THE WISE BLAZAR-LIKE RADIO-LOUD SOURCES: AN ALL-SKY CATALOG OF CANDIDATE γ-RAY BLAZARS

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Received 2014 March 10; accepted 2014 September 27; published 2014 October 31

ABSTRACT

We present a catalog of radio-loud candidate γ-ray emitting blazars with WISE mid-infrared colors similar to the colors of confirmed γ-ray blazars. The catalog is assembled from WISE sources detected in all four WISE filters, with colors compatible with the three-dimensional locus of the WISE γ-ray emitting blazars, and which can be spatially cross-matched with radio sources from one of the three radio surveys: NVSS, FIRST, and/or SUMSS. Our initial WISE selection uses a slightly modified version of previously successful algorithms. We then select only the radio-loud sources using a measure of the radio-to-IR flux, the $q_{22}$ parameter, which is analogous to the $q_4$ parameter known in the literature but which instead uses the WISE band-four flux at 22 μm. Our final catalog contains 7855 sources classified as BL Lacs, FSRQs, or mixed candidate blazars; 1295 of these sources can be spatially re-associated as confirmed blazars. We describe the properties of the final catalog of WISE blazar-like radio-loud sources and consider possible contaminants. Finally, we discuss why this large catalog of candidate γ-ray emitting blazars represents a new and useful resource to address the problem of finding low-energy counterparts to currently unidentified high-energy sources.

Key words: BL Lacertae objects: general – catalogs – galaxies: active – radiation mechanisms: non-thermal

Online-only material: color figures, machine readable table

1. INTRODUCTION

The largest known class of γ-ray sources is represented by the rarest class of active galactic nuclei (AGNs), blazars (e.g., Abdo et al. 2010; Nolan et al. 2012). This population of radio-loud sources is mainly characterized by flat radio spectra, superluminal motions, and variable and high polarization from the radio to the optical band (Urry & Padovani 1995; Massaro et al. 2009). Their emission is strongly dominated by non-thermal radiation over the entire electromagnetic spectrum, featuring two broad components in their spectral energy distributions: the low-energy one peaking between the IR and the X-ray and the high-energy one exhibiting its maximum in the γ-ray energies.

Blazars are historically divided into two main classes on the basis of their optical spectra. The first class includes the BL Lac objects, characterized by featureless spectra with emission/absorption lines of equivalent width lower than 5 Å (Stickel et al. 1991; Stocke et al. 1991; Laurent-Muehleisen et al. 1999). The second class is represented by the flat spectrum radio quasars (FSRQs), that show normal quasar-like spectra. In the following we adopt the nomenclature proposed in the Multi-wavelength Blazar Catalog5 (BZCat, Massaro et al. 2009, 2011a), that labels BL Lac objects as BZBs and FSRQs as BZQs.

The ROMA-BZCat is based on by-eye inspection of multi-frequency data and the extensive review of the literature for each member. The minimal requirements that a source has to meet to be included in the BZCat, are the optical identification and/or availability of optical spectrum, an X-ray luminosity equal to or larger than $10^{43}$ erg s$^{-1}$ and a compact radio morphology. These stringent requirements and the use of heterogeneous data make for a very reliable but incomplete list of bona fide blazars. The selection of large, homogeneous samples of blazars is intrinsically difficult because of their peculiar spectral characteristics and extreme variability. New simpler criteria can be useful to extract larger and less incomplete samples of candidate blazars, whose nature has to be confirmed through additional follow-up observations.

We have recently discovered that γ-ray emitting blazars have infrared colors that distinguish them from other galactic and extragalactic sources in the three-dimensional color space of the mid-IR WISE magnitudes (Massaro et al. 2011b; D’Abrusco et al. 2012). We used this result to devise a new method for the association of the Fermi Large Area Telescope (LAT) unidentified γ-ray sources through a parameterization of the region occupied by γ-ray blazars in the WISE color space, the so-called WISE blazar locus (D’Abrusco et al. 2013; Massaro et al. 2013a).

In this paper, we present a catalog of candidate γ-ray emitting blazars extracted from the AllWISE Data Release.9 This catalog is composed of radio-loud WISE sources detected in all four WISE filters, whose mid-IR colors are similar to the typical colors of confirmed γ-ray emitting blazars (see D’Abrusco et al. 2013), spatially associated with a radio source and selected as radio-loud. Hereinafter, such sources will be called “WISE blazar-like radio-loud sources,” or WIBRaLS.

The paper is organized as follows: in Section 2 we give a brief summary of the procedure used to select the WIBRaLS and the basic information about the final catalog.

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5 http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/
6 http://www.asdc.asi.it/bzcat/
7 http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/
8
in Section 2.1 we discuss the method used to select the WISE sources with IR colors similar to the colors of the γ-ray emitting blazars. Section 2.2 is devoted to the description of the technique used to perform the spatial association of the WISE sources with the radio counterparts, and in Section 2.3 we introduce the radio-loudness parameter \( q_{22} \) and discuss its application to select radio-loud sources among the sample of WISE blazar-like sources with a radio association. In Section 3, we describe the final catalog of WIBRaLS and in Section 4 we compare the WIBRaLS with other WISE-based techniques optimized for the selection of AGNs (Section 4.1) and with the VERONCAT (Véron-Cetty & Véron 2010) (Section 4.2) to indirectly characterize the nature of the sources in our catalog and assess possible contamination from non-blazars. Finally, in Section 5, we summarize the results and draw our conclusions.

We use cgs units and spectral indices are based on the definition of the flux density as \( S_\nu = \nu^{-\alpha} \).

The WISE magnitudes in the [3.4], [4.6], [12], and [22] \( \mu \)m nominal filters are in the Vega system. The values of three WISE magnitudes, namely [3.4], [4.6], and [12], and of the colors derived using those magnitudes, have been corrected for galactic extinction according to the extinction law presented by Draine (2003).

2. THE SELECTION OF THE WISE BLAZAR-LIKE RADIO-LOUD SOURCES

The three steps followed to select WIBRaLS can be summarized as follows.

1. WISE sources detected in all four filters—[3.4], [4.6], [12], and [22] \( \mu \)m—are selected according to their mid-IR colors using a slightly modified version of the technique for the association of high-energy sources with WISE candidate blazars presented by D’Abrusco et al. (2013) (see Section 2.1). We designate these sources as “WISE blazar-like sources.”

2. The WISE blazar-like sources selected with the method described in Section 2.1 are positionally cross-matched with the catalogs of sources detected in three different radio surveys: the NRAO VLA Sky Survey (NVSS; Condon et al. 1998),10 the Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003)11, and the Faint Images of the Radio Sky at Twenty-cm survey (FIRST; Becker et al. 1995).12 Only WISE blazar-like sources that can be associated with at least one radio source from any one of the three radio surveys within the maximum radial distances discussed in Section 2.2 are further considered.

3. We retain only the WISE blazar-like sources with radio counterparts that satisfy the radio-loudness criterion \( q_{22} \leq -0.5 \) (Section 2.3) in order to minimize the contamination in our catalog from sources whose radio emission is not associated with AGN activity.

We anticipate that the final number of unique WIBRaLS selected with our method is 7855. A workflow representing the procedure for the extraction of the catalog of WIBRaLS is shown in Figure 1. In the following sections, we will discuss in detail the three steps summarized above.

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10 http://heasarc.gsfc.nasa.gov/W3Browse/all/nvss.html
11 http://heasarc.gsfc.nasa.gov/W3Browse/all/sumss.html
12 http://heasarc.gsfc.nasa.gov/W3Browse/all/first.html
source with each of the three cylinders of the model the score. The score can be calculated in two steps: (1) the \textit{WISE} colors of the source (and corresponding uncertainties) are projected onto the PC space where an error ellipsoid is defined, and (2) the position of the ellipsoid relative to the \textit{locus} model is translated to a numeric value, the \textit{score}, which varies continuously between zero and one, and is weighted by the volume of the error ellipsoid in the PC space (see Section 3.2 of D’Abrusco et al. 2013, for the definition of \textit{score}). In general, the larger the \textit{score values} are, the closer the source is to the \textit{locus} model and the more similar the \textit{WISE} colors are to the colors of confirmed \textit{γ}-ray emitting blazars.

