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ON THE NATURE OF THE GAMMA-RAY SOURCE 2FGL J1823.8+4312: THE DISCOVERY OF A NEW CLASS OF EXTRAGALACTIC X-RAY SOURCES

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ABSTRACT

One of the unsolved mysteries of gamma-ray astronomy concerns the nature of the unidentified gamma-ray sources. Recently, using the Second *Fermi* LAT source catalog (2FGL) and the Wide-field Infrared Survey Explorer (WISE) archive, we discovered that the WISE counterparts of gamma-ray blazars, a class of active galactic nuclei, delineate a region (the WISE Gamma-ray Strip) in the 3-dimensional infrared color space well separated from the locus of the other astronomical objects. Based on this result, we built an association procedure to recognize if there are WISE blazar candidates within the positional uncertainty region of the unidentified gamma-ray sources. Here we **report on our analysis of 2FGL J1823.8+4312,** a gamma-ray active galactic nucleus of uncertain type associated with the X-ray source 1RXS J182418.7+430954 according to the 2FGL, to verify whether it is a blazar. Applying our association method we found two sources with IR colors typical of gamma-ray blazars, located within the 99.9% confidence region of 2FGL J1823.8+4312: WISE J182352.33+431452.5 and WISE J182409.25+431404.7. Then we searched in the *Chandra*, NVSS and SDSS archival observations for their counterparts. We discovered that WISE J182352.33+431452.5, our preferred gamma-ray blazar candidate according to our WISE association procedure, is detected in the optical and in the X-rays but not in the radio, making it extremely unusual if it is a blazar. Given its enigmatic spectral energy distribution, we considered the possibility that it is a "radio faint blazar" or the prototype of a new class of extragalactic sources, our conclusion is independent **of** whether WISE J182352.33+431452.5 is the actual counterpart of 2FGL J1823.8+4312.

Subject headings: X-rays: galaxies - galaxies: active - galaxies: BL Lacertae objects - radiation mechanisms: non-thermal

1. INTRODUCTION

One of the biggest challenges in contemporary gamma-ray astronomy is classification and identification of the unidentified gamma-ray sources (e.g., Thompson 2004; Reimer 2005). According to the Second Fermi LAT catalog (2FGL, Nolan et al. 2012), which comprises 1873 gamma-ray sources, about 1/3 of high-energy gamma-ray emitters are still of unknown origin although statistical studies suggest that many are members of known classes (Ackermann et al. 2012).

Since the era of the Compton Gamma-Ray Observatory (e.g., Hartman et al. 1999), blazars, an intriguing class of radio loud active galactic nuclei (AGNs), have constituted the largest population of known gamma-ray sources (e.g., Mukherjee et al. 1997) even up to TeV energies[5].

Blazars are characterized by non-thermal radiation over the entire electromagnetic spectrum, flat radio spectra that steepen toward the infrared (IR), apparent superluminal motions, rapid spectral variability and a double-humped spectral energy distributions (SEDs) (e.g., Urry & Padovani 1995). Blazars have two subclasses: BL Lac objects, characterized by weak or absent optical emission lines, and flat spectrum radio quasars showing broad emission lines similar to quasars (e.g., Stickel et al. 1991; Stoke et al. 1991).

Recently, using the blazar ROMA-BZCAT catalog[6] (Massaro et al. 2009; Massaro et al. 2010; Massaro et al. 2011a) combined with the Wide-field Infrared Survey Explorer (WISE) preliminary data release[7] (Wright et al. 2010), Massaro et al. (2011b) showed that blazars cover a distinct 3-dimensional region (the WISE Blazar Strip) in IR color space that is well distinct from the locus of other Galactic and extragalactic sources . They also found that the subregion delineated by gamma-ray blazars in the IR color-color plots (i.e., the WISE Gamma-ray Strip) is even narrower than the WISE Blazar Strip (D'Abrusco et al. 2012a; Massaro et al. 2012a). These results subsequently have been confirmed using the WISE all-sky data release[8] (Massaro et al. 2012b).

