi: [10.1088/0004-637X/716/1/30](https://doi.org/10.1088/0004-637X/716/1/30)
- Abdo, A. A., et al. 2013, *ApJS*, 208, 17
- Abdollahi, S., Acero, F., Ackermann, M., et al. 2020, *The Astrophysical Journal Supplement Series*, 247, 33, doi: [10.3847/1538-4365/ab6bcb](https://doi.org/10.3847/1538-4365/ab6bcb)
- Abdollahi, S., Acero, F., Baldini, L., et al. 2022, *ApJS*, 260, 53, doi: [10.3847/1538-4365/ac6751](https://doi.org/10.3847/1538-4365/ac6751)
- Abell, G. O., et al. 1989, *ApJS*, 70, 1
- Abolfathi, B., et al. 2018, *ApJS*, 235, 42
- Ajello, M., et al. 2017, *ApJS*, 232, 18
- Ajello, M., Baldini, L., Ballet, J., et al. 2022, *ApJS*, 263, 24, doi: [10.3847/1538-4365/ac9523](https://doi.org/10.3847/1538-4365/ac9523)
- Arsioli, B., Chang, Y.-L., & Ighina, L. 2025, *MNRAS*, 539, 1458, doi: [10.1093/mnras/staf329](https://doi.org/10.1093/mnras/staf329)
- Arsioli, B., Chang, Y. L., & Musiimenta, B. 2020, *MNRAS*, 493, 2438, doi: [10.1093/mnras/staa368](https://doi.org/10.1093/mnras/staa368)
- Avakyan, A., et al. 2023, *A&A*, 675, A199
- Ballet, J., Bruel, P., Burnett, T. H., & Lott, B. 2023, <https://arxiv.org/abs/2307.12546>
- Beckmann, V., & Shrader, C. 2012, *Active Galactic Nuclei* (Wiley-VCH). <https://www.wiley.com/en-au/Active+Galactic+Nuclei-p-9783527666805>
- Blanton, M. R., et al. 2017, *AJ*, 154, 28
- Bonato, M., Liuzzo, E., Herranz, D., et al. 2019, *MNRAS*, 485, 1188, doi: [10.1093/mnras/stz465](https://doi.org/10.1093/mnras/stz465)
- Bonning, E., Urry, C. M., Bailyn, C., et al. 2012, *ApJ*, 756, 13, doi: [10.1088/0004-637X/756/1/13](https://doi.org/10.1088/0004-637X/756/1/13)
- Brunner, H., et al. 2022, *A&A*, 661, A1
- Bulgarelli, A., et al. 2019, *VizieR Online Data Catalog*
- Callingham, J. R., Ekers, R. D., Gaensler, B. M., et al. 2017, *ApJ*, 836, 174, doi: [10.3847/1538-4357/836/2/174](https://doi.org/10.3847/1538-4357/836/2/174)
- Chang, Y. L., Brandt, C. H., & Giommi, P. 2020, *Astronomy and Computing*, 30, 100350, doi: [10.1016/j.ascom.2019.100350](https://doi.org/10.1016/j.ascom.2019.100350)
- Chang, Y.-L., et al. 2019, *A&A*, 632, A77
- Collaboration, P. 2016, *A&A*, 594, A27
- Condon, J. J., et al. 1998, *AJ*, 115, 1693
- Cutri, R. M., et al. 2012, *VizieR Online Data Catalog*, II
- D’Abrusco, R., Álvarez Crespo, N., Massaro, F., et al. 2019, *ApJS*, 242, 4, doi: [10.3847/1538-4365/ab16f4](https://doi.org/10.3847/1538-4365/ab16f4)
- De Breuck, C., Tang, Y., de Bruyn, A. G., Röttgering, H., & van Breugel, W. 2002, *A&A*, 394, 59, doi: [10.1051/0004-6361:20021115](https://doi.org/10.1051/0004-6361:20021115)
- Dermer, C. D., & Menon, G. 2009, *High Energy Radiation from Black Holes: Gamma Rays, Cosmic Rays, and Neutrinos* (Princeton University Press)
- Doro, M., Nigro, C., Prandini, E., et al. 2021, *PoS, ICRC2019*, 666, doi: [10.22323/1.358.0666](https://doi.org/10.22323/1.358.0666)
- Douglas, J. N., Bash, F. N., Bozayan, F. A., Torrence, G. W., & Wolfe, C. 1996, *AJ*, 111, 1945, doi: [10.1086/117932](https://doi.org/10.1086/117932)
- Duchesne, S. W., et al. 2024, *PASA*, 41, e003
- Eisenhardt, P. R. M., Marocco, F., Fowler, J. W., et al. 2020, *ApJS*, 247, 69, doi: [10.3847/1538-4365/ab7f2a](https://doi.org/10.3847/1538-4365/ab7f2a)
- Elvis, M., et al. 1992, *ApJS*, 80, 257
- Evans, I. N., et al. 2010, *ApJS*, 189, 37
- Evans, P. A., et al. 2020, *ApJS*, 247, 54
- Everett, W. B., Zhang, L., Crawford, T. M., et al. 2020, *ApJ*, 900, 55, doi: [10.3847/1538-4357/ab9df7](https://doi.org/10.3847/1538-4357/ab9df7)
- Flesch, E. W. 2015, *PASA*, 32, e010
- Fronte, L., Mazzon, B., Metruccio, F., et al. 2023, *Journal of Physics: Conference Series*, 2429, 012045, doi: [10.1088/1742-6596/2429/1/012045](https://doi.org/10.1088/1742-6596/2429/1/012045)
- Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al. 2023, *A&A*, 674, A1, doi: [10.1051/0004-6361/202243940](https://doi.org/10.1051/0004-6361/202243940)
- Giommi, P. 2025, in *Proceedings of the 8th Heidelberg γ -ray symposium, Milan*, Vol. Accepted for publication. <https://arxiv.org/abs/2503.04434>
- Giommi, P., Capalbi, M., Fiocchi, M., et al. 2002, in *Blazar Astrophysics with BeppoSAX and Other Observatories*, ed. P. Giommi, E. Massaro, & G. Palumbo, 63, doi: [10.48550/arXiv.astro-ph/0209596](https://doi.org/10.48550/arXiv.astro-ph/0209596)
- Giommi, P., & Padovani, P. 2021, *Universe*, 7, 492, doi: [10.3390/universe7120492](https://doi.org/10.3390/universe7120492)
- Giommi, P., Sahakyan, N., Israyelyan, D., & Manvelyan, M. 2024a, *Astrophys. J.*, 963, 48, doi: [10.3847/1538-4357/ad20cb](https://doi.org/10.3847/1538-4357/ad20cb)
- Giommi, P., Arrigo, G., Barres de Almeida, U., et al. 2018, in *ESPI-UNISPACE+50, Vol. Space 2030 and Space 4.0: Synergies for Capacity Building in the XXI Century*. <https://arxiv.org/abs/1805.08505>
- Giommi, P., et al. 2024b, in preparation