In D’Abrusco et al. (2013), the sources with null scores were discarded, while \textit{WISE} sources with non-null \textit{scores} were classified into three classes, namely A, B, and C, based on \textit{score} thresholds defined as the 90th, 60th, and 20th percentiles of the \textit{score} distribution of the \textit{locus} sample, separately for each of the three regions of the \textit{locus}. The three classes A, B, and C are sorted according to decreasing compatibility with the model of the \textit{locus}: class A sources are considered to be the most likely \textit{WISE} blazar-like sources, while the positions of class B and class C sources are still compatible with the model of the \textit{locus} but at a lesser degree than class A sources.

In this paper, we use the same approach described in D’Abrusco et al. (2013) to determine the value of the \textit{score} thresholds, except for the percentile associated with the lowest threshold. In order to select the largest possible number of \textit{WISE} blazar-like sources, we set the three thresholds to the 20th, 60th, and 90th percentiles of the \textit{score} distribution of the \textit{locus} sample (see Figure 2 and compare them with Figure 6 in D’Abrusco et al. 2013). The adoption of a lower threshold for the definition of the class C sources makes our selection more complete but, at the same time, potentially increases the contamination of the class C from sources that only marginally have \textit{WISE} colors similar to the colors of the confirmed \textit{WISE} \textit{γ}-ray emitting blazars. The presence of class C contaminants is mitigated by considering only the \textit{WISE} blazar-like sources which can be positionally associated with sources in either one of the three radio surveys (NVSS, FIRST, SUMSS) used in this paper (Section 2.2).

For each distinct region of the model (BZB, BZQ, or mixed), class A sources have a score of \( s \geq s_{90\%} \), class B sources have a score of \( s_{60\%} \leq s < s_{90\%} \), and class C sources have a score of \( s_{20\%} \leq s < s_{60\%} \). The values of the \textit{score} thresholds derived from the \textit{score} distributions of the sources in the \textit{locus} for the three regions of the model are reported in Table 1. Each source with a score larger than the \( s_{20\%} \) threshold for one of the
cylinders of the model is assigned the corresponding type (BZB, BZQ, or mixed). The WISE blazar-like sources whose types are BZB or BZQ have IR colors similar to the colors of the bona fide WISE-detected $\gamma$-ray emitting blazars classified as BZBs or BZQs, respectively. The mixed type, conversely, does not indicate any particular spectral class since the mixed cylinder contains comparable fractions of both BZBs and BZQs.

The total number of WISE blazar-like sources selected by our method is 265,170 (see Table 2), split into 32,789 BZB-type candidates, 169,703 BZQ-type candidates, and 62,678 sources compatible with the mixed region of the locus. The sample of 265,170 WISE blazar-like sources is split into 3554 ranked as Class A, 17,500 as Class B, and the remaining 244,116 classified as Class C candidates. The Class C candidates represent $\sim$92% of the total number of WISE blazar-like sources, while the Class A and Class B candidates account only for the $\sim$1.3% and $\sim$6.6%, respectively. These fractions result from the conservative choices of the score thresholds used to define the classes of the sources based on their WISE colors and uncertainties (see D’Abrusco et al. 2013 for more details).

2.2. Spatial Cross-match with Radio Catalogs

In order to determine the optimal radius for the spatial association of the WISE blazar-like sources with radio sources in the NVSS, SUMSS, and FIRST catalogs, we used a modified version of the procedure used by Donoso et al. (2009) and Best et al. (2005). In these two papers, the authors determined the optimal radius for the spatial association of NVSS and FIRST radio sources to optical sources in SDSS by setting a threshold radius $r_{\text{thr}}=3\arcs$ for the NVSS and $7/4\arcs$ for the NVSS and SUMSS surveys, respectively. The number of WIBRaLS sources with radio counterparts (multiple radio counterparts of WISE blazar-like sources are counted separately).

In this paper, we will use as the optimal association radius the radial distance corresponding to a given fixed efficiency of the selection $e_{\text{thr}}=99\%$ called “reliability” the “efficiency,” which corresponds to a contamination of $c_{\text{thr}}=1\%$ where the contamination is defined as $c(r)=100\%-e(r)$. This choice of efficiency results in minimizing the fraction of spurious sources selected and optimizes the success likelihood of the follow-up observations required to confirm their nature at the cost of a limited completeness. The efficiency of the selection is defined as $e(r)$ is defined as

$$e(r) = 100\% \left( \frac{n_{\text{real}}(r)-n_{\text{mock}}(r)}{n_{\text{real}}(r)} \right).$$

We have estimated $n_{\text{real}}(r)$ by counting the number of WISE sources detected in all four bands within circular regions of radius $r$ between 0$\arcs$ and 60$\arcs$ centered on a sample of $5 \times 10^4$ sources randomly extracted from each of the three radio surveys. In order to estimate the corresponding $n_{\text{mock}}(r)$ values, we have created 100 mock realizations of the coordinates of each real radio source by shifting its position by a radial distance randomly drawn from the interval [60, 120]$\arcs$ in a random direction. The numbers of WISE sources associated with real and mock radio positions are shown in the upper panels of Figure 3 as functions of the radial distance (real and mock cross-matches are shown as solid and dashed black curves, respectively). The numbers of cross-matches around mock positions can be fractional as they have been averaged over the 100 mock realizations of the real radio positions. The lower panels in Figure 3 show the contamination $c(r)$, calculated with the Equation (1), as a function of the radial distance from the radio coordinates. In the lower panels, the horizontal line corresponding to the threshold contamination $c_{\text{thr}}=1\%$ (efficiency $e(r)=99\%$) and the vertical lines indicate the optimal radii, corresponding to the intersection of the horizontal lines with the completeness curve.

The optimal cross-match radii determined with this method are $r_{\text{NVSS}}=10.3\arcs$, $r_{\text{SUMSS}}=7.4\arcs$ for the NVSS and SUMSS surveys, respectively. The number of WIBRaLS sources with radio counterparts (multiple radio counterparts of WISE blazar-like sources are counted separately).

Table 1

| Score | BZB | Mixed | BZQ |
|-------|-----|-------|-----|
| $s_{20\%}$ | 0.36 | 0.26 | 0.23 |
| $s_{60\%}$ | 0.75 | 0.77 | 0.79 |
| $s_{90\%}$ | 0.92 | 0.93 | 0.89 |

Notes. These values are determined as the 20th, 60th, and 90th percentiles of the distribution of scores of the locus sample split by BZB, mixed, and BZQ regions.

Table 2

| WISE Blazar-like Sources | WISE Blazar-like Sources with Radio Counterparts | WIBRaLS |
|--------------------------|-----------------------------------------------|---------|
|                         | BZB | Mixed | BZQ | Total | BZB | Mixed | BZQ | Total | BZB | Mixed | BZQ | Total |
| Class A                  | 1345 | 519 | 1690 | 3554 | 193 | 236 | 783 | 1212 | 45 | 30 | 86 | 161 |
| Class B                  | 3985 | 3611 | 9904 | 17500 | 536 | 635 | 1663 | 2834 | 244 | 220 | 476 | 940 |
| Class C                  | 27459 | 58548 | 158109 | 265170 | 2694 | 4583 | 9522 | 16799 | 1813 | 2507 | 4581 | 8901 |
| Total                    | 32789 | 62678 | 169703 | 265170 | 45 | 30 | 86 | 161 |

Notes. For further details on WISE classes and types, see Section 2.1. Where applicable, the numbers of radio counterparts for each radio survey are also shown. The right side of the table shows the spectral classes and WISE-based partition in classes for WIBRaLS sources (multiple radio counterparts of WISE blazar-like sources are counted separately).
distinct NVSS and SUMSS radio counterparts selected, as a consequence, is 11928 and 2325, respectively.