On the basis of our results we developed an association procedure able to recognize gamma-ray blazar candidates from their IR colors. This has been adopted to investigate the AGN of uncertain type (Massaro et al. 2012a) defined according to the 2FGL, and successfully used to provide a candidate blazar counterpart for 156 out of 313 unidentified gamma-ray sources (Massaro et al. 2012c).

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[8] http://wise2.ipac.caltech.edu/docs/release/allsky/

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In the present work, we apply our association procedure to the gamma-ray source 2FGL J1823.8+4312, classified as AGN of uncertain type in the The Second LAT AGN Catalog detected by *Fermi* (2LAC, Ackermann et al. 2011), previously not investigated with our method because it does not lie in the footprint of the WISE preliminary data release (Massaro et al. 2012a).

We investigated the radio, X-ray and optical observations available for the WISE candidates to identify the most plausible counterpart of 2FGL J1823.8+4312. This paper is organized as follows: in § 2 we select our WISE gamma-ray blazar candidates, and we describe all the multifrequency data collected to verify if 2FGL J1823.8+4312 is a gamma-ray blazar. In § 3 we summarize our results, and § 4 is devoted to our conclusions.

2. INVESTIGATING THE FIELD OF 2FGL J1823.8+4312

The gamma-ray source 2FGL J1823.8+4312 is classified as an AGN of uncertain type in the 2LAC sample. Recently, AGILE reported an increase of the gamma-ray emission from a region including 2FGL J1823.8+4312, thus indicating that it could be a variable source (Lucarelli et al. 2012). 2FGL J1823.8+4312 was not detected in The First *Fermi* LAT source catalog (Abdo et al. 2010).

According to the association procedures used in the 2LAC, the candidate counterpart is 1RXS J182418.7+430954 detected by ROSAT with a positional uncertainty of 60″ (Edge et al. 2003). It lies 7″.11 from the closest radio source, NVSS J182419+430949 (Condon et al. 1998), and 5′.74 from the nominal position of 2FGL J1823.8+4312. Figure 1 shows that 1RXS J182418.7+430954 lies outside the elliptical source location region corresponding to the 68% level of confidence (i.e., 5′.46) but within the one at 95% level of confidence (Ackermann et al. 2011).

Next, we describe the observations used to investigate the natures of the candidate counterparts selected for 2FGL J1823.8+4312. All the sources considered in our multifrequency analysis, grouped with their counterparts, are listed in Table 4.

2.1. *Infrared (WISE - 2MASS)*

According to our association procedure, we defined the *strip parameters* s_b and s_q, ranging between 0 and 1, to evaluate the distance, in the IR color space, between the BZB and BZQ subregions of the WISE Gamma-ray Strip and the location of a generic WISE source, respectively (Massaro et al. 2012a; Massaro et al. 2012c; Massaro et al. 2012d). Then we rank all the WISE sources within a *searching region* of radius θ_{999}=1.52×θ_{95}, centered on the gamma-ray position, on the basis of their *strip parameters*; where θ_{95} is the semimajor axis of the elliptical source location region at 95% confidence level (Nolan et al. 2012). The gamma-ray blazar candidate corresponds to the positionally closest source with the highest values of the *strip parameters*, while sources with s_b <0.10 or s_q <0.14 are *outliers* from the WISE Gamma-ray Strip. The efficiency of our method is ∼87% (Massaro et al. 2012c), assuming that all the 2LAC blazar associations, based on different methods, are correct.

There is only one gamma-ray blazar candidate for 2FGL J1823.8+4312 selected by our procedure out of 2351 sources in the *searching region*: WISE J182352.33+431452.5. To be conservative, we also consider the second source ranked by our procedure: WISE J182409.25+431404.7, the only other with s_b >0 and s_q >0 even if below the above thresholds.

WISE J182352.33+431452.5 lies 121″.998 from the nominal gamma-ray position of 2FGL J1823.8+4312, but it is not coincident with the counterpart associated in the 2LAC (i.e, 1RXS J182418.7+430954) lying 414″.977 away (Figure 1).

WISE J182409.25+431404.7 lies at 205″.642 away from the nominal gamma-ray position of 2FGL J1823.8+4312.

Neither of these WISE source is in the 2MASS catalog (Skrutskie et al. 2006).