- Glauch, T., Kersch, T., & Giommi, P. 2022, *Astronomy and Computing*, 41, 100646, doi: [10.1016/j.ascom.2022.100646](https://doi.org/10.1016/j.ascom.2022.100646)
- Gordon, Y. A., Boyce, M. M., O’Dea, C. P., et al. 2020, *Research Notes of the AAS*, 4, 175
- Green, D. A. 2025, *J. Astrophys. Astron.*, 46, 1
- Gregory, P. C., & Condon, J. J. 1991, *ApJS*, 75, 1011, doi: [10.1086/191559](https://doi.org/10.1086/191559)
- Gregory, P. C., Scott, W. K., Douglas, K., & Condon, J. J. 1996, *ApJS*, 103, 427, doi: [10.1086/192282](https://doi.org/10.1086/192282)
- Hale, C. L., et al. 2021, arXiv preprint arXiv:2109.00956
- Harris, D. E., et al. 1990, Cambridge
- Healey, S. E., et al. 2007, *ApJS*, 171, 61
- Helfand, D. J., White, R. L., & Becker, R. H. 2015, *ApJ*, 801, 26
- Helou, G., & Walker, D. W., eds. 1988, *Infrared Astronomical Satellite (IRAS) Catalogs and Atlases. Volume 7: The Small Scale Structure Catalog*, Vol. 7
- Hurley-Walker, N., Callingham, J. R., Hancock, P. J., et al. 2017, *MNRAS*, 464, 1146, doi: [10.1093/mnras/stw2337](https://doi.org/10.1093/mnras/stw2337)
- Intema, H. T., Jagannathan, P., Mooley, K. P., & Frail, D. A. 2017, *A&A*, 598, A78, doi: [10.1051/0004-6361/201628536](https://doi.org/10.1051/0004-6361/201628536)
- Jones, D. H., et al. 2009, *MNRAS*, 399, 683
- Kaur, A., Falcone, A. D., Stroh, M. D., Kennea, J. A., & Ferrara, E. C. 2019, *ApJ*, 887, 18, doi: [10.3847/1538-4357/ab4ceb](https://doi.org/10.3847/1538-4357/ab4ceb)
- Kharchenko, N. V., et al. 2013, *A&A*, 558, A53
- Kube, J., et al. 2003, *A&A*, 404, 1159
- Kuehr, H., Witzel, A., Pauliny-Toth, I. I. K., & Nauber, U. 1981, *A&AS*, 45, 367
- Lane, W. M., Cotton, W. D., van Velzen, S., et al. 2014, *MNRAS*, 440, 327, doi: [10.1093/mnras/stu256](https://doi.org/10.1093/mnras/stu256)
- Lasker, B. M., et al. 2008, *AJ*, 136, 735
- Lien, A. Y., Krimm, H. A., Markwardt, C. B., et al. 2025, *ApJ*, 989, 161, doi: [10.3847/1538-4357/ade676](https://doi.org/10.3847/1538-4357/ade676)
- Liu, T., et al. 2015, *VizieR Online Data Catalog*
- Maddox, S. J., Valiante, E., Cigan, P., et al. 2018, *ApJS*, 236, 30, doi: [10.3847/1538-4365/aab8fc](https://doi.org/10.3847/1538-4365/aab8fc)
- Magnier, E. A., Schlafly, E. F., Finkbeiner, D. P., et al. 2020, *ApJS*, 251, 6, doi: [10.3847/1538-4365/abb82a](https://doi.org/10.3847/1538-4365/abb82a)
- Mainzer, A., Bauer, J., Cutri, R. M., et al. 2014, *ApJ*, 792, 30, doi: [10.1088/0004-637X/792/1/30](https://doi.org/10.1088/0004-637X/792/1/30)
- Manch, B., et al. 2003, *MNRAS*, 342, 1117
- Manchester, R. N., et al. 2005, *AJ*, 129, 1993
- Masci, F. J., Laher, R. R., Rusholme, B., et al. 2019, *PASP*, 131, 018003, doi: [10.1088/1538-3873/aae8ac](https://doi.org/10.1088/1538-3873/aae8ac)
- Massardi, M., Bonaldi, A., Bonavera, L., et al. 2016, *MNRAS*, 455, 3249, doi: [10.1093/mnras/stv2561](https://doi.org/10.1093/mnras/stv2561)
- Massaro, E., et al. 2015, *Ap&SS*, 357, 1
- McConnell, D., Sadler, E. M., Murphy, T., & Ekers, R. D. 2012, *MNRAS*, 422, 1527, doi: [10.1111/j.1365-2966.2012.20726.x](https://doi.org/10.1111/j.1365-2966.2012.20726.x)