Our method does not produce a reasonable estimate of the optimal radius for the FIRST survey (see right plot in Figure 3) likely because of the very high density of FIRST sources in the sky compared to the other two surveys. The black solid line in the right plot of Figure 3 declines very steeply at small radial distances, with \(-85\%\) of the total cross-matches found at distances smaller than 5\'. Based on this fact, we have adopted a different approach to determine a cross-match radius for FIRST. We have chosen as the optimal radial distance three times the combined positional uncertainties of AllWISE and FIRST detections. The maximum allowed positional uncertainty of AllWISE detections along each axis is 0.5\', even though for most of the sources detected the error is \(~0.02\) per axis, yielding a total positional uncertainty of \(~0.1\). In order to be conservative in our analysis, we have assumed a positional uncertainty for AllWISE sources \(\sigma_{\text{AllWISE}} = 0.5\'). The astrometric accuracy of FIRST radio sources down to the survey flux threshold is consistently better than 1\' (White et al. 1997). Nonetheless, also in this case we will assume a conservative positional uncertainty \(\sigma_{\text{FIRST}} = 1\') for FIRST detections. Thus, the combined positional uncertainty can be estimated as \(\sigma_{\text{AllWISE} + \text{FIRST}} = \sqrt{\sigma_{\text{AllWISE}}^2 + \sigma_{\text{FIRST}}^2} \sim 1\'2\), which yields an optimal radius for FIRST sources \(r_{\text{FIRST}} = 3\sigma_{\text{AllWISE} + \text{FIRST}} = 3\'4\). Using this maximum radial distance, we select 106 WIBRaLS sources with FIRST radio counterparts that cannot be associated with an NVSS source.

We do not attempt to estimate the completeness of our selection procedure because the properties of the parent population of our sample of WIBRaLS are impossible to determine. In the case of the FIRST survey, the adoption of a smaller maximum radial distance compared to the radii used for NVSS and SUMSS surveys possibly results in a lower completeness. However, we estimate the loss of real cross-matches to be small: the increase in the number of sources selected with our procedure using radial distance \(r = 10\ '') is only 104, corresponding to \(\sim 10\%\) of the number of WIBRaLS selected with the optimal radius \(r_{\text{FIRST}} = 3\'4\).

The number of WISE blazar-like sources with at least one radio counterpart within the maximum radial distances discussed above is 11928, 6592, and 2325 for NVSS, FIRST, and SUMSS surveys, respectively (see Table 2), for a total of 20,845 WISE blazar-like sources spatially associated with distinct radio counterparts from either of these three catalogs. We find that 1552 WISE blazar-like sources are associated with one NVSS and one SUMSS radio source, while 3660 WISE blazar-like sources are cross-matched to one NVSS source and one FIRST radio source. For this reason, the final number of unique WISE blazar-like sources with at least one radio counterpart is 16,632.

### 2.3. Radio-loudness Selection

Blazars are by definition radio-loud AGNs. For this reason, in our analysis, we only consider WISE blazar-like sources that can be spatially associated with at least one radio counterpart in one of the three radio surveys within the maximum radial distance discussed in Section 2.2. However, radio emission can also be produced by physical mechanisms not due to the presence of an AGN. For example, it is well known that the far-IR and radio emission are tightly and linearly correlated in star-forming systems (see, e.g., Sargent et al. 2010; Bonzini et al. 2012 and references therein for more details). The strength of the correlation between radio and far-IR emissions is usually expressed via the so-called \(q\) parameter, defined as the logarithm of the ratio of far-IR to radio flux density, (e.g., Helou et al. 1985). Unfortunately, flux density measurements at far-IR frequencies required to compute the \(q\) parameter are often not available. However, Padovani et al. (2011) and Bonzini et al. (2013) have recently shown that it is possible to define a \(q_{24}\) parameter as

\[
q_{24} = \log \left( \frac{S_{24}}{S_{1.4 \text{ GHz}}} \right),
\]

where \(S_{24}\) is the observed flux density at 24 \(\mu\)m and \(S_{1.4 \text{ GHz}}\) is the flux density measured at 1.4 GHz. The use of the observed flux densities minimizes the uncertainties introduced by the modeling of the spectral energy distribution (Bonzini...
values of $q_{22}$ peaks at $\Delta q_{22} = q_{22}(843 \text{ MHz}) - q_{22}(1.4 \text{ GHz}) \sim 0.08$ and does not depend on the WISE spectral class of the sources considered. Moreover, $\Delta q_{22}$ is almost constant over the range of $q_{22}$ spanned by our sample of WISE blazar-like sources with radio counterparts in both the NVSS and SUMSS surveys. For this reason, for radio-loud WISE blazar-like radio sources with only a SUMSS radio counterpart, we have used the corrected $q_{22}(843 \text{ MHz}) = q_{22}(843 \text{ MHz}) + \Delta q_{22}$ where $\Delta q_{22} = 0.08$. The change in the number of sources selected using the corrected $q_{22}$ is $\sim 3.5\%$ of the total sample of WIBRaLS (see Section 3). It is worthwhile to stress that the scatter of the two $q_{22}$ estimates for the subset of 73 candidate blazars in this sample associated with a confirmed blazar of the ROMA-BZCat catalog within $3^\prime/3$ (stars in Figure 4) is smaller ($\sigma_{\Delta q_{22}} = 0.12$) and their distribution is less biased ($\langle \Delta q_{22} \rangle = 0.01$) than the distribution of the whole sample. Nonetheless, we have used the correction $\Delta q_{22}$ derived from the whole sample because the nature of most WISE blazar-like sources with radio counterparts has not yet been confirmed.

Bonzini et al. (2013) showed that the $q_{22}$ parameter has a redshift dependence (see Figure 2 in Bonzini et al. 2013): the $q_{22}$ values of all classes of sources considered (radio-loud AGNs, radio-quiet AGNs, and star-forming galaxies) become smaller for larger redshifts. For this reason, the boundary between the regions of the redshift versus $q_{22}$ plane (Figure 2 in Bonzini et al. 2013) dominated by the radio-loud AGNs and the other radio sources is also a function of the redshift. In principle, if redshift estimates for all WISE blazar-like sources associated with a radio counterpart were available, we could have removed the redshift dependence and selected radio-loud WISE blazar-like sources with a radio counterpart at each redshift. Since redshifts are not available, we can only set a fixed threshold for the $q_{22}$. Figure 5 shows the distribution of $q_{22}$ values calculated for the confirmed $\gamma$-ray emitting blazars in the $\textit{locus}$ sample as a function of the redshifts and color-coded according to their spectral classification from the BZCat. We have excluded the sources of the $\textit{locus}$ (mostly BZBs) whose redshifts are not well determined or unknown. All $\textit{locus}$ sources have $q_{22}$ lower than 0 and $\sim 96.5\%$ have $q_{22} \leq -0.5$ (≈94\% for sources classified as BZB—blue points—and $\sim 99\%$ for sources classified as BZQ—red points). Based on this observational evidence, we will require WIBRaLS sources to have $q_{22} \leq -0.5$ in order to minimize the contamination from radio-quiet AGNs which can have similar WISE colors at the cost of decreasing the overall completeness of the selection by less than 5\%.

It is interesting to discuss how the $q_{22} \leq -0.5$ condition affects the completeness of our selection. By assuming completeness limits of $\sim 2.5 \text{ mJy}$ at 1.4 GHz for NVSS catalog (Condon et al. 1998), $\sim 1 \text{ mJy}$ at 1.4 GHz for FIRST (Becker et al. 1995), and $\sim 8 \text{ mJy}$ at 843 MHz (Mauch et al. 2003) and with a flux limit $\sim 6 \text{ mJy}$ in the WISE [22] filter (coverage depth 11, 17 the determination of the redshifts of BZBs can be intrinsically difficult because of the lack of significant features in their optical spectra. In order to increase the number of confirmed blazars with reliable spectroscopy, we are carrying out an extensive observational program to acquire the spectra of a large number of WISE-selected candidate blazars. The first results are discussed in Paggi et al. (2014).

