Using X–ray catalogues to find counterparts for unassociated high–energy *Fermi*/LAT sources

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Figure 1:

Introduction

Recently, we have started a program of identification of those *Fermi* high–energy sources (1FHL, Ackermann et al. 2013), which are still unassociated. The 1FHL catalogue contains 514 objects detected above 10 GeV. The majority of these sources are identified with known objects (449 or 87% of the sample): approximately 75% with AGN (mostly blazars), while Galactic sources (pulsars, PWNs, SNRs, high–mass binaries, and star–forming regions) collectively represent 10% of the sample. The fraction of unassociated sources is less than 14% corresponding to 71 objects, of which 6 are likely to be associated to a SNR, a PWN or a combination of both, thereby leaving a list of 65 still unidentified objects. The third *Fermi* catalogue (Acero et al. 2015), which has recently been published, contains most of these unassociated 1FHL sources except for 13 objects which are missing. The main motivation behind the 1FHL catalogue was to find the hardest gamma–ray sources in the sky and to get a sample of objects which are good candidate for detection at TeV energies.

As a first step we have cross-correlated the sample of 65 objects with both the *ROSAT* Bright (Voges et al. 1999) and the *XMM–Newton*/Slew (Saxton et al. 2008) catalogues, following the prescription of Stephen et al. (2010) and finding the likely counterpart for 19 1FHL sources. Secondly, we have extended this search using data collected with the X–ray telescope (XRT) on–board *Swift* (Gehrels et al. 2004), by cross–correlating the list of unassociated 1FHL sources with all the XRT pointings available up to March 15, 2015 and found to be within around 9 arcmin from the *Fermi* best–fit position. This analysis has led us to investigate further 23 objects.

The remaining 1FHL sources have also been investigated on individual basis. The nature of each likely counterpart has then been studied by means of a multi–waveband approach and generally found to conform to that of blazar of the BL Lac type. In this report we concentrate on 15 objects which were found to have a conterpart in the third *Fermi* catalogue and the same association found by our analysis. They are all classified in the third *Fermi* catalogue as blazar of unknown type; here, we provide evidence that they are all BL Lac candidates.

Table 1: List of the X–ray detections and their WISE properties found for each high–energy *Fermi* source.

***Fermi* source**	**X–ray detection**				**WISE counterpart**					**Association**†
	Instr.	R.A. (J2000)	Dec. (J2000)	error (arcsec)	Name	Magnitudes W1[3.4 μm]	W2[4.6 μm]	W3[12 μm]	W4[22 μm]	
1FHL J0030.1–1647	RASSBSC	00 30 19.60	–16 47 23.50	16.0	WISE J003020.42–164713.0	14.054	13.279	11.270	8.821	**L**
1FHL J0044.0–1111	RASSBSC	00 43 49.40	–11 16 12.00	13.0	WISE J004348.65–111607.0	13.904	13.163	11.230	8.821	**L**
1FHL J0332.1+6307	XRT	No detection								
1FHL J0338.4+1304	XRT #1	03 38 29.09	+13 02 13.20	3.6	WISE J033829.26+130215.6	13.834	13.042	11.164	8.296	**L**
	XRT #2	03 38 40.46	+13 07 22.40	4.3	WISE J033840.67+130723.7	15.132	14.178	12.011	8.415	U
1FHL J0425.3+6320*	RASSBSC	04 25 23.00	+63 20 16.00	27.0	WISE J042525.35+632001.6	14.275	13.512	11.865	9.251	**L**
1FHL J0439.9–1858	XRT	04 39 49.54	–19 01 02.50	4.8	WISE J043949.71–190101.5	14.476	13.798	11.587	9.284	**L**
1FHL J0509.9–6419	RASSBSC	05 09 57.90	–64 17 41.50	6.0						**L**
1FHL J0803.4–0334	XRT	08 03 12.02	–03 36 01.20	3.9	WISE J080312.09–033600.8	14.433	13.759	11.306	8.187	**L**
1FHL J0804.8–0626	RASSBSC	08 04 58.30	–06 24 32.50	14.0	WISE J080457.73–062426.2	14.040	13.519	11.370	8.705	**L**
1FHL J1328.5–4728	XRT	13 28 40.45	–47 27 48.40	4.8	WISE J132840.61–472749.2	13.710	13.081	11.002	8.637	**L**
1FHL J1512.1–2255	RASSBSC	15 12 13.10	–22 55 15.00	13.0	WISE J151212.76–225508.4	13.808	12.950	11.052	8.921	**L**
1FHL J1549.9–0658	XRT	15 49 52.17	–06 59 08.30	3.6	WISE J154952.04–065907.8	13.695	13.014	10.885	8.745	**L**
1FHL J1841.1+2914	RASSBSC	18 41 21.70	+29 09 40.50	15.0	WISE J184121.73+290940.9	13.202	12.593	10.499	8.575	**L**
1FHL J2002.6+6303	RASSBSC	20 02 45.10	+63 02 26.30	9.0	WISE J200245.37+630233.3	15.319	14.664	11.553	9.651	**L**
1FHL J2036.9–3325	RASSBSC	20 36 50.90	–33 28 17.00	21.0	WISE J203649.49–332830.5	14.248	13.492	11.411	9.080	**L**