2.2. *X-rays (ROSAT-Chandra)*

The two WISE blazar candidates and 1RXS J182418.7+430954 **appear to have counterparts in archival** *Chandra* **observations** (e.g., Gilmour et al. 2009, Figure 2).

WISE J182352.33+431452.5 has an X-ray counterpart, CXO J182352.2+431452, 0″.72 away the IR position, consistent with the *Chandra* positional uncertainty of 0″.88 reported in the *Chandra* source catalog (Evans et al. 2010).

We analyzed the *Chandra* observation finding that the X-ray spectrum of CXO J182352.2+431452 is well described by a power-law model with the Galactic absorption ($N_{H,Gal}$=3.62×10^{20} cm^{-2}, Kalberla et al. 2005) (i.e., χ^2_r= 1.13 for 10 degrees of freedom). Its X-ray spectral index is α_X= 0.38±0.18 and the observed X-ray flux $F_{0.5-7keV}$= $1.82^{+0.15}_{-0.17}$ ×10^{-13} erg cm^{-2} s^{-1}, consistent with those in the *Chandra* source catalog (Evans et al. 2010).

WISE J182409.25+431404.7 is positionally associated with the X-ray source CXO J182409.1+431404, 1″.68 away; consistent with the combination of the WISE and *Chandra* location uncertainties (Figure 2). However, the number of counts in the *Chandra* observation do not permit a detailed spectral analysis. To build its SED we used the X-ray flux $F_{0.5-7keV}$= $2.11^{+2.50}_{-1.73}$ ×10^{-14} erg cm^{-2} s^{-1} reported in Evans et al. (2010).

According to the ROSAT analysis of Edge et al. (2003), 1RXS J182418.7+430954 is a galaxy cluster, and the cluster nature of this source is clearly visible in both the *Chandra* and the WISE images (Figure 1 and Figure 2). On the other hand, according to the *Chandra* source catalog, the point-like X-ray source CXO J182419.0+430948, is located in its central region (Figure 2). Therefore we considered CXO J182419.0+430948 as a possible third candidate counterpart of 2FGL J1823.8+4312, even thought its radio and X-ray emissions could be contaminated by those of the galaxy cluster 1RXS J182418.7+430954.

WISE J182419.04+430949.6 is likely to be the IR counterpart of CXO J182419.0+430948 as shown in Figure 2) and will be considered our third WISE candidate. The IR colors of WISE J182419.04+430949.6 are consistent with those of the gamma-ray blazars that constitute the WISE Gamma-ray Strip, but only in the [3.4]-

[4.6]-[12] μm color-color projection, being undetected at 22μm.

2.3. *Radio (NVSS)*

WISE J182352.33+431452.5 has no radio counterpart in the NVSS catalog (Figure 1).

WISE J182409.25+431404.7 is associated with the radio source NVSS J182409+431407 which has a flux of 2.7 mJy at 1.4 GHz (Condon et al. 1998) (Figure 1).

WISE J182419.04+430949.6 has a radio counterpart, NVSS J182419+430949, with a radio flux density of 33 mJy at 1.4 GHz (Condon et al. 1998) also associated with the X-ray counterpart (see Table 1 position uncertainties and offsets).

2.4. *Optical (SDSS)*

The searching region chosen is entirely covered by the archival images of the SDSS DR8 (Hiroaki et al. 2011) (Figure 2 and Figure 3) Unfortunately, for the three selected sources no optical spectra are available. We performed a photometric analysis of the optical colors. According to Massaro et al. (2012d), $u-r$ color of 1.4 mag is the approximate dividing line between BL Lacs dominated by the nuclear component and those by the galactic component.

WISE J182352.33+431452.5 is positionally associated to SDSS J182352.34+431452.7. It is detected in all the SDSS bands and classified as a "GALAXY" according to the SDSS algorithm (e.g., Hiroaki et al. 2011). It has a $u-r$ color of 1.23±0.30, marginally consistent with the optical colors of BL Lacs which are nuclear dominated.

WISE J182409.25+431404.7 is associated with SDSS J182409.13+431404.8 lying $1''.309$ away. It is classified as a point-like source (i.e.,"STAR") and is also detected in all the SDSS bands. Its value of the $u-r$ color is 1.24±0.78, suggesting that the source could be nuclear dominated; however the large uncertainty does not permit a precise classification.