We have also evaluated the actual redshift distribution on the distribution of the $q_{22}$ values of the WISE blazar-like sources and on the fraction of sources selected by the $q_{22} \leq -0.5$ condition. We have calculated the $q_{22}$ values for each confirmed $\gamma$-ray emitting blazar in the $\textit{locus}$ sample after varying its redshift on a regularly spaced grid in the interval [0, 4], and assuming a power-law spectral energy distribution with a slope defined by the observed flux densities at 22 $\mu$m and at 1.4 GHz. We found that $\sim 94\%$ of the estimated $q_{22}$ values for all redshift values are still smaller than $-0.5$. 18

Following Bonzini et al. (2013), we used the flux density at 1.4 GHz as the radio flux density $S_{\text{radio}}$. Since flux density measurements at 1.4 GHz are not available in the SUMSS survey, for the SUMSS counterparts, we used the flux densities at 843 MHz instead. A well known property of the blazars is the flatness of their radio spectra (see e.g., Healey et al. 2007) which extends up to low radio frequencies well below 1 GHz (see also Massaro et al. 2013a, 2013c, 2013d, 2014a, for a recent discussion). For this reason, the use of the flux density at 843 MHz instead of the flux density at 1.4 GHz to estimate the $q_{22}$ parameter negligibly affects our analysis. Nonetheless, we checked that the differences introduced in the value of the parameter $q_2$ by the use of the flux density measured at 843 MHz instead of the flux density at 1.4 GHz are small. We used the 553 WISE blazar-like sources with one radio counterpart in the SUMSS catalog and another in the NVSS catalog (see Section 2.2). For these sources we calculated $q_{22}$ parameter values using both flux densities measured at 1.4 GHz and 843 MHz. Figure 4 shows the $q_{22}(1.4 \text{ GHz})$ versus $q_{22}(843 \text{ MHz})$ distribution for this sample of sources. The difference between the values of $q_{22}(1.4 \text{ GHz})$ and $q_{22}(843 \text{ MHz})$ for all the WISE blazar-like sources with radio counterparts in the two surveys is smaller than 10\% of the $q_{22}(1.4 \text{ GHz})$ value for $\sim 88\%$ of the sources. We also note that the distribution of the differences between the values of the two

15 http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec6_3a.html
16 http://wise2.ipac.caltech.edu/docs/release/prelim/expsup/sec4_3g.html

Figure 4. Values of the $q_{22}(1.4 \text{ GHz})$ and $q_{22}(843 \text{ MHz})$ parameters for all WISE blazar-like sources associated with a radio counterpart in both the NVSS and SUMSS surveys. The stars represent the 73 confirmed blazars in this sample that can be cross-matched to a BZCat counterpart. The spectral classification of the WISE blazar-like sources based on their WISE colors (see Section 2.1) is color-coded.

(A color version of this figure is available in the online journal.)

et al. 2013). It is worth noting that the 24 $\mu$m band of the Multi-band Imaging Photometer for Spitzer (MIPS), used to measure the $S_{24 \mu m}$ in previous analyses, is similar to the WISE [22]$\mu$m band (Wright et al. 2010; Cutri et al. 2011). The passbands of the WISE [22] and MIPS-24 band are similar, although the [22] WISE filter is slightly bluer in response. For all the WISE blazar-like sources associated with one radio source using the method described in Section 2.2, we calculated the $q_{22}$ parameter as follows:

$$q_{22} = \log \left( \frac{S_{22 \mu m}}{S_{\text{radio}}} \right).$$

(3)
Figure 5. Scatterplot of the $q_{22}$ values for the confirmed $\gamma$-ray emitting blazars in the locus sample as a function of their redshifts (from the BZCat), with marginal histograms (locus sources with undetermined or uncertain redshifts are excluded). The black solid line shows the threshold $q_{22} \leq -0.5$ used to select the WIBRaLS (see discussion in Section 2.3).

(A color version of this figure is available in the online journal.)

SNR = 11), the nominal value for our selection $q_{22} \leq -0.5$ (see Figure 5) at the WISE 22 $\mu$m limit therefore implies a flux density in the radio $\geq 20$ mJy, within the detection limit of all the radio catalogs. Therefore, our WISE-selected sample should be complete in this regard. On the other hand, some fainter blazars detected in the radio may have escaped detection with WISE in the [22] filter, and the BZB class would be most likely to suffer from this deficit because typically, the synchrotron peak of their spectral energy distributions is at higher energies than FSRQs. Future deep mid-IR followups, perhaps with the James Webb Space Telescope, might extend the sample of bona fide blazars with measured mid-IR properties.

We have explored the possibility that Steep-Spectrum Radio Quasars (SSRQs) contaminate the sample of WIBRaLS selected with our method. The SSRQs are powerful radio sources characterized by a radio spectral index $\alpha_R > 0.5$, usually calculated between 1.4 GHz and 4.85 GHz. In order to evaluate the contamination from SSRQs, we have used a sample of 18 bona fide SSRQs selected by Gu & Li (2013) among the SDSS optical quasars in the Stripe 82 region and with radio counterparts in the FIRST, PMN, and GB6 surveys. The cross-match of the SSRQs radio positions with the WISE AllWISE catalog within a maximum radius of 3.4 (the cross-match radius for FIRST radio counterparts estimated in Section 2.2) yields 18 unique WISE counterparts. Two of these WISE counterparts not detected in the W4 band have been discarded. The application of the WISE color selection method described in Section 2.1 to the 16 remaining WISE SSRQs counterparts produced 11 sources selected as WISE blazar-like sources, all classified as BZB-type candidates. The distribution of the $q_{22}$ values for the WISE counterparts of the 11 SSRQs spans the interval $[-2.2, 0.3]$, and 8 of them ($\sim 73\%$) have $q_{22} < -0.5$, i.e., are compatible with the $q_{22} \leq -0.5$ condition used to extract the WIBRaLS. Therefore, 50% of the SSRQs sample produced by Gu & Li (2013) is included in the WIBRaLS catalog. We found that the WIBRaLS catalog can contain SSRQs and that it is not possible to selectively exclude this class of sources using the $q_{22}$ since their $q_{22}$ values have a similar distribution to the $q_{22}$ values for the confirmed $\gamma$-ray emitting blazars. While a quantitative estimate of the contamination from SSRQs contaminants based on this small sample is impossible, we discuss this point further in Section 4.2.

The distribution of the $q_{22}$ values for all sources in the catalog of WISE blazar-like sources with at least one radio counterpart, color-coded according to the WISE spectral classification in BZB-type, BZQ-type candidates, and sources compatible with the mixed region of the locus model, is shown in Figure 6. The solid colors represent the sources selected as WIBRaLS based on the criterion $q_{22} < -0.5$. The distribution of $q_{22}$ values for the sources classified as BZB-type candidates and mixed show only one peak located in the $-1.5 < q_{22} < -0.5$ range, while the distribution of $q_{22}$ values for sources classified as BZQ is clearly bimodal, with another peak at $q_{22} \sim 0.5$.

The number of total distinct WISE blazar-like sources with a radio counterpart selected as WIBRaLS is 10,002. Using the $q_{22} \leq -0.5$ criterion, we selected 6362, 1775, and 1865 distinct radio sources in the NVSS, FIRST, and SUMSS surveys, respectively (see Table 2). The final number of unique WIBRaLS
is 7855 (see Table 3). In Section 3, we provide more details on the composition of the final catalog of WIBRaLS.

### 3. The WIBRALS Catalog

We applied the three-steps procedure described in Section 2 to the whole WISE AllWISE Catalog of sources detected in all four WISE filters, selecting a total of $\sim 2.65 \times 10^5$ WISE blazar-like sources (the composition of this sample in terms of WISE classes and types is shown in Table 2). Then, we selected the WISE blazar-like sources that can be spatially associated with one radio source from three radio surveys, namely, the NVSS, SUMSS, and FIRST surveys, using the optimal radii established in Section 2.2. We found a total of 20,845 WISE blazar-like sources with at least one counterpart from any one of the three radio surveys. In particular, 11928, 6592, and 2325 WISE blazar-like sources have a unique radio counterpart in the NVSS, FIRST, and SUMSS surveys, respectively. 3660 WISE blazar-like sources can be associated with one source in both the NVSS and FIRST surveys and 553 WISE blazar-like sources can be associated with one radio source in both the NVSS and SUMSS surveys, respectively. For consistency, in the case of multiple radio counterparts from distinct surveys, we have always adopted as the final radio counterpart of the WISE blazar-like source the NVSS source (FIRST and SUMSS footprints do not overlap), because NVSS covers the largest area among the radio surveys used in this paper. The final list of single distinct radio counterparts of our sample of WISE blazar-like sources contains 11,928 NVSS sources, 2932 FIRST sources, and 1772 SUMSS sources (see Table 2), for a total of 16,632 WISE blazar-like sources with a unique radio counterpart. We finally extract the catalog of WIBRaLS by selecting only the WISE blazar-like sources with a radio-loudness parameter of $q_{22} \leq -0.5$ (see Section 2.3 for details on the $q_{22}$ parameter and the selection performed).