† *L* = Likely, *U* = Unlikely;

* Object at lowGalactic latitude, i.e. within ±10° of the Galactic plane.

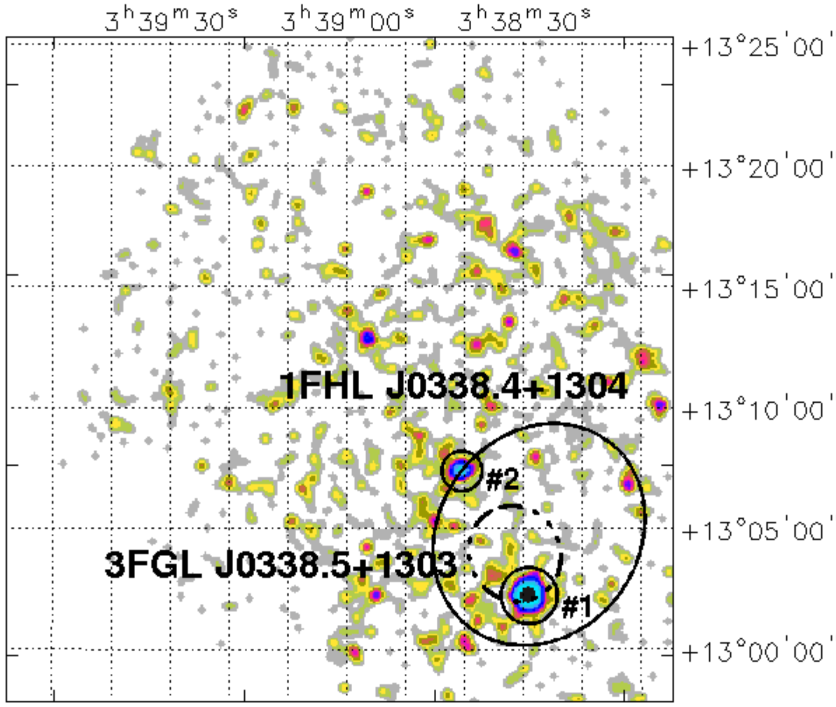

Figure 2: XRT 0.3–10 keV image of the region surrounding 1FHL J0338.4+1304. Black circles depict the location of each XRT detection. Black ellipse and black–dashed–dotted ellipse depict the positional uncertainty of the 1FHL J0338.4+1304 and 3FGL J0338.5+1303, respectively.