WISE J182419.04+430949.6 is positionally associated with the optical point-like (i.e.,"STAR") SDSS J182419.05+430949.5, lying in the direction of the 1RXS J182418.7+430954 galaxy cluster with a very peculiar $u-r = 0.67\pm0.04$, quite consistent with BL Lacs dominated by nuclear emission (Massaro et al. 2012e).

3. RESULTS

We compared the broadband SEDs of our three candidates (Figure 4) to identify the most plausible low-energy counterpart of 2FGL J1823.8+4312. We took into account the interstellar reddening correction, with $E(B-V)$ values from Schlafly & Finkbeiner (2011) and the corrections described in Cardelli et al. (1989). The X-ray spectra have been also corrected for Galactic absorption (Kalberla et al. 2005).

WISE J182352.33+431452.5 is the most intriguing of the sources we investigated. This unique gamma-ray blazar candidate, selected with our WISE association procedure, has no radio counterpart which is surprising and unlike any of the blazars re-associated using our procedure (e.g., Massaro et al. 2012b). It shines brightly in the *Chandra* observation, showing a hard power-law X-ray spectrum. It is classified as a "GALAXY" in the SDSS, and it has a $u-r$ color unusual for a BL Lac object and different from the typical optical colors of the SDSS quasars as analyzed by D'Abrusco et al. (2009). Figure 4 shows its enigmatic SED. Consequently, WISE J182352.33+431452.5 does not fit any known class of extragalactic sources.

WISE J182409.25+431404.7 is point-like in the SDSS images and it has both a radio and an X-ray counterpart. However, both its IR and its optical colors are only marginally consistent with those of blazars, suggesting that an optical spectrum is necessary to confirm its nature. Its SED, reported in Figure 4, appears similar to that of a blazar with a bump in the optical band that could be attributed to its host galaxy.

1RXS J182418.7+430954 is not likely responsible for the gamma-ray emission detected by *Fermi*-LAT, being a galaxy cluster; thus the 2LAC association should be considered unlikely. However, the point-like source WISE J182419.04+430949.6 with both optical and IR colors of a nuclear dominated BL Lac object, located in the direction of the galaxy cluster 1RXS J182418.7+430954, could be a possible counterpart of 2FGL J1823.8+4312. Its SED is very unlike those of BL Lacs, being strongly contaminated by the emission of the galaxy cluster. In addition, as occurs for ∼96% of gamma-ray blazars, a detection at 22μm is expected (Massaro et al. 2012b).

4. CONCLUSIONS: A NEW CLASS OF EXTRAGALACTIC SOURCES

We have investigated three possible WISE IR counterparts to the gamma-ray source 2FGL J1823.8+4312, and one X-ray counterpart. We can firmly exclude the X-ray counterpart, 2LAC source 1RXS J182418.7+430954, because it is coincident with a galaxy cluster and almost surely represents the cluster emission. The candidate counterparts fromWISE are more complex. WISE J182352.33+431452.5, WISE J182409.25+431404.7 and WISE J182419.04+430949.6 each are quite different from "typical" gamma-ray blazars (e.g., Massaro et al. 2011a). WISE J182352.33+431452.5 lacks radio emission (at least at the sensitivity limit of the NVSS), and thus is not a blazar according to the most basic definition. WISE J182409.25+431404.7 has unusual lR and optical colors for a blazar. WISE J182419.04+430949.6 also has an unusual SED that is probably strongly contaminated by the emission of the nearby galaxy cluster.

Our investigation of WISE J182352.33+431452.5 reveals that, although its lack of detected radio flux means it is not a traditional blazar, its curious broadband SED is not like that of any other known class of extragalactic source either (Figure 4). The SED is reminiscent of the sub-class of BL Lacs peaking in the IR, the "Low frequency peaked BL Lacs" (Padovani & Giommi 1995), but these sources are typically about two orders of magnitude brighter in the radio than WISE J182352.33+431452.5 for similar IR fluxes (e.g., Massaro et al. 2011a), as it is also the case for the flat spectrum radio quasars. There is one confirmed BL Lac object in the ROMA-BZCAT, whose radio flux density is lower than 1 mJy, BZB J1248+0830, but its WISE colors are completely different from those of WISE J182352.33+431452.5; it is not detected at

22μm and its $u-r$ color is 3.12±2.04 mag, suggesting that the flux is dominated by the host galaxy emission (Massaro et al. 2012d).