- Mehrtens, N., Romer, A. K., Hilton, M., et al. 2012, *MNRAS*, 423, 1024, doi: [10.1111/j.1365-2966.2012.20931.x](https://doi.org/10.1111/j.1365-2966.2012.20931.x)
- Merloni, A., et al. 2024, *A&A*, 682, A34
- Middei, R., Giommi, P., Perri, M., et al. 2022, *MNRAS*, 514, 3179, doi: [10.1093/mnras/stac1185](https://doi.org/10.1093/mnras/stac1185)
- Miville-Deschênes, M.-A., et al. 2017, *ApJ*, 834, 57
- Monet, D. G., Levine, S. E., Canzian, B., et al. 2003, *AJ*, 125, 984, doi: [10.1086/345888](https://doi.org/10.1086/345888)
- Morrissey, P., Conrow, T., Barlow, T. A., et al. 2007, *ApJS*, 173, 682, doi: [10.1086/520512](https://doi.org/10.1086/520512)
- Mufakharov, T., Mingaliev, M., Sotnikova, Y., Naiden, Y., & Erkenov, A. 2015, *MNRAS*, 450, 2658, doi: [10.1093/mnras/stv772](https://doi.org/10.1093/mnras/stv772)
- Murphy, T., Sadler, E. M., Ekers, R. D., et al. 2010, *MNRAS*, 402, 2403, doi: [10.1111/j.1365-2966.2009.15961.x](https://doi.org/10.1111/j.1365-2966.2009.15961.x)
- Neronov, A., & Semikoz, D. 2025, arXiv e-prints, arXiv:2506.08497, doi: [10.48550/arXiv.2506.08497](https://doi.org/10.48550/arXiv.2506.08497)
- Norris, R. P., Marvil, J., Collier, J. D., et al. 2021, *PASA*, 38, e046, doi: [10.1017/pasa.2021.42](https://doi.org/10.1017/pasa.2021.42)
- Onken, C. A., Wolf, C., Bessell, M. S., et al. 2024, *PASA*, 41, e061, doi: [10.1017/pasa.2024.53](https://doi.org/10.1017/pasa.2024.53)
- Padovani, P., & Giommi, P. 1995, *Astrophys. J.*, 444, 567, doi: [10.1086/175631](https://doi.org/10.1086/175631)
- Padovani, P., Alexander, D. M., Assef, R. J., et al. 2017, *A&A Rv*, 25, 2, doi: [10.1007/s00159-017-0102-9](https://doi.org/10.1007/s00159-017-0102-9)
- Page, M. J., Brindle, C., Talavera, A., et al. 2012, *MNRAS*, 426, 903, doi: [10.1111/j.1365-2966.2012.21706.x](https://doi.org/10.1111/j.1365-2966.2012.21706.x)
- Panzer, M. R., et al. 2003, *A&A*, 399, 351
- Piffaretti, R., et al. 2011, *A&A*, 534, A109
- Planck Collaboration, Akrami, Y., Argüeso, F., et al. 2018, *A&A*, 619, A94, doi: [10.1051/0004-6361/201832888](https://doi.org/10.1051/0004-6361/201832888)
- Principe, G., & others. 2018, *A&A*, 618, A22
- Reuter, H. P., Kramer, C., Sievers, A., et al. 1997, *A&AS*, 122, 271, doi: [10.1051/aas:1997333](https://doi.org/10.1051/aas:1997333)
- Sahakyan, N., Vardanyan, V., Giommi, P., et al. 2024, *AJ*, 168, 289, doi: [10.3847/1538-3881/ad8231](https://doi.org/10.3847/1538-3881/ad8231)
- Salveti, D., Chiaro, G., La Mura, G., & Thompson, D. J. 2017, *MNRAS*, 470, 1291, doi: [10.1093/mnras/stx1328](https://doi.org/10.1093/mnras/stx1328)
- Saxton, R. D., et al. 2008, *A&A*, 480, 611
- Sazonov, S., Burenin, R., Filippova, E., et al. 2024, *A&A*, 687, A183, doi: [10.1051/0004-6361/202348950](https://doi.org/10.1051/0004-6361/202348950)
- Schlafly, E. F., et al. 2019, *ApJS*, 240, 30
- Shimwell, T. W., Tasse, C., Hardcastle, M. J., et al. 2019, *A&A*, 622, A1, doi: [10.1051/0004-6361/201833559](https://doi.org/10.1051/0004-6361/201833559)

- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, 131, 1163, doi: [10.1086/498708](https://doi.org/10.1086/498708)
- Stein, Y., Vollmer, B., Boch, T., et al. 2021, *A&A*, 655, A17, doi: [10.1051/0004-6361/202039659](https://doi.org/10.1051/0004-6361/202039659)
- Tripathi, D., Giommi, P., Di Giovanni, A., et al. 2024, *AJ*, 167, 116, doi: [10.3847/1538-3881/ad216a](https://doi.org/10.3847/1538-3881/ad216a)
- Valiante, E., Smith, M. W. L., Eales, S., et al. 2016, *MNRAS*, 462, 3146, doi: [10.1093/mnras/stw1806](https://doi.org/10.1093/mnras/stw1806)
- Voges, W., et al. 2000, *IAU Circ.*, 7432, 3
- Webb, N. A., et al. 2020, *A&A*, 641, A136
- Whipple, F. L. 1966, *Smithsonian Astrophysical Observatory Star Catalog*
- White, N. E., et al. 2000, *VizieR Online Data Catalog*, IX/31
- White, R. L., & Becker, R. H. 1992, *ApJS*, 79, 331, doi: [10.1086/191656](https://doi.org/10.1086/191656)
- White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, *ApJ*, 475, 479
- Wright, A. E., Griffith, M. R., Burke, B. F., & Ekers, R. D. 1994, *ApJS*, 91, 111, doi: [10.1086/191939](https://doi.org/10.1086/191939)
- Yamamura, I., Makiuti, S., Ikeda, N., et al. 2010,, *VizieR On-line Data Catalog: II/298*. Originally published in: *ISAS/JAXA* (2010)
- Ye, H., Sweijen, F., van Weeren, R. J., et al. 2024, *A&A*, 691, A347, doi: [10.1051/0004-6361/202348103](https://doi.org/10.1051/0004-6361/202348103)
- Zwicky, F., Herzog, E., & Wild, P. 1968, *California Institute of Technology (CIT)*