Objects already associated but of uncertain optical

In the following, we provide detailed information as available in the literature and in various archives on each individual *Fermi* high–energy source analysed in this work. Besides the X–ray information we also checked the radio, infrared (by exploiting the Wide–field Infrared Survey Explorer (WISE, Wright et al. (2010)), and optical characteristics of each possible counterpart in order to understand in more detail its nature and assess the likelihood of its association with the *Fermi* object. More specifically, in Table 1 we report for each *Fermi* high–energy source for which we find one or more X–ray counterparts, the *Fermi* name, the X–ray instrument used for the search, the number of X–ray detections, their coordinates and error radius, the name of the WISE counterpart and its magnitudes ($W1 = 3.5$, $W2 = 4.6$, $W3 = 12$, $W4 = 22$ micron)[1], and the likelihood of association between the gamma–ray and X–ray source. It is evident from Table 1 that the X–ray location accuracy allows a significant reduction in the *Fermi* positional uncertainty, thus making the search for possible optical counterparts much easier. In most cases, the soft X–ray error radius is sufficiently small to highlight only one optical counterpart. We use the WISE colours as discussed by Massaro et al. (2013a) to test the possible blazar nature of each source: these authors found that in the $W2 - W3$ versus $W1 - W2$ colour–colour plot the positions of gamma–ray emitting blazars are all within a well defined region known as the "Blazar Strip". Therefore, objects with IR colours compatible with this strip could be AGN of the blazar type and hence be an even more likely counterparts to the *Fermi* high–energy sources. For the radio information we

[1]available at:
http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=II%2F311.

either use data collected at 20 cm by the NRAO VLA Sky Survey (or NVSS, Condon et al. 1998), at 36 cm by the Sydney University Molonglo Sky Survey (or SUMSS, Mauch et al. 2003) and at 92 cm by the Westerbork Northern Sky Survey (or WENSS, Rengelink et al. 1997) or Westerbork In the Southern Hemishpere (or WISH, De Breuck et al. 2002). We note that only one source (1FHL J0425.3+6320) is located close to the Galactic plane, suggesting that the remaining 14 sources are most certaintly of extragalactic nature.

In the following each individual source is discussed separately.

1FHL J0030.1–1647

Within the relatively large *ROSAT* positional uncertainty we find only a radio source with a 20 cm flux of $\sim$9.4 mJy associated to a WISE object displaying near–infrared colours $W2 - W3 = 2.01$ and $W1 - W2 = 0.77$, which locate the source within the blazar strip. This source is reported in the 3FGL catalogue as 3FGL J0030.2–1646 associated to 1RXS J003019.6–164723, i.e. the *ROSAT* source found by our cross correlation analysis.

1FHL J0044.0–1111

This *ROSAT* source has a radio counterpart showing a 20 cm flux of $\sim$24.6 mJy. The source is likely an AGN according to Mahony et al. (2010), but of uncertain classification. The source is also detected in WISE with colours $W2 - W3 = 1.93$ and $W1 - W2 = 0.74$, which are again compatible with those of gamma–ray selected blazars. In the 3FGL catalogue this objects is listed as 3FGL J0030.2–1646 and is associated to 1RXS J004349.3–111612, i.e. the *ROSAT* source found by our analysis.

1FHL J0332.1+6307

Swift/XRT observations of this sky region failed to detect an X–ray counterpart inside the *Fermi* positional uncertainty. In the 3FGL catalogue this source (3FGL J0332.0+6308) is associated to GB6 J0331+6307, a flat spectrum radio source of unknown optical class. The fact that this source has no detection in X–rays casts however some doubts on its true association to the *Fermi* object.