Plotkin et al. (2010), in their analysis of optically selected BL Lacs, show that there are blazar candidates with weak radio emission. However these objects *always* have blue colors in the SDSS, completely unlike WISE J182352.33+431452.5. Moreover, these weak radio BL Lac counterparts, when seen in the infrared by WISE, actually reside in the locus of the WISE Gamma-ray Strip typically populated by "High frequency peaked BL Lacs" (Padovani & Giommi 1995) - sources with a rising SED from the IR to the optical band and peaking in the UV-X-ray energy range. All these features are completely different for WISE J182352.33+431452.5, whose SED does not appear to fit any currently recognized blazar subclass (Figure 4).

Urgently needed to unveil the nature of WISE J182352.33+431452.5 are an optical spectrum and a deeper radio observation. If optical observations confirm the source as a "radio-faint blazar", and if at least the IR-to-X-ray SED is due to jet dominated radiation, the absence of radio emission is very difficult to accommodate in **current blazar models.**

Independently of whether or not WISE J182352.33+431452.5 is the actual counterpart of 2FGL J1823.8+4312, several important implications would follow if it is identified to be a "radio-faint blazar":

- The classification of blazars will need to be revised, since this new class implies that the "High frequency peaked BL Lacs" (Padovani & Giommi 1995) are not the only blazars with low radio fluxes.
- We cannot firmly identify counterparts to gamma-ray sources using association methods based only on radio and X-ray surveys.
- Searches for similar sources, using the X-ray emission, red optical colors, and lack of radio emission, would probably lead to their classification as radio quiet AGNs.

On the other hand, the IR colors would be essential to flag them as potential "radio-faint blazars".

We remark that sources with steep IR spectra such as WISE J182352.33+431452.5 could be confused with cold stars if selected solely in the IR; however, this is not the case here given the X-ray emissions coupled with the SDSS "GALAXY" flag.

Finally, the hard *Chandra* spectrum of WISE J182352.33+431452.5, and its possible extrapolation to the hard X-rays (Figure 4), suggest that similar sources could be candidate counterparts for the unidentified hard X-ray sources found with INTEGRAL and SWIFT BAT surveys (e.g., Bird et al. 2010; Cusumano et al. 2010; Baumgartner et al. 2010, respectively) and good candidates for hard X-ray pointed observations by the ongoing NuSTAR mission (Harrison et al. 2010, Figure 4).

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[9] http://www.star.bris.ac.uk/∼mbt/topcat/

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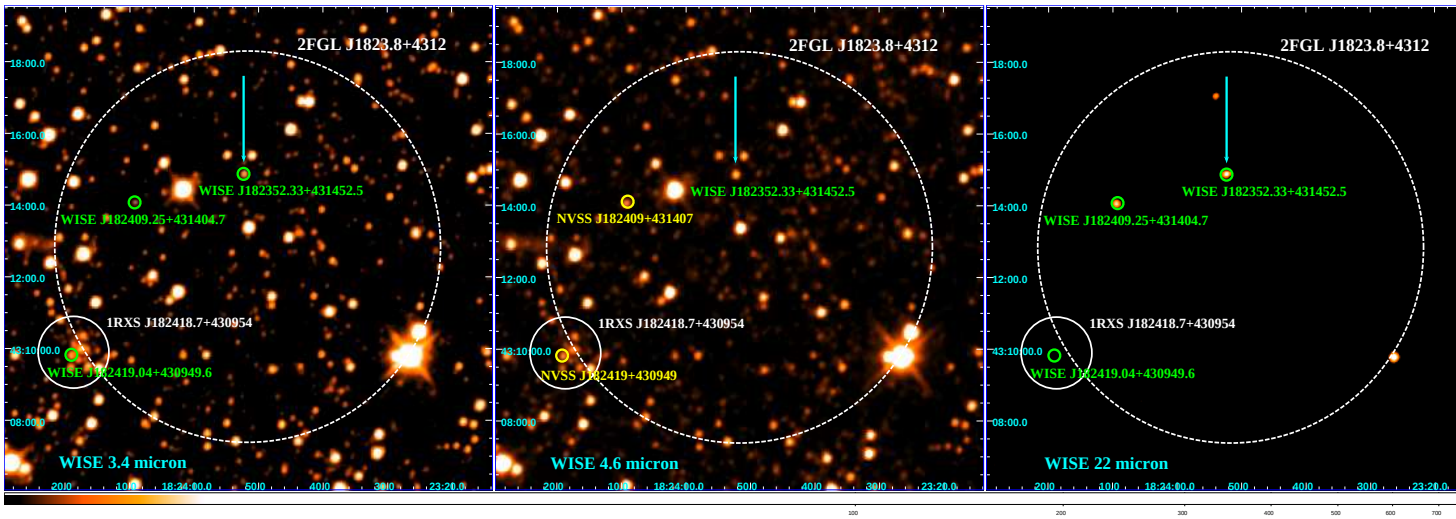