The final catalog of WIBRaLS contains 7855 unique sources that satisfy all our criteria: 6362 of these WISE sources are associated with an NVSS counterpart, 1407 with a source in the SUMSS survey, and the remaining 86 can be cross-matched to a unique source from the FIRST survey (Table 3). The final WIBRaLS sample, according to the spectral classification based on the WISE colors and discussed in Section 2.1, is composed of 1682 sources classified as BZBs, 3973 sources classified as BZQs, and 2194 sources whose colors are compatible with the mixed region of the locus model. The WIBRaLS can also be split into 129 class A sources ($\sim 2.4\%$ of the total sample), 714 class B sources ($\sim 9.1\%$), and 7012 class C sources ($\sim 89\%$). These fractions are similar to the class fractions for the sample of WISE blazar-like sources before the selection based on the radio counterparts and $q_{22}$ radio-loudness parameters (Section 2.1). They follow from the stringent definition of Class A (see Section 2.1) in terms of the threshold on the WISE score. The composition of the final WIBRaLS catalog is shown in Table 3.

Among the 7855 WIBRaLS, 1295 sources ($\sim 16.5\%$) can be spatially re-associated with a known blazar listed in the ROMA-BZCAT (v4.1)20 (Massaro et al. 2009, 2011a) within $3\,\prime\prime$ (see also D’Abrusco et al. 2012, 2013, for the choice of this association radius), corresponding to $\sim 41\%$ of the 3149 total members of the ROMA-BZCat. Moreover, 454 of the 1295 ROMA-BZCat counterparts of the WIBRaLS can be spatially associated with a $\gamma$-ray emitting source of the locus sample ($\sim 76.5\%$), extracted from the 2FGL catalog (Nolan et al. 2012) of $\gamma$-ray sources. This fraction is lower than the $81\%$ fraction of locus sources contained, by definition, in the model of the locus in the WISE color space (D’Abrusco et al. 2013). The fraction of confirmed ROMA-BZCat sources in the locus sample that can be spatially associated with one member of the WIBRaLS catalog ($\sim 76.5\%$) is also significantly lower than the $96.5\%$ of locus sources selected by directly applying the condition on the $q_{22}$ value to their radio and WISE counterparts (see Section 2.3). The reason for the discrepancy between the $81\%$ of the locus sample contained in the locus model by definition, and the $\sim 76.5\%$ of locus sources that are selected as WIBRaLS can be found in the significant differences between the WISE photometry of $\sim 10\%$ of the WISE counterparts of the locus sources in the AllSky release used to define the locus model by D’Abrusco et al. (2013) and the photometry in the AllWISE WISE release, used here.

The distribution of the final catalog of WIBRaLS in the three-dimensional space generated by the WISE colors [3.4]–[4.6], [4.6]–[12], and [12]–[22], is shown in Figure 7 where each

![Figure 6](image-url)
source is color-coded according to the spectral class assigned based on its WISE colors. The three projections of the WIBRaLS 3D WISE color distribution onto the three color–color planes clearly show that in each plane, the peaks of the density distributions lie in the regions occupied by the sources classified as BZQs. Moreover, in Figure 7, 10^5 generic WISE sources located at high galactic latitude (|b| > 15°) and detected in all four filters have been used to plot the gray arbitrary log-spaced isodensity contours. The comparison with the black density contours of the WIBRaLS data set shows that significant overlap between the distributions of WIBRaLS and generic WISE sources in each of the three color–color diagrams can only be removed in the 3D WISE color space.

The sky distribution in galactic coordinates of all WIBRaLS, color-coded according to their WISE spectral class, is shown in Figure 8. The sky density of this sample depends on the spatial density of the sources in the WISE photometric catalog whence the WISE sources with colors compatible with the locus of the γ-ray emitting blazars are extracted and from the surface density of the three radio surveys. Contrary to the radio surveys that reach an almost homogenous depth over their footprints, the limiting sensitivity of the WISE catalog in each band is not uniform on the sky (compare with Figure 8 at the Explanatory Supplement to the AllWISE Data Release Products21). An excerpt of the catalog of WIBRaLS is shown in Table 4. The catalog contains the following columns: WIBRaLS unique name, AllWISE WISE name, Right Ascension and declination of the WISE source position, values of the three WISE colors and their uncertainties (corrected for galactic absorption), values of the scores for the BZB, BZQ, and mixed regions of the locus model, WISE-based type and spectral class, name of the final radio counterpart associated with the WISE source, and value of the q22 parameter. The whole catalog will be available through Vizier and as a Cone Search service through all tools compatible with the Virtual Observatory (VO) specifications.

4. DISCUSSION

The nature of candidate blazars can only be confirmed through optical spectroscopic follow-up observations or by collecting extensive multi-wavelength photometric data to model their spectral energy distribution. Several recent efforts have validated the nature of a large number of candidate blazars, selected with different techniques and associated with unidentified γ-ray sources in the 2FGL, using new and archival spectroscopic data (Shaw et al. 2013; Masetti et al. 2013; Paggi et al. 2014; Landoni et al. 2014; Massaro et al. 2014b). Nonetheless, given the current lack of observations that would firmly establish the nature of the whole sample of WIBRaLS, the only valuable information about the nature of the catalog discussed in this paper can be indirectly inferred by comparison of our sample with similarly WISE-based AGN selection techniques (Section 4.1). The comparison with AGN selection techniques allows us to rule out significant contamination from non-AGNs, especially in the more numerous subclass of WIBRaLS classified as BZQs. This comparison also underlines the significant difference in the WISE colors of the WIBRaLS classified as BZBs (BL Lacs) compared to the FSRQ subclass and the general population of radio-quiet mid-IR AGNs. Finally, in order to identify the possible contamination in our WIBRaLS catalog from AGNs not classified as blazars, in Section 4.2 we also discuss the intersection of our sample and one of the largest compilations of AGNs, QSOs, and BL Lacs available, the VERONCAT (Véron-Cetty & Véron 2010).

4.1. Comparison with Other WISE-based AGN Selection Techniques

Selection techniques for AGNs based on their photometric mid-IR properties have become commonplace with the availability of WISE data. Most such techniques have been fine-tuned to identify AGNs usually selected by other mid-IR colors (Spitzer) and their X-ray emission. In this Section, we will compare the sample of WIBRaLS with WISE-based selection criteria from Jarrett et al. (2011), Stern et al. (2012),