1FHL J0338.4+1304

This is a case where two possible X–ray counterparts are found: one (source #1 in Figure 2) is the brightest of the two and the only one located well inside the *Fermi* positional uncertainty. This is also the source which has a counterpart in the NVSS catalogue (NVSS J033829+130215) with a 20 and 6 cm flux of $\sim$15.1 and $\sim$19 mJy, respectively; this suggests a rather flat spectrum. The source is also listed in the WISE catalogue with colours ($W2 - W3 = 1.88$ and $W1 - W2 = 0.79$), which are once again compatible with the blazar strip. As for source #2, it has no radio detection, but is listed in the WISE catalogue with colours ($W2 - W3 = 2.167$ and $W1 - W2 = 0.95$), just compatible with the blazar strip. 1FHL J0338.4+1304 is associated with 3FGL J0338.5+1303, which is identified in the third *Fermi* catalogue with RX J0338.4+1302, an AGN of unknown type. This *ROSAT* source is faint in X–rays and located with an uncertainty of 30 arcsec (Brinkmann et al. 1997); its positional uncertainty is however compatible with source #1 which is also by our analysis the most likely counterpart to both *Fermi* detections.

1FHL J0425.3+6320

The *ROSAT* source, found by the cross–correlation analysis, has a large positional uncertainty, but thanks to an unpublished *Swift*/XRT pointing is possible to localise the object with a few arcsec accuracy at R.A.(J2000)= $04^{h}25^{m}25^{s}.54$ and Dec.(J2000) = $+63°19'54''.82$, error = 4.66 arcsec). The source is likely associated with a radio object detected at 20 and 92.2 cm with a flux of ∼24.1 and ∼33 mJy respectively, which suggests that the source has a flat radio spectrum (Massaro et al. 2014); the NVSS morphology indicates slightly extended emission on one side. The WISE colours ($W2 - W3 = 1.65$ and $W1 - W2 = 0.76$) locate the source just outside the blazar strip. This 1FHL object is listed as 3FGL J0425.2+6319 in the third *Fermi* catalogue, itself associat to 1RXS J042523.0+632016 (the *ROSAT* source discussed here).

1FHL J0439.9–1858

Within the small XRT error circle we find a radio counterpart (NVSS J043949–190059) with a 20 cm flux of ∼60 mJy; the source has a radio spectrum [2] with index ~ -0.7 (Petrov et al. 2013). This source has also a WISE counterpart displaying colours $W2 - W3 = 2.21$ and $W1 - W2 = 0.678$, which are compatible with the blazar strip. This source is associated with 3FGL J0439.9–1859, which has a counterpart in the radio source PMN J0439–1900: this object is localised with an uncertainty of 30 arcsec. Within its error box we find the XRT object discussed here. We therefore confirm the association and by restricting the radio positional uncertainty provide a unique optical counterpart.

1FHL J0509.9–6419

This *ROSAT* source has also a *XMM–Newton* (XMMSL1 J050956.5-641745, 5 error radius) and *Swift*/XRT (1SXPS J050957.5–641740, 3.6 arcsec error radius) counterpart; all these soft X–ray emitters are associated to RBS 625, reported as an AGN behind the Magellanic clouds by Kozlowski & Kochanek (2009) and classified in Simbad as a QSO. RBS 625 is fairly bright in X–ray with a flux of $9.5\ 10^{-12}$ ergs cm^{-2} s^{-1}, while the only radio detection of the source is at 36 cm with a flux of ∼24.7 mJy. Interestingly, the source has no WISE counterpart. RBS 625 is also the counterpart listed in the 3FGL catalogue where this source is reported as 3FGL J0509.7–6418.

1FHL J0803.4–0334

The only X–ray source detected by XRT within the *Fermi* error ellipse has a radio counterpart in a NVSS object, namely NVSS J080311–033558, having a 20 cm flux of ∼231.1 mJy. It is also WISE-detected with colours $W2 - W3 = 2.453$ and $W1 - W2 = 0.67$, typical of gamma–ray blazars. The radio source has a power law spectrum with index –0.91 between 3 and 6 cm (Petrov et al. 2013). This 1FHL source is associated to 3FGL J0803.3–0339, which has a counterpart in TXS 0800–034, an alternative name for the object discussed here.