APPENDIX

A. MULTI-FREQUENCY SURVEY

The SEDs as well as the multi-wavelength skymaps, in the version of f used for this work, are obtained from openly accessible catalogs and survey data, reported in Tab. 5. Overall we consult 26 catalogs in Radio/Microwave, 9 in Infrared, 10 in Optical/Ultraviolet, 20 in X-rays, 9 in Gamma-rays, and other 16, for a total of 90 catalogs.

Table 5. Catalogs and surveys used by f : Radio- γ -ray and other catalogs. Flag: E = used in ERCI, S = used in generating SED. (Ordered by wavelength range and alphabetical within subgroups).

Catalog name and description	Reference	Flag
Radio/Microwave		
☐ ALMA – ALMA photometry of extragalactic radio sources	M. Bonato et al. (2019)	S
☐ AT20G – The Australia Telescope 20 GHz Survey	T. Murphy et al. (2010)	S
☐ ATPMN – 5 and 8 GHz data from PMN survey	D. McConnell et al. (2012)	S
☐ CRATES – Candidate Radio and AGN Source Survey	S. E. Healey et al. (2007)	E
☐ EMU – Evolutionary Map of the Universe	R. P. Norris et al. (2021)	E+S
☐ EPRS – Extragalactic Radio Sources at Low Frequencies	J. R. Callingham et al. (2017)	S
☐ FIRST – Faint Images of the Radio Sky at Twenty-Centimeters	D. J. Helfand et al. (2015); R. L. White et al. (1997)	E+S
☐ GB6 – Green Bank 6cm survey	P. C. Gregory et al. (1996)	E+S
☐ GB87 – 87GB Catalog of radio sources	P. C. Gregory & J. J. Condon (1991)	S
☐ GLEAMV2 – All-sky Murchison Widefield Array (GLEAM) survey	N. Hurley-Walker et al. (2017)	S
☐ KUEHR – Radio Sources with $F_r > 1\text{Jy}$	H. Kuehr et al. (1981)	S
☐ LOFAR – The LOFAR 120 to 168 MHz observations	H. Ye et al. (2024)	S
☐ LoTSS – The LOFAR Two-metre Sky Survey	T. W. Shimwell et al. (2019)	S
☐ MM-MONITORING – mm measurements of extragalactic sources	H. P. Reuter et al. (1997)	S
☐ NORTH20 – Green Bank 1.4 GHz Northern Sky Survey	R. L. White & R. H. Becker (1992)	S
☐ NVSS – NRAO VLA Sky Survey	J. J. Condon et al. (1998)	E+S
☐ PACO – Planck-ATCA Co-eval Observations	M. Massardi et al. (2016)	S
☐ PCNT – Planck multi-frequency catalog	Planck Collaboration et al. (2018)	S
☐ PMN – Parkes-MIT-NRAO survey	A. E. Wright et al. (1994)	E+S
☐ RACS/RACSMID/RACSHIGH – Rapid ASKAP Continuum low, mid and high frequency surveys	C. L. Hale et al. (2021); S. W. Duchesne et al. (2024)	E+S
☐ RATAN600 – radio observations of Fermi blazars	T. Mufakharov et al. (2015)	S
☐ SPECFIND – SPECFIND V3 catalog of radio sources	Y. Stein et al. (2021)	S
☐ SUMSS – Sydney University Molonglo Sky Survey	B. Manch et al. (2003)	E+S
☐ TEXAS – Texas Survey of Radio Sources	J. N. Douglas et al. (1996)	S
☐ VLASSQL – VLA Sky Survey 3GHz, Quick Look	Y. A. Gordon et al. (2020)	E+S
☐ VLSSR – VLA Low-frequency Sky Survey Redux	W. M. Lane et al. (2014)	S
☐ WISH – Westerbork survey	C. De Breuck et al. (2002)	S
☐ TGSS150 – The GMRT 150 MHz all-sky radio survey	H. T. Intema et al. (2017)	S
Infrared		
☐ 2MASS – Two Micron All Sky Survey	M. F. Skrutskie et al. (2006)	E+S
☐ AKARIBSC – AKARI/FIS All-Sky Survey Point Source Catalogue	I. Yamamura et al. (2010)	S
☐ CatWISE – WISE	P. R. M. Eisenhardt et al. (2020)	S
☐ H-ATLAS-DR1 – Herschel-ATLAS DR1	E. Valiante et al. (2016)	S
☐ H-ATLAS-DR2 – Herschel-ATLAS DR2 Galactic poles	S. J. Maddox et al. (2018)	S
☐ IRAS-PSC – IRAS catalogue of Point Sources	G. Helou & D. W. Walker (1988)	S
☐ SMARTS – Opt+IR monitoring of blazars	E. Bonning et al. (2012)	S
☐ UnWISE – WISE	E. F. Schlafly et al. (2019)	E+S
☐ WISE – Wide-field Infrared Survey Explorer	R. M. Cutri et al. (2012)	S
Optical/Ultraviolet		
☐ 6DF – Six-degree Field Galaxy Survey	D. H. Jones et al. (2009)	S

Table 5 continued

Table 5 (continued)