FIG. 1.— Left panel) WISE image at 3.4μm where we indicated all the WISE selected sources. Middle panel) WISE image at 4.6μm where all the NVSS counterparts of the sources analyzed are shown. Right panel) WISE image at 22μm where all the WISE sources considered in our analysis are reported. The white straight circle points to the galaxy cluster 1RXS J182418.7+430954 and it corresponds to the ROSAT localization error (Edge et al. 2003). The galaxy cluster is clearly visible also in the WISE images. The white dashed circle is the region of radius θ_{68}, where θ_{68} is the major axis of the elliptical source location region at 68% level of confidence centered on the gamma-ray position reported in the 2FGL and in the 2LAC (Nolan et al. 2012; Ackermann et al. 2011, respectively).

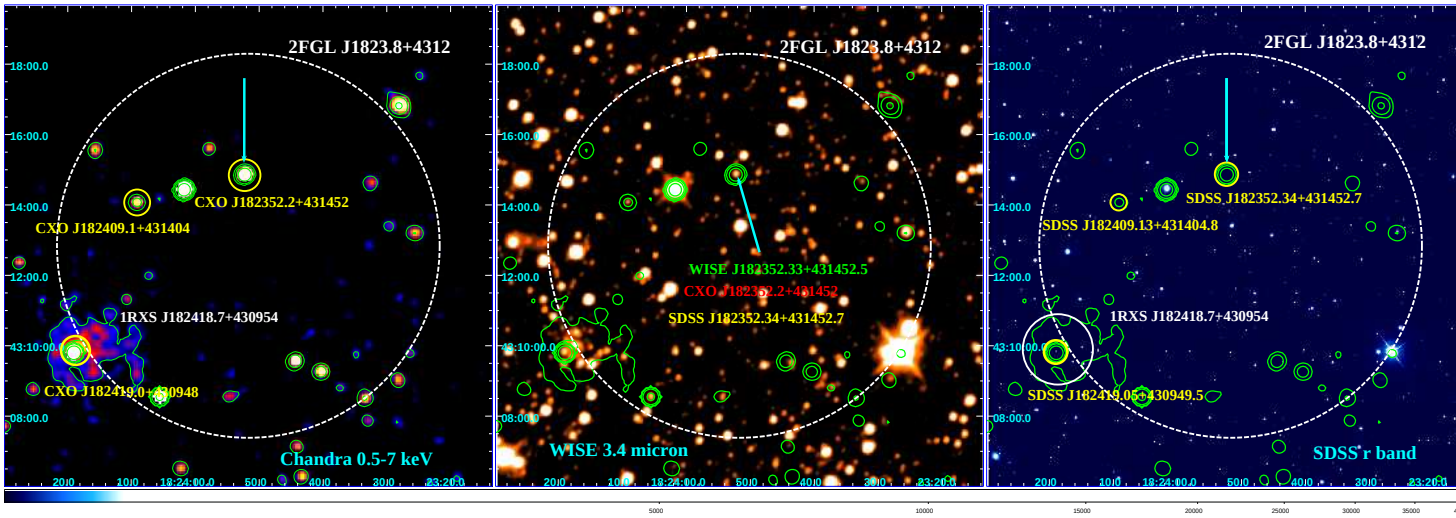