![Figure 7. Three-dimensional distribution of the sources in the WIBRaLS catalog (each source is color-coded according to the WISE spectral classification) in the space generated by the WISE [3.4]–[4.6], [4.6]–[12], and [12]–[22] colors. The black and gray lines displayed on the three planes represent the projected isodensity contours associated with 10 log-spaced levels of the three-dimensional distribution of WIBRaLS and of a sample of random sources detected in all four WISE filters, respectively. The approximate locations of different typical classes of objects in the [4.6]–[12] vs. [3.4]–[4.6] color–color plane, according to Wright et al. (2010), are also shown.](http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/sec4_2.html)
### Table 4
Sample of Rows of the Catalog of WIBRaLS

| WIBRaLS\(^a\) | WISE\(^b\) Name | R.A.\(^c\) (deg) | Decl.\(^d\) (deg) | \(c_{12}\)\(^e\) (mag) | \(\sigma_{c_{12}}\)\(^f\) (mag) | \(c_{23}\)\(^g\) (mag) | \(\sigma_{c_{23}}\)\(^h\) (mag) | \(c_{34}\)\(^i\) (mag) | \(\sigma_{c_{34}}\)\(^j\) (mag) | \(s_{BZB}\)\(^k\) | \(s_{MX}\)\(^l\) | \(s_{BZQ}\)\(^m\) | Type\(^n\) | Class\(^o\) | Radio\(^p\) Name | \(q_{22}\)\(^q\) |
|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| WB J0004−4736  | J000435.65−473619.6 | 1.149 | −47.605 | 1.09 | 0.03 | 3.32 | 0.03 | 2.31 | 0.07 | 0.0 | 0.0 | 0.83 | BZQ | B | SUMSSJ000435−473620 | −1.65 |
| WB J0005+1609  | J000559.23+160949.0 | 1.497 | 16.164 | 1.06 | 0.03 | 2.61 | 0.03 | 2.36 | 0.06 | 0.0 | 0.87 | 0.0 | MIXED | B | NVSSI00559+160946 | −1.48 |
| WB J0005+3820  | J000557.18+382015.1 | 1.488 | 38.338 | 1.1 | 0.03 | 3.27 | 0.03 | 2.68 | 0.03 | 0.0 | 0.0 | 0.95 | BZQ | A | NVSSI00557+382015 | −0.87 |
| WB J0005+5428  | J000504.36+542825.0 | 1.268 | 54.474 | 1.09 | 0.04 | 2.47 | 0.06 | 2.37 | 0.13 | 0.0 | 0.7 | 0.0 | MIXED | C | NVSSI00504+542825 | −1.43 |
| WB J0005−1648  | J000517.92−164804.4 | 1.325 | −16.801 | 1.02 | 0.04 | 2.46 | 0.06 | 2.41 | 0.18 | 0.11 | 0.54 | 0.0 | MIXED | C | NVSSI00517−164805 | −1.61 |
| WB J0005−2758  | J000558.54−275857.7 | 1.494 | −27.983 | 1.01 | 0.03 | 2.4 | 0.06 | 2.23 | 0.22 | 0.53 | 0.11 | 0.0 | BZB | C | NVSSI00558−275900 | −1.79 |
| WB J0005−4518  | J000536.67−451845.6 | 1.403 | −45.313 | 1.11 | 0.05 | 2.69 | 0.12 | 2.64 | 0.33 | 0.0 | 0.08 | 0.32 | BZQ | C | SUMSSJ00536−451848 | −0.66 |
| WB J0005−6223  | J000527.13−622302.6 | 1.363 | −62.384 | 1.21 | 0.04 | 2.87 | 0.05 | 2.58 | 0.13 | 0.0 | 0.0 | 0.71 | BZQ | C | SUMSSJ00527−622302 | −0.73 |
| WB J0006+1235  | J000623.05+123553.1 | 1.596 | 12.598 | 1.29 | 0.03 | 2.81 | 0.03 | 2.32 | 0.07 | 0.0 | 0.0 | 0.41 | BZQ | C | NVSSI00623+123558 | −1.03 |
| WB J0006+3422  | J000607.37+342202.4 | 1.531 | 34.372 | 1.06 | 0.04 | 2.66 | 0.06 | 2.03 | 0.21 | 0.32 | 0.21 | 0.0 | BZB | D | NVSSI00607+342220 | −1.01 |

**Notes.** The complete catalog in electronic format will be available on Vizier and as a Cone Search service through all VO-compatible tools.

\(^a\) WIBRaLS name (IAU format).

\(^b\) WISE name.

\(^c\) Right Ascension.

\(^d\) Declination.

\(^e\) [3.4]−[4.6] WISE color (corrected for galactic extinction).

\(^f\) Uncertainty on the [3.4]−[4.6] WISE color.

\(^g\) [4.6]−[12] WISE color (corrected for galactic extinction).

\(^h\) Uncertainty on the [4.6]−[12] WISE color.

\(^i\) [12]−[22] WISE color (corrected for galactic extinction).

\(^j\) Uncertainty on the [12]−[22] WISE color.

\(^k\) Score for the BZB region of the *locus*.

\(^l\) Score for the mixed region of the *locus*.

\(^m\) Score for the BZQ region of the *locus*.

\(^n\) Spectral type (see Section 2.1).

\(^o\) Class (see Section 2.1).

\(^p\) Name of the radio counterpart.

\(^q\) \(q_{22}\) value.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Mateos et al. (2012), and Assef et al. (2013). The essential description of each of these selection techniques is given.

1. Jarrett et al. (2011) defined a region of the $\text{[3.4]}$–$\text{[4.6]}$ WISE color–color diagram (the WISE AGNs "box"), using the Spitzer color classification criteria determined by Stern et al. (2005) to validate the WISE selection. The AGN box is defined as the region of the $\text{[4.6]}$–$\text{[12]}$ versus $\text{[3.4]}$–$\text{[4.6]}$ diagram bounded by the constant lines: $\text{[4.6]}$–$\text{[12]} > 2.2$, $\text{[4.6]}$–$\text{[12]} < 4.2$, and $\text{[3.4]}$–$\text{[4.6]} < 1.7$ and the relation $\text{[3.4]}$–$\text{[4.6]} > 0.1(\text{[4.6]}$–$\text{[12]})+0.38$.

2. Stern et al. (2012) defined a WISE color criterion of $\text{[3.4]}$–$\text{[4.6]} > 0.8$ for sources with a magnitude $\text{[4.6]} < 15.0$, which identifies $\sim 62 \pm 5.4$ AGNs per deg$^2$. This condition selects 78\% of the Spitzer AGN candidates selected as discussed in Stern et al. (2005), with an efficiency of 95\%.

3. Assef et al. (2013) extended the selection proposed by Stern et al. (2012) based on the WISE photometry in the $\text{[3.4]}$ and $\text{[4.6]}$ bands to provide a parameterized criterion that can be changed to maximize either the efficiency or the completeness of the selection. The general form of the constraint is $\text{[3.4]}$–$\text{[4.6]} > \alpha_R \exp[\beta_R(\text{[4.6]} - \gamma_R)^2]$. In this paper, we have used two different sets of the parameters $[\alpha_R, \beta_R, \gamma_R]$, namely, $[\alpha_R, \beta_R, \gamma_R] = [0.662, 0.232, 13.97]$ and $[\alpha_R, \beta_R, \gamma_R] = [0.530, 0.183, 13.76]$, which yield efficiencies of 90\% and 75\%, respectively (Assef et al. 2013).

4. Mateos et al. (2012) presented a selection based on the WISE magnitudes in the $\text{[3.4]}$, $\text{[4.6]}$, and $\text{[12]}$ bands, defined in a wedge bounded by the following constraints: $\text{[4.6]}$–$\text{[12]} \geq 2.517$ and $0.315(\text{[4.6]}$–$\text{[12]}$) $- 0.222 < \text{[3.4]}$–$\text{[4.6]} < 0.315(\text{[4.6]}$–$\text{[12]}$)+0.796. This method takes into account uncertainties on the WISE photometry of the sources and is able to recover $\sim 97\%$ and $\sim 77\%$ of the type-1 and type-2 bona-fide AGNs observed in the Bright Ultra-Hard XMM-Newton Survey (Mateos et al. 2013). The same authors discuss a modified WISE-based AGN selection technique that employs photometry in all four WISE filters. We will not consider this selection technique further in this paper because it attains a lower efficiency and completeness (Mateos et al. 2012).

The projections of the WIBRaLS distribution onto the WISE $\text{[4.6]}$–$\text{[12]}$ versus $\text{[3.4]}$–$\text{[4.6]}$ color–color plane and the $\text{[3.4]}$–$\text{[4.6]}$ versus $\text{[4.6]}$ color–magnitude plane are shown in Figure 9. The regions of the two planes used to select the AGNs according to the four AGN selection methods described above are overplotted on the distribution of the WISE blazar-like radio sources.