1FHL J0804.8–0626

This *ROSAT* source has a counterpart in a radio object which has a 20 cm flux of ∼20.3 mJy. The WISE colours are $W2 - W3 = 2.15$ and $W1 - W2 = 0.52$, which once again locate the source well

[2] Here and in the following we use $S = A^{\nu}$.

inside the blazar strip. The 3FGL association for this source is 3FGL J0805.0–0622 and the reported counterpart is indeed the *ROSAT* object found by our analysis.

1FHL J1328.5–4728

The XRT source found in this work is associated to a relatively bright radio object, namely SUMSS J132840–472748, displaying a flux of around ∼124 mJy at 32 cm and a flat ($\alpha \sim -0.4$) radio spectrum (Petrov et al. 2013). It is also WISE–detected with colours $W2 - W3 = 2.08$ and $W1 - W2 = 0.63$, typical of gamma–ray blazars and it is flagged as variable in the WISE catalogue. The source is classified in NED as an AGN of unknown type and is discussed by Massaro et al. (2013b) as a blazar candidate. Hassan et al. (2013) have recently suggested that it might be a BL Lac. This gamma–ray source is reported as 3FGL J1328.5–4728 in the latest *Fermi* survey where it is associated to 1WGA J1328.6–4727. This *ROSAT* source has a large positional uncertainty (50 arcsec) but its location is nevertheless compatible with that of the XRT source found in this analysis. This source has recently been optically classified as a BL Lac by Ricci et al. (2015).

1FHL J1512.1–2255

The position of this *ROSAT* objects is compatible with that of a *Swift*/XRT source (1SXPS J151212.6–225506) having a positional uncertainty of only 3.8 arcsec. This allows to reduce the *ROSAT* error circle considerably and to associate the soft X–ray counterpart to a radio source, having a 20 cm flux of ∼19 mJy. The source could be part of a galaxy cluster (MCXC J1512.2–2254) at $z = 0.315$ whose center is very close to the source discussed here. The WISE colours are $W2 - W3 = 1.898$ and $W1 - W2 = 0.858$, which once again locate the source well inside the blazar strip. This 1FHL source is associated to 3FGL J1512.2–2255, which has a counterpart in 1RXS J151213.1–225515, i.e the *ROSAT* source discussed above.

1FHL J1549.9–0658

The XRT association found for this gamma–ray emitter coincides with a radio source listed in the NVSS catalogue (NVSS J154952–065907) with a 20 cm flux of ∼12.6 mJy. The WISE colours $W2 - W3 = 2.12$ and $W1 - W2 = 0.68$ again suggest a source compatible with a blazar type of AGN. The source has a bright UV counterpart (GALEXASC J154952.10–065907.5), displaying far– and near–UV magnitudes of 21.2 and 20.7, respectively. It is also reported in the *XMM–Newton* Slew full catalogue as XMMSL1 J154951.9–065903, but not in the clean one. The pulsar PSR J1549–06 is at only 1.7 arcmin away from the gamma–ray source and indeed it is listed in Simbad as the possible counterpart to 1FGL J1549.7–0659 and 2FGL J1549.7–0657. This source has however no visible X–ray emission in the XRT image, which makes unlikely its association with the 1FHL source. Indeed in the third *Fermi* survey this gamma–ray source, reported as 3FGL J1549.7–0658, is associated to the X–ray/radio source discussed here.

1FHL J1841.1+2914

This soft X–ray source is associated to a 2MASS extended object (2MASX J18412170+2909404) classified as a galaxy in NED. The source is listed in CRATES, an All–Sky Survey of Flat–Spectrum Radio Sources (Healey et al. 2007) since it shows a radio spectrum with $\alpha = -0.29$. At 20 cm the source flux is ∼63.7 mJy; radio polarization measurements are available at 8.4 GHz (Jackson et al. 2007). The source is also listed in the set of BL Lac candidates for TeV observations discussed by Massaro et al. (2013b). Indeed, the WISE colours ($W2 - W3 = 2.09$ and $W1 - W2 = 0.61$) locate this object well inside the blazar strip. In the third *Fermi* catalogue this source is associated with 3FGL J1841.2+2910, which, in turn, is associated with MC3 J184126+2910, a radio name of the X–ray source discussd above.