FIG. 2.— Left panel) The *Chandra* image in the 0.5-7 keV energy range. The galaxy cluster 1RXS J182418.7+430954 is clearly visible. The *Chandra* counterparts of the sources analyzed are highlighted, at the position of the *Chandra* source catalog (Evans et al. 2010). Middle panel) WISE image at 3.4μm where WISE J182352.33+431452.5 is highlighted with the names of all its counterparts. Right panel) SDSS image in r band, all the optical counterparts of the sources analyzed are indicated. The *Chandra* X-ray contours are overlaid in each panel (green). The white dashed circle corresponding to the region of radius θ_{68} is shown (see also Figure 1).

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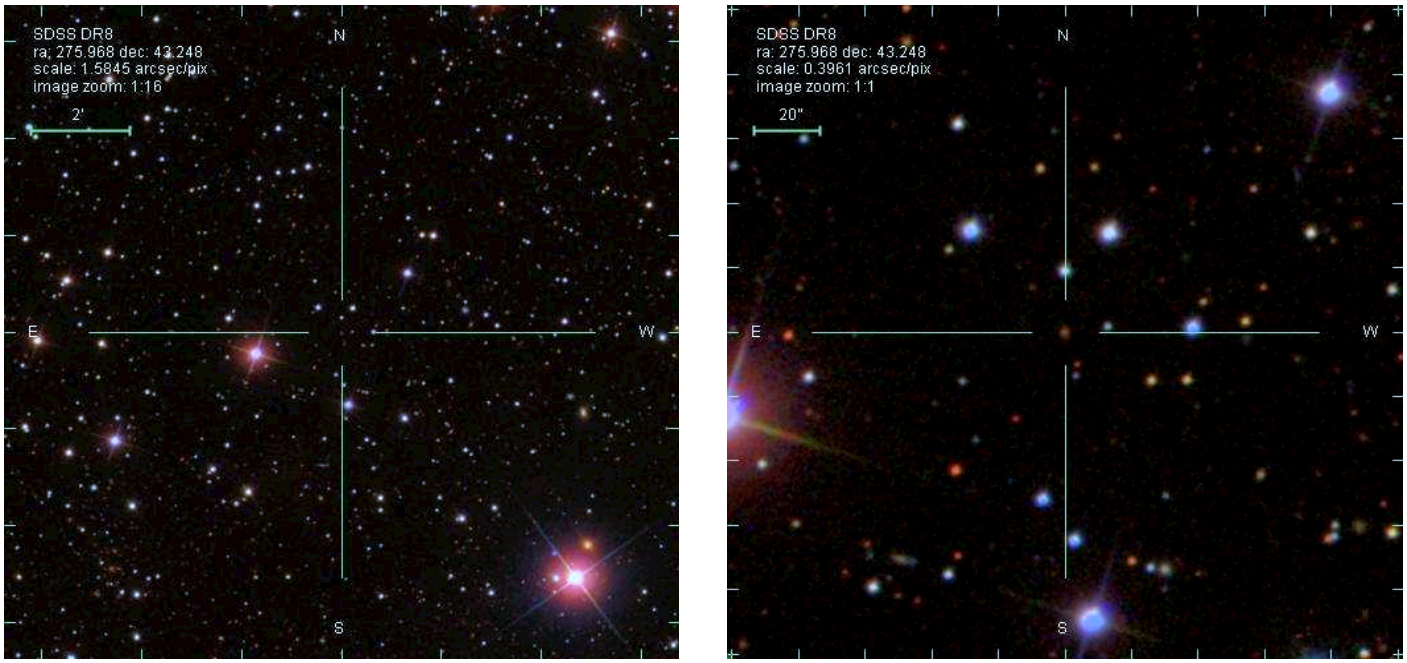

FIG. 3.— Left panel) SDSS RGB image of the region investigated for 2FGL J1823.8+4312 centered on the position of WISE J182352.33+431452.5. Right panel) Zoom of the left panel to highlight the SDSS detection and its optical colors of WISE J182352.33+431452.5.