We have applied the four distinct AGN selection criteria to the 7855 members of the catalog of WIBRaLS. The numbers and fractions of WIBRaLS selected as candidate AGNs by each of the four AGN selection methods, split according to their spectral classification based on their WISE colors, are reported in Table 5 and shown in Figure 10.

The selection methods from Jarrett et al. (2011) and Stern et al. (2012) recover the largest fractions of WIBRaLS sources (97\% and 94\%, respectively). The criterion from Assef et al. (2013) with efficiency $e = 75\%$, selects 90\% of the whole sample of WIBRaLS, while the same method with selection efficiency $e = 90\%$ and the method from Mateos et al. (2012) both recover 75\% and 85\% of our catalog, respectively. Figure 10 shows the percentage of WIBRaLS selected as AGN candidates by each method for each WISE spectral class. The fractions of WIBRaLS classified as BZBs and in the mixed region that are selected as AGNs by either of the four methods discussed is larger than 90\%, while the corresponding fractions of WIBRaLS classified as BZBs are significantly

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**Figure 8.** Aitoff projection of the sky distribution in galactic coordinates of the catalog of WIBRaLS, color-coded according to their WISE spectral classification into BZBs, BZQs, or mixed. The empty region is not covered by any of the three radio surveys used in this paper to associate the WISE blazar-like sources. (A color version of this figure is available in the online journal.)
Figure 9. Upper panel: projection of the distribution of WIBRaLS onto the [4.6]–[12] vs. [3.4]–[4.6] WISE color–color plane. The regions used by the AGN selection techniques from Jarrett et al. (2011) and Mateos et al. (2012) are also shown. Lower panel: projection of the distribution of WISE blazar-like radio sources onto the [3.4]–[4.6] vs. [4.6] WISE color–magnitude plane, showing also the curves used to select AGNs according to (Stern et al. 2012) and Assef et al. (2013; the yellow dotted line represents the selection with an efficiency of \( e = 90\% \), the dashed-dotted line the selection with \( e = 75\% \)). In both panels, the WIBRaLS are color-coded according to their WISE-based spectral classification, with red, blue, and magenta symbols associated with sources classified as BZQs, BZBs, and mixed, respectively. Moreover, the two-dimensional density distributions of the whole WIBRaLS catalog in the two planes are represented by the isodensity contours (black solid lines).

(A color version of this figure is available in the online journal.)

Table 5

Fraction of WIBRaLS Selected as AGNs by Three Distinct WISE-based Selection Methods: Method (A) (Jarrett et al. 2011), Method (B) (Stern et al. 2012), Method (C) (Assef et al. 2013), and Method (D) (Mateos et al. 2012)

| WISE | BZB | Mixed | BZQ | Total |
|------|-----|-------|-----|-------|
| Method (A) | 1396 (~83%) | 2194 (100%) | 3979 (100%) | 7569 (~96%) |
| Method (B) | 1136 (~68%) | 2192 (~100%) | 3928 (~99%) | 7526 (~92%) |
| Method (C) (\( e = 90\% \)) | 682 (~41%) | 1599 (~73%) | 3612 (~97%) | 5893 (~75%) |
| Method (C) (\( e = 75\% \)) | 1238 (~74%) | 1982 (~90%) | 1982 (~90%) | 7100 (~90%) |
| Method (D) | 565 (~35%) | 1978 (~90%) | 3979 (~100%) | 6522 (~83%) |

Notes. The selection technique discussed in (Assef et al. 2013) is applied with two different sets of parameters associated with efficiencies of \( e = 90\% \) and \( e = 75\% \), respectively. The fraction of selected sources relative to the number of WIBRaLS in each spectral class is shown in parentheses.

lower, spanning from ~35% of the Mateos et al. (2012) method to ~84% of the Jarrett et al. (2011) method.

The total fraction of WIBRaLS sources not selected by either one of these AGN selection techniques is ~5%, almost entirely (~94%) classified as BZB by our method (Figure 9). The total fraction of WIBRaLS classified as BZB selected by any of the five AGN selection techniques used is ~68%. On the other hand, the fact that WIBRaLS classified as BZQs are overwhelmingly selected as AGNs by each of the methods considered (see Table 5) is explained by the large overlap between the region occupied by the WIBRaLS classified as candidate BZQs and the AGNs boxed in the two-dimensional WISE [3.4]–[4.6] versus [4.6]–[12] color space (see the upper panel in Figure 9 and discussion in Wright et al. 2010; Jarrett et al. 2011; D’Abrusco et al. 2012). The BZQ-type WIBRaLS have mid-IR properties that are similar to the mid-IR and optical properties of generic quasars and, more specifically, to the population of radio-quiet AGNs usually selected by mid-IR-based
techniques. The contamination from non-FSRQs in the WIBRaLS catalog is further reduced by selecting only sources that can be positionally associated with radio counterparts and with \( q_{22} \) values compatible with the values of confirmed blazars. A relevant fraction of the WIBRaLS classified as BZBs (from \( \sim 15\% \) to \( \sim 65\% \) for the AGN selection methods in Table 5) are bluer than the typical AGNs in WISE and, for this reason, are not selected by the techniques discussed in this section.

### 4.2. Cross-match with the VERONCAT

We have positionally cross-matched the WIBRaLS catalog with the Veron Catalog of Quasars & AGNs (VERONCAT; Véron-Cetty & Véron 2010, v13). The VERONCAT is an inhomogeneous compilation of known AGNs, containing \( \sim 1.7 \times 10^5 \) sources in its 13th version. Sources in the VERONCAT are broadly classified in AGNs (i.e., Seyfert galaxies and LINERs fainter than \( M_B = -22.25 \)), QSOs (star-like sources with an absolute magnitude of \( M_B < -22.25 \) and broad emission lines) and BL Lac objects (confirmed or potential BL Lac objects based on optical and radio observations). For the cross-match, we used a conservative maximum radius of 1″ around the position of the radio counterparts for each of the WIBRaLS, since all coordinates reported in the VERONCAT are based on radio or optical observations and their positional uncertainties are systematically smaller than 1″.\(^{22}\) We found counterparts in VERONCAT for 797 WIBRaLS (\( \sim 10.1\% \) of the total number of WIBRaLS): based on the classification available in the VERONCAT, 57% of the counterparts are classified as quasars, 13% as Seyferts, 14% as BL Lacs, and the remaining \( \sim 16\% \) are classified as generic AGNs. It is relevant to emphasize that the classification available in the VERONCAT is not always reliable. For example, a non-negligible fraction of sources classified as BL Lacs in the VERONCAT is not classified as blazars in the ROMA-BZCat (Massaro et al. 2011a). In terms of the WISE spectral classification, the cross-matched WIBRaLS are split into 512 BZQ (\( \sim 52\% \)) candidates, 213 BZB (\( \sim 20\% \)) candidate blazars, and the remaining 70 WIBRaLS are located in the mixed region of the locus model. The fact that the \( \sim 90\% \) of WIBRaLS cannot be associated with a VERONCAT source likely depends on a lack of optical spectroscopic observations and redshift measurements required for a source to be included in the VERONCAT. In particular, given that the optical spectra of BL Lacs are typically featureless and the estimation of the redshift can be problematic, we expect the VERONCAT to miss a large fraction of confirmed blazars. This conclusion is further reinforced by the fact that the positional cross-match between the most recent version of the ROMA-BZCat and VERONCAT within 1″ only returns 1649 cross-matches on 3149 total sources, corresponding to \( \sim 52.4\% \) of the ROMA-BZCat.