1FHL J2002.6+6303

This *ROSAT* source has a counterpart in the *XMM–Newton* (XMMSL1 J200245.2+630226, 6 arcsec error radius) and *Swift*/XRT (1SXPS J200245.3+630228, error radius 4.4 arcsec) catalogues; it is associated with a radio source, NVSSJ200244+630230, which displays a 20 cm flux of ∼10.4 mJy. The source radio structure is clearly extended on one side. The WISE colours of this source are $W2 - W3 = 3.11$ and $W1 - W2 = 0.66$ which place the object outside the blazar strip. In the third *Fermi* survey this gamma–ray source is reported as 3FGL J2002.7+6303 and is associated to the X–ray/radio source discussed here.

1FHL J2036.9–3325

This *ROSAT* source is also detected by *Swift*/XRT as 1SXPS J203649.3–332829, but with a smaller positional uncertainty of only 3.5 arcsec. The source is also reported in the NVSS but at the limit of the instrument sensitivity (around ∼3 mJy at 20 cm); it is also a WISE object with colours $W2 - W3 = 2.08$ and $W1 - W2 = 0.76$, which again locate the source within the blazar strip. This 1FHL source is associated to 3FGL J2036.6-3325, which has a counterpart in 1RXS J203650.9-332817, i.e the *ROSAT* source discussed here.

Conclusions

The first result of this work is that we have uncovered a number of likely X–ray counterparts to unassociated 1FHL gamma–ray sources. The majority of these associations are likely to be of extragalactic nature, most probably blazars of some type. In most, if not all cases, the proposed association has a radio detection and WISE colours compatible with the blazar strip, in other words qualified to be a beamed AGN. As already noted by Stephen et al. (2010) and confirmed by Masetti et al. (2013), the association of *Fermi* sources with soft X–ray counterparts favours in general the discovery of blazar of the BL Lac type. Indeed, one source (1FHL J1328.5–4728) is classified in this way. The preference to find BL Lac, when using soft X–ray data, is likely related to the SED of these objects compared to Flat Spectrum Radio Quasars. In fact, the X–ray selection favours the discovery of high synchrotron peaked or HSP blazars, which are also good candidates for TeV emission, as the Compton peak in these AGN is expected in this energy range due to the presence of high–energy electrons.

As discussed by Masetti et al. (2013) and references therein, these objects populate a well defined region of the WISE colour–colour diagram, i.e a square located in the lower part of the blazar strip. In fact if we plot in the WISE colour–colour diagram (see Figure 3) the most likely counterparts to 1FHL source listed in Table 1 (i.e. considering only those sources flagged with *L* in the last column of the Table) we find that most fall along the blazar strip or close to it but, most importantly, ?? of them lie within the limits of the locus populated by TeV-emitting BL Lacs. We therefore conclude once again that the association among unassociated high–energy *Fermi* sources and soft X–ray objects appears to select preferentially blazars, for a large fraction of the HSP BL Lac type, i.e. good candidates for TeV emission. Clearly, only optical spectroscopy of all soft X–ray