Catalog name and description	Reference	Flag
☐ GAIA3 – Gaia DR3	Gaia Collaboration et al. (2023)	E+S
☐ GALEX – Galaxy Evolution Explorer UV catalog	P. Morrissey et al. (2007)	S
☐ HSTGSC – Hubble Guide Star Catalog	B. M. Lasker et al. (2008)	E+S
☐ PanSTARRS – PanSTARRS DR2	E. A. Magnier et al. (2020)	E+S
☐ SDSS – Sloan Digital Sky Survey DR19	M. R. Blanton et al. (2017); B. Abolfathi et al. (2018)	E+S
☐ Skymapper – Skymapper Southern Survey Data Release 4	C. A. Onken et al. (2024)	S
☐ SWIFTUVOT-MMDC – Swift optical/UV monitor	N. Sahakyan et al. (2024)	S
☐ USNO – The USNO-B Catalog	D. G. Monet et al. (2003)	E+S
☐ XMMOM – XMM optical monitor	M. J. Page et al. (2012)	S
X-rays		
☐ 2SXPS – Swift-XRT Point Source Catalog	P. A. Evans et al. (2020)	E+S
☐ 4XMM-DR14 – XMM-Newton 4th Source Catalog	N. A. Webb et al. (2020)	E+S
☐ 1OUSX – 1st Open Universe Soft X-ray Catalog	P. Giommi et al. (2024b)	E+S
☐ BAT157 – Swift-BAT 157 months	A. Y. Lien et al. (2025)	S
☐ BeppoSAX – BeppoSAX spectra of blazars	P. Giommi et al. (2002)	S
☐ BMW – Brera Multi-scale Wavelet ROSAT HRI Catalog	M. R. Panzera et al. (2003)	E+S
☐ CSC2.1 – Chandra Source Catalog Version 2.1	I. N. Evans et al. (2010)	E+S
☐ eFEDS – eROSITA Final Equatorial Depth Survey	H. Brunner et al. (2022)	E+S
☐ eRASS1 – eROSITA All-Sky Survey	A. Merloni et al. (2024)	E+S
☐ eRASS1-S – eROSITA All-Sky Survey South Subset	A. Merloni et al. (2024)	E+S
☐ IPC2E – Einstein IPC X-ray Source Catalog	D. E. Harris et al. (1990)	E+S
☐ IPCSL – Einstein IPC Slew Survey	M. Elvis et al. (1992)	S
☐ NuBlazar – Open Universe NuSTAR blazars spectra	R. Middei et al. (2022)	S
☐ RASS – ROSAT All-Sky Survey	W. Voges et al. (2000)	E+S
☐ SRG/ART-XC all-sky X-ray survey	S. Sazonov et al. (2024)	S
☐ SUFST – Swift-XRT ultra-fast analysis	Casotto et al. 2025	S
☐ SWIFTXRT-MMDC – Swift XRT spectra of blazars	N. Sahakyan et al. (2024)	S
☐ SWXCS – Swift X-ray Cluster Survey	T. Liu et al. (2015)	E
☐ XCS – XMM X-Ray Cluster Survey	N. Mehrtens et al. (2012)	E
☐ XMMSL3 – XMM-Newton Slew Survey Catalog DR3	R. D. Saxton et al. (2008)	E+S
☐ WGACAT – ROSAT PSPC Catalog	N. E. White et al. (2000)	E+S
Gamma-rays		
☐ 1FLE – LAT catalog below 100 MeV	G. Principe & others. (2018)	S
☐ 2AGILE – AGILE 2nd Gamma-ray Source Catalog	A. Bulgarelli et al. (2019)	S
☐ 2BIGB – Catalog of HSP γ -ray blazars	B. Arsioli et al. (2020)	S
☐ 3FHL – LAT 3rd Hard Source Catalog	M. Ajello et al. (2017)	E+S
☐ 4FGL-DR3 – LAT 4th Source Catalog DR3	S. Abdollahi et al. (2022)	S
☐ 4FGL-DR4 – LAT 4th Source Catalog DR4	J. Ballet et al. (2023)	E+S
☐ 4LAC-DR3 – LAT 4th AGN Catalog	M. Ajello et al. (2022)	E
☐ FERMI-LAT-MMDC – Fermi-LAT spectra	N. Sahakyan et al. (2024)	S
☐ MAGIC – Spectral data from selected papers	M. Doro et al. (2021)	S
Multiwavelength / Known sources / Other		
☐ 3HSP – High Synchrotron Peaked Blazar Catalog	Y.-L. Chang et al. (2019)	E
☐ 5BZCat – 5th edition of the Roma-BZCAT	E. Massaro et al. (2015)	E
☐ ABELL – Abell Catalog of Rich Clusters of Galaxies	G. O. Abell et al. (1989)	E
☐ CVCAT – Cataclysmic Variable Catalog	J. Kube et al. (2003)	E
☐ Fermi3PSR – Third LAT Gamma-Ray Pulsar Catalog	A. A. Abdo et al. (2013)	E
☐ MCXC – Catalog of X-ray detected Clusters	R. Piffaretti et al. (2011)	E
☐ PULSAR – ATNF Pulsar Catalog	R. N. Manchester et al. (2005)	E
☐ PSZ2 – Second Planck SZ Catalog	P. Collaboration (2016)	E
☐ RASS – ROSAT All-Sky Survey	W. Voges et al. (2000)	E
☐ SAO – Smithsonian Astrophysical Observatory Star Catalog	F. L. Whipple (1966)	E
☐ SNRGREEN – Green’s Supernova Remnant Catalog	D. A. Green (2025)	E
☐ SPTSZ – SPT-SZ Survey	W. B. Everett et al. (2020)	E

Table 5 continued

Table 5 (continued)

Catalog name and description	Reference	Flag
☐ MilliQuas – Million Quasars Catalog	E. W. Flesch (2015)	E
☐ MWMC – Milky Way Molecular Clouds	M.-A. Miville-Deschênes et al. (2017)	E
☐ MWSC – Milky Way Stellar Clusters	N. V. Kharchenko et al. (2013)	E
☐ XRBCAT – X-ray binaries catalog	A. Avakyan et al. (2023)	E
☐ ZWCLUSTERS – Zwicky Cluster Catalog	F. Zwicky et al. (1968)	E

B. STEP BY STEP PROCEDURE FOR SOURCE ASSOCIATION

Hereafter we list the step-by-step procedure used for source association for this work

1. From the *f* portal, load the 4FGL catalog of high-latitude sources with **Data Access--> User Input --> Import a new table** command, see Fig. 11. The file, properly formatted contain information such as source name, positional error, association name.

#	name	ra	dec	fov	major	minor	angle	comment	pick
2088	4FGL J1014.8-0537	153.716	-5.6222	10.234	7.872	5.706	-47	AT20G J101446-054049 153.69185 -5.67970	pick
2089	4FGL J1015.0+4926	153.768	49.4336	0.679	0.522	0.516	22.1	1H 1013+498 153.76725 49.43353	pick
2090	4FGL J1015.6+5553	153.9105	55.8893	5.515	4.242	3.684	-12.6	TXS 1012+560 153.93507 55.85017	pick
2091	4FGL J1016.0+0512	154.0093	5.2089	1.583	1.218	1.158	22.4	TXS 1013+054 154.01307 5.21732	pick
2092	4FGL J1016.1-4247	154.0399	-42.7854	2.894	2.226	1.998	19	No 4FGL counterpart	pick
2093	4FGL J1016.4+7703	154.1099	77.06	4.898	3.768	3.354	-62.4	1RXS J101647.6+770239 154.19833 77.04430	pick
2094	4FGL J1016.5-2650	154.1403	-26.8434	4.742	3.648	3.324	39.6	NVSS J101634-265057 154.14458 -26.84994	pick
2095	4FGL J1016.8-0606	154.2038	-6.1059	5.359	4.122	3.72	-29.3	No 4FGL counterpart	pick
2096	4FGL J1017.2-1549	154.3184	-15.8274	4.657	3.582	2.574	89.6	NVSS J101718-154933 154.32463 -15.82600	pick
2097	4FGL J1017.3+5204	154.3484	52.0726	8.12	6.246	4.302	36.3	7C 1013+5217 154.27779 52.04644	pick