Using the optical B magnitude and radio flux density at 6 cm available for a subset of sources in the VERONCAT, we defined as radio-loud AGNs the sources with a radio-loudness parameter \( \log R \geq 1 \) where \( R = S_{6\,\text{cm}}/S_B \) is the ratio between the 6 cm radio and the B flux densities. We assumed that sources with no radio flux measurement are radio-quiet. We found that 644 out of the 797 total cross-matches (\( \sim 81\% \)) between the WIBRaLS catalog and VERONCAT obtained with a maximum radial distance of 1″ are radio-loud, suggesting a contamination from radio-quiet AGNs in our catalog smaller than \( \sim 19\% \). We also checked the contamination from SSRQs in our sample by determining the radio spectral index \( \alpha_R \) between the flux densities measured at 20 cm and 6 cm, both available for all 644 VERONCAT-WIBRaLS counterparts. We have considered the sources with \( \alpha_R > 0.5 \) to be SSRQs. We found only 73 sources that can be classified as SSRQs, corresponding to \( \sim 11\% \) of the total number of VERONCAT counterparts. A more detailed quantitative estimate of the contamination in the WIBRaLS sample introduced by SSRQs is made difficult by the shortage of large catalogs of SSRQs. Nonetheless, based on the result obtained from the VERONCAT, we can assume that the fraction of SSRQs in the WIBRaLS sample will not exceed \( \sim 10\% \). Furthermore, it has been shown that confirmed BL Lacs from the ROMA-BZCat can have steep radio spectra (see, for instance, Figure 11 in Massaro et al. 2013d), making the observational differences in the definition of the two classes of AGNs less sharp. This fact, in principle, indicates that the effective contamination from SSRQs is smaller than the nominal \( \sim 11\% \) determined here.

We do not observe significant differences between the distributions of the WISE colors and fluxes of the sources that have been associated with VERONCAT counterparts and the remainder of the WISE blazar-like radio sources. As expected, the WIBRaLS classified as BZB-type candidate blazars are overwhelmingly (\( \sim 92\% \)) associated with VERONCAT counterparts classified as BL Lac objects, while the fractions of VERONCAT counterparts classified as BL Lac objects and associated with WIBRaLS of BZQ-type or mixed type are small (\( \sim 6\% \) and \( \sim 19\% \), respectively). Even though our results are based on a small subset of the catalog of WIBRaLS cross-matched with a VERONCAT source, they indicate that the fraction of AGNs not classified as blazars is much larger for BZQ and mixed candidate blazars than for BZB candidate blazars.

### 5. SUMMARY AND CONCLUSIONS

We have presented a catalog of candidate \( \gamma \)-ray blazars extracted from the AllWISE WISE Data Release, using a modified version of the association method for \( \gamma \)-ray unidentified sources from D’Abrusco et al. (2013). This method is based on a model

\[^{22}\text{Using a radius of 3″, we found 1618 unique cross-matches with VERONCAT sources. The fractions of different WISE spectral classes of the WIBRaLS associated with this larger radius and the composition of the cross-matches in terms of the classification available in the VERONCAT are similar to the ones described for the smaller sample obtained with radius 1″.}\]
of the three-dimensional locus occupied by the confirmed γ-ray emitting blazars in the WISE color space. The WISE blazar-like sources have been spatially associated with radio sources in either the NVSS, FIRST, or SUMSS surveys. A further selection based on their radio-loudness has been performed using the $q_{12}$ parameter to retain only radio-loud AGNs in our sample and minimize the contamination from other extragalactic radio sources. The main results of this paper can be summarized as follows.

1. The final catalog of unique WIBRaLS contains 7855 sources, split into 1682 BZB-type candidate blazars, 3973 BZQ-type candidate blazars, and 2194 candidate blazars classified as mixed. The sky distribution of the members of the catalog reflects the coverage of the radio surveys used and the variable limiting sensitivity of the WISE survey, especially in the [22] filter.

2. Out of the total 7855 WIBRaLS, 1295 sources ~16.5% can be spatially associated with bona-fide blazars in the ROMA-BZCat. The number of WIBRaLS that can be cross-matched with one confirmed γ-ray emitting blazars extracted from the ROMA-BZCat and used to define the model of the locus is 454 (~76.5% of the locus sample). Moreover, 797 WIBRaLS (mostly classified as BZQs according to our method based on WISE colors) can be cross-matched to VERONCAT sources within 1″. Their VERONCAT counterparts are classified as quasars (57%), Seyferts (13%), BL Lacs (14%), and generic AGNs (~16%).

3. The comparison of the catalog of WIBRaLS with other WISE-based AGN selection techniques suggests that the contamination from non-AGNs in our catalog is very low. While almost all the WISE blazar-like sources classified as BZQs (representing ~50% of the total sample) are selected by either one of the other techniques, the fraction of WIBRaLS classified as BZBs that are recovered by the other methods is significantly lower (from ~30% to ~70%). These differences depend on the fact that BL Lac candidates (BZB-type WIBRaLS) are significantly bluer than the typical AGNs in WISE, especially in the [3.4] and [4.6] μm filters.

4. We have estimated the contamination in the WIBRaLS catalog from radio-quiet AGNs and SSRQs. Using a sample of 797 WIBRaLS spatially associated with VERONCAT sources, we found that only ~19% of our sample can be considered radio-quiet. This fraction represents an upper limit for the contamination because we considered VERONCAT sources missing radio flux density measurements at 6 cm to be radio-quiet. We also confirmed that SSRQs can contaminate the WIBRaLS catalog using a bona fide sample of 18 SSRQs produced by Gu & Li (2013). Also in this case, using the VERONCAT, we showed that the fraction of SSRQ contaminants in our catalog does not exceed ~10%.

Our catalog of WISE-selected γ-ray blazar candidates is intended to be a useful resource for the future investigations of the unidentified sources detected in both the γ-ray and X-ray energies. In this paper, we do not address the problem of quantifying the effect of several factors that can, in principle, prevent a γ-ray blazar candidate from our catalog from being observed in current and future γ-ray observations (including variability, intrinsic scatter in the distribution of mid-IR versus γ-ray fluxes for confirmed blazars, and the procedure for source detection in the Fermi LAT data). Nonetheless, we expect that the catalog of WIBRaLS will provide astronomers with a valuable resource for constraining the nature of unidentified high-energy sources.

As an example, Paggi et al. (2013) have shown that a large fraction of the unassociated γ-ray sources located in regions of the sky observed by the X-Ray Telescope (XRT) on board the Swift satellite can be associated with X-ray counterparts whose coordinates are compatible with the position of WISE candidate blazars selected with the method discussed by D’Abrusco et al. (2013). Moreover, Maselli et al. (2013) have used WISE candidate γ-ray emitting blazars to associate 24 unidentified hard X-ray sources of the Third Palermo Swift Burst Alert Telescope. Cowperthwaite et al. (2013) have also used the method for the extraction of candidate γ-ray emitting blazars based on the locus in the WISE color space to associate 13 sources, extracted from the Astronomer’s Telegrams, that exhibit non-periodic variability, mostly at high energies. These examples clearly show that WISE-based selection of γ-ray emitting candidate blazars can be successfully used to constrain the nature of unidentified high-energy sources observed in different spectral ranges and with different techniques.

The authors thank the anonymous referee for the insightful comments that have helped to significantly improve the manuscript. This investigation is supported by the NASA grants NNX12AO97G and NNX13AP20G. The work by G.T. is supported by the ASI/INAF contract 1/005/12/0. H.A.S. acknowledges partial support from NASA/JPL grant RSA 1369566. This research has made use of data obtained from the high-energy Astrophysics Science Archive Research Center (HEASARC) provided by NASA’s Goddard Space Flight Center, the SIMBAD database operated at CDS, Strasbourg, France, and the NASA/IPAC Extragalactic Database (NED) operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. Part of this work is based on the NVSS (NRAO VLA Sky Survey): The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation and on the VLA low-frequency Sky Survey (VLSS). The Molonglo Observatory site manager, Duncan Campbell-Wilson, and the staff, Jeff Webb, Michael White, and John Barry, are responsible for the smooth operation of the Molonglo Observatory Synthesis Telescope (MOST) and the day-to-day observing program of SUMSS. The WENSS project was a collaboration between the Netherlands Foundation for Research in Astronomy and Leiden Observatory. We acknowledge the WENSS team consisting of Ger de Bruyn, Yuan Tang, Roeland Rengelink, George Miley, Huub Rottgering, Malcolm Bremer, Martin Bremer, Wim Brouw, Ernst Raimond, and David Fullagar for extensive work aimed at producing the WENSS catalog. TOPCAT24 (Taylor, 2005) was used for the preparation and manipulation of the tabular data and the images.

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