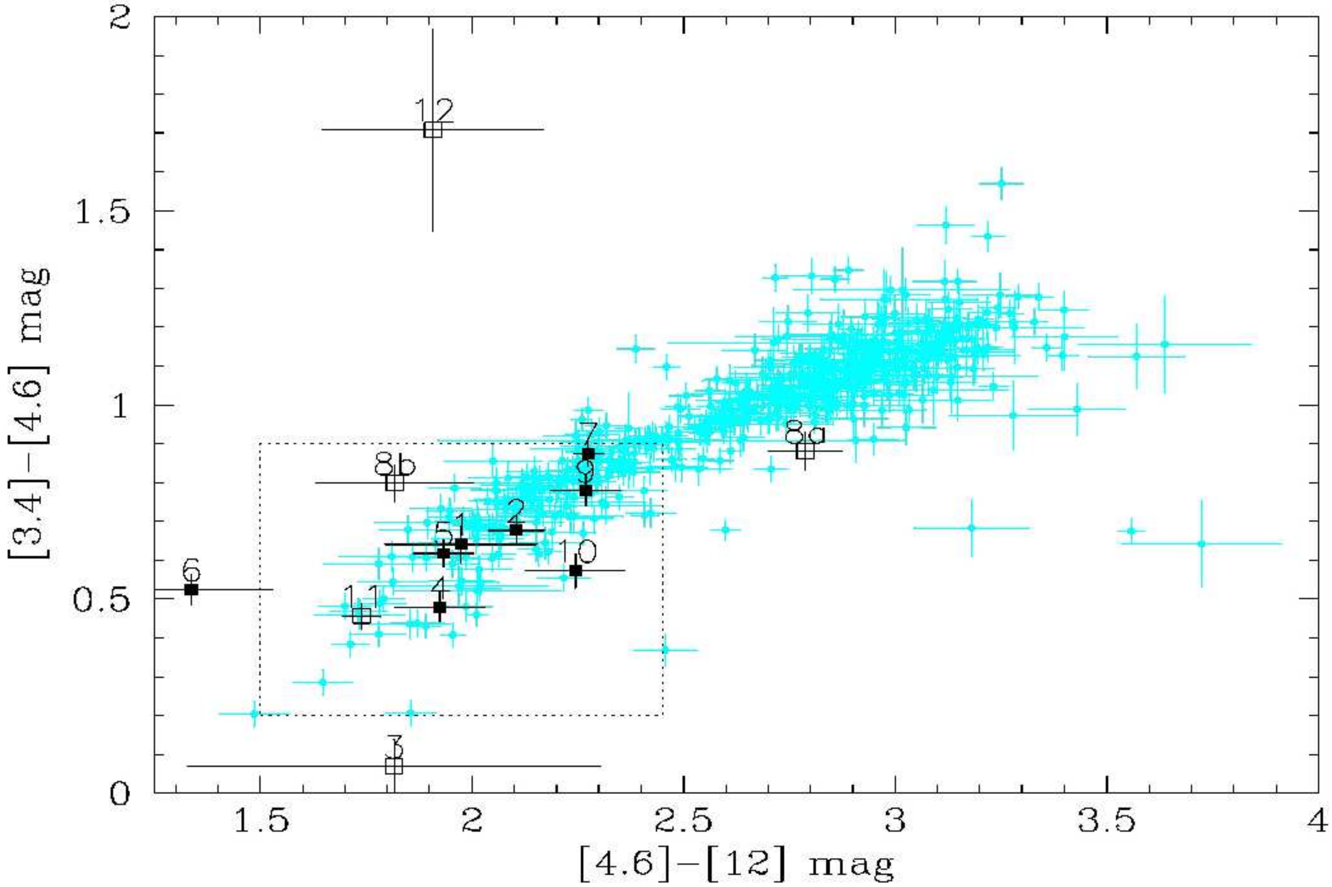

Figure 3: The [4.6]-[12]/[3.4]-[4.6] MIR color-color plot reporting the positions of gamma-ray emitting blazars (in cyan) associated with WISE sources forming the blazar strip (see Massaro et al. (2013a) for more details), together with the BL Lac objects identified in this paper.

counterparts discussed in this work can confirm this suggestion and provide further insight into gamma–ray selected blazars in general and BL Lac in particular.

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