Figure 11. Table for 5,063 LAT 4FGL catalog sources of interest, uploaded on the *f* platform for counterpart search.

2. By using the command **pick**, select the source. This automatically launches the ERCI algorithm for candidate identification. Because *f* stores previous searches on a specific source direction, it is possible to **Force run** to re-run the procedure from scratch. During this step, freely accessible multi-wavelength online catalogs are parsed. In case the catalog is not available during a first call, further two calls are made on the specific catalog. The availability of external catalogs is not always guaranteed by their providers; for this reason, *f* is evolving toward a version in which the multi-wavelength catalogs are, whenever possible, stored locally. As an output, *f* provides zero, one or more plausible candidate associations. This is shown in Fig. 12 (left).
3. A comparison is made with LAT catalogs (4FGL, 4LAC) and sources are classified based on the LAT proposed localization, the *f* proposed location, the check of SEDs at these localization (using option **Get SED data**) and if needed by the inspection of the **Aladin** multi-wavelength sky maps. See Fig. 12 (center).
4. On the select source, **Get SED data** automatically run **blast** and **wpeak**. The output values of the synchrotron peak and flux are recorded. See Fig. 12 (right).

C. 4LAC-DR3 SOURCES NOT IN 4FGL-DR4

The list of sources in 4LAC not present in 4FGL-DR4 includes 24 sources:

- 12 sources have different naming in 4FGL-DR3 than 4FGL-DR4 probably due to updated sky coordinates. For example, 4FGL J0301.6-7155, listed as such in 4FGL-DR3, is listed as 4FGL J0301.5-7156 in 4FGL-DR4. Their complete list is (4FGL label omitted): **CLASS1="fsrq"**: J0301.6-7155, J1423.5-7829; J2207.5-5346; **CLASS1="rdg"**: J0322.6-3712e, J1324.0-4330e; **CLASS1="bcu"**: J0430.2-0356, J0623.7-3348, J0728.0+6735, J1416.1+1320; **CLASS1="b11"**: J2346.7+0705, J2236.6+3706; J2317.4+4533

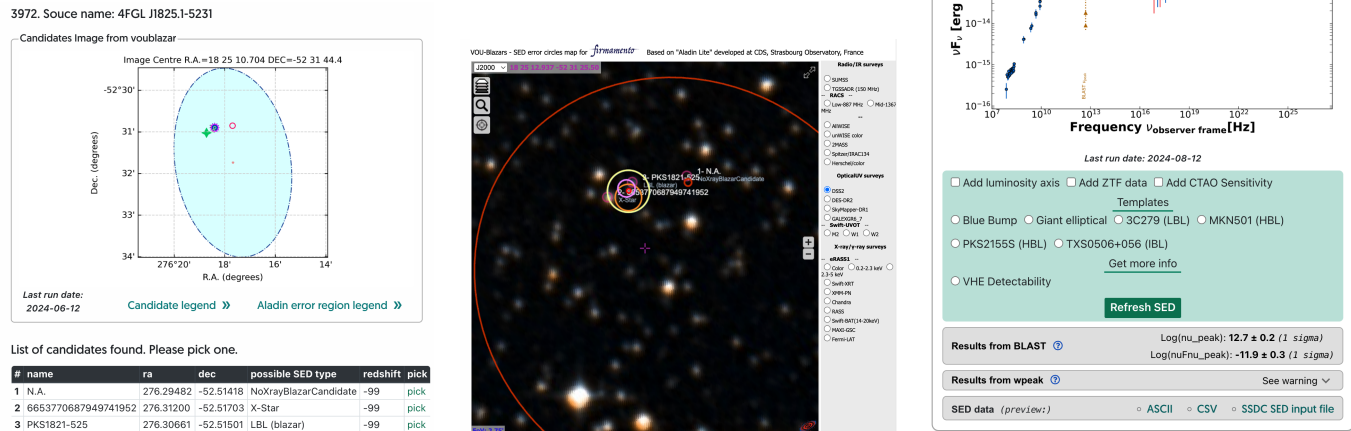


Figure 12. Example of f graphical view after a tentative association 4FGL J1825.1-5231. (left) The candidate 4FGL J1825.1-5231 is picked from a list (ID 3972), ERCI returns three candidates out of which only one is putative blazar, the 3rd one, PKS1821-525. (center) An aladin skymap shows the multi-wavelength morphology with all available catalog error circles. The yellow circle is a 4LAC source. Candidate 3 therefore agrees with 4LAC. (right) Multi-wavelength SED generated by f on the selected association

- 12 sources appear in 4FGL-DR3 with "c" (confusion) letter after the name (4FGL label omitted): J0344.2+3203c, J0506.0-0357c, J0517.9-6930c, J0521.8+5658c, J0535.7-6604c, J0539.7-0521c, J0545.0+0613c, J0554.3-1009c, J0733.7+0205c, J0743.3-4912c, J1644.8-2154c, J2108.7+7532c. They have all CLASS1="bcu".

Because we could not find an automatic procedure, and their number is small compared to the 4FGL-DR3/4LAC blazars, we neglected their screening with f at this time.

D. DESCRIPTION OF THE FITS VERSION OF THE 1FLAT CATALOG.

The catalog has been released in FITS format, following standard conventions for binary table extensions. The file `1FLAT.fits` is produced from the original CSV table and includes all relevant fields describing the source properties. During the conversion, column names have been sanitized to ensure compatibility with the FITS standard (only uppercase/lowercase letters, digits, and underscores are used). The final table therefore provides a clean dataset suitable for scientific analysis.

The FITS file is structured as a binary table in the first extension (HDU 1). Each row corresponds to a source entry, and each column contains a catalog parameter such as identifiers, associations, spectral properties, variability, and classification tags. Metadata such as column names and types are stored in the FITS header. The data can be easily accessed using common astronomical software libraries such as **Astropy** in Python, or visualized with FITS viewers. A detailed description of the individual columns, together with their units, is provided in [Tab. 6](#). In [Tab. 7](#) we report the labels taken by the entries **TAG** and **CLASS**.

Table 6. Description of the `1FLAT.fits` binary table columns. Catalog options in [Tab. 7](#)

Column	Format	Unit	Description
1FLAT f related entries ↓			
1FLAT_name	24A		1FLAT JHHMMSS.f+/-DDMMSS source name 4GFL source name for unassociated
RAJ2000	E	deg	Right ascension (J2000) of f association Right ascension (J2000) of 4GFL-DR4 for unassociated
DEJ2000	E	deg	Declination (J2000) of f association Declination (J2000) of 4GFL-DR4 for unassociated
CLASS	6A		Class designation for associated source
nu_syn	E	Hz	Synchrotron-peak frequency from wpeak (observer frame; $\log_{10}$)
nuFnu_syn	E	$\text{erg cm}^{-2} \text{s}^{-1}$	$\nu F\nu$ at synchrotron peak from wpeak (observer frame; $\log_{10}$)
TAG	30A		Classification tag
LAT 4FGL-DR4 related entries ↓			
4FGL_Source_Name	18A		Source name 4FGL JHHMM.f+DDMM (4FGL designation)
4FGL_ASSOC1	30A		Name of identified or likely associated source (primary)
4FGL_CLASS1	6A		Class designation for associated source (primary)
4FGL_ASSOC2	30A		Name of identified or likely associated source (secondary)
4FGL_CLASS2	6A		Class designation for associated source (secondary)
4FGL_Signif_Avg	E		Source significance in σ over 50 MeV–1 TeV
4FGL_PL_Index	E		Photon index from PowerLaw fit
4FGL_Energy_Flux100	E	$\text{erg cm}^{-2} \text{s}^{-1}$	Energy flux 100 MeV–100 GeV from spectral fit
4FGL_Frac_Variability	E		Fractional variability index
LAT 4LAC-DR3 related entries ↓			
4LAC_ASSOC1	30A		Name of identified or likely associated source
4LAC_CLASS	6A		Class designation for associated source
4LAC_nu_syn	E	Hz	Synchrotron-peak frequency (observer frame; $\log_{10}$)
4LAC_nuFnu_syn	E	$\text{erg cm}^{-2} \text{s}^{-1}$	$\nu F\nu$ at synchrotron peak (observer frame; $\log_{10}$)

Table 7. Values for classification **TAG**, **CLASS** used in 1FLAT

Column/Options	Description
TAG	
BLAZAR confirmed	For blazars in which f agrees with LAT in unassisted way
BLAZAR confirmed visual	For blazars in which f agrees with LAT in assisted way
BLAZAR different	For blazars in which f provides an alternative association to 4FGL or 4LAC
BLAZAR new	Blazars discovered with f and not found in 4FGL or 4LAC
UNCERTAIN	For sources in which f does not find a valid candidate whereas LAT does
NOC confirmed	For sources in which f agrees with LAT that no counterparts are found
NOC new	For sources where f does not find a counterpart whereas LAT does
GALAXY confirmed	For galaxies in which f agrees with LAT
GALAXY new	For galaxies in which f disagrees with LAT
CLASS	
HSP	$\log_{10}(\nu_{\text{peak}}/\text{Hz}) \geq 15$
IBL	$13.5 \leq \log_{10}(\nu_{\text{peak}}/\text{Hz}) < 15$
LSP	$\log_{10}(\nu_{\text{peak}}/\text{Hz}) < 13.5$
noC	No candidate found by f
galaxy	A galaxy
uncertain	Uncertain classification