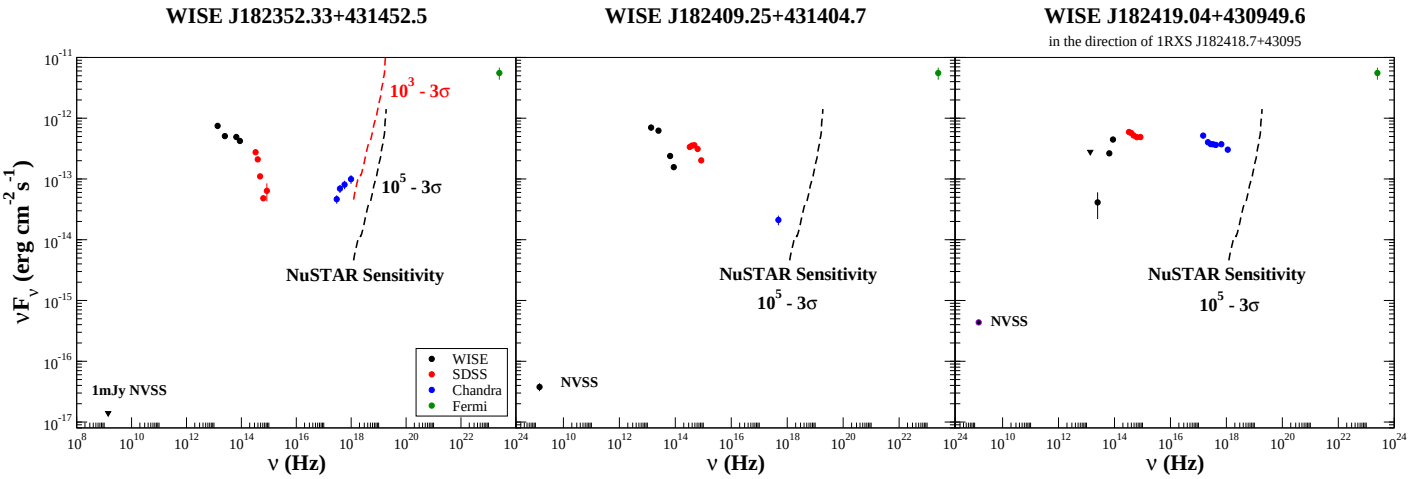

FIG. 4.— The SEDs of the three sources investigated: WISE J182352.33+431452.5 (left panel), which could be the prototype of a new class of extragalactic objects, WISE J182409.25+431404.7 (middle panel) and WISE J182419.04+430949.6 (right panel) that lies in the direction of the galaxy cluster 1RXS J182418.7+430954 (see § 3 for details). WISE data are shown in black, SDSS in red, *Chandra* in blue while the gamma-ray flux of 2FGL J1823.8+4312 taken from the 2FGL is indicated in green. NVSS detections are also shown for WISE J182409.25+431404.7 and WISE J182419.04+430949.6 while in the case of WISE J182352.33+431452.5 we indicate the 1mJy NVSS expected flux. WISE J182352.33+431452.5 SED is extremely peculiar and it is not similar to any other known extragalactic sources. We also show the NuSTAR sensitivity for a 3σ detection corresponding to an exposure of 10^5s (dashed black line) and 10^3s (dashed red line), respectively. It is remarkable that extrapolating the *Chandra* X-ray spectrum of WISE J182352.33+431452.5, it could be detectable by NuSTAR (Harrison et al. 2010). The black triangle shown in the SED of WISE J182419.04+430949.6 corresponds to the upper limit at 22μm (§2).

TABLE 1
2FGL J1823.8+4312

We report the WISE sources with their coordinates (R.A. J2000, Dec. J2000) and those of each counterpart associated in the *Chandra*, NVSS and SDSS catalogs.
We also report the positional uncertainties for each catalog and the distances of each counterpart from the WISE positions.

	WISE	*Chandra*	NVSS	SDSS
	WISE J182352.33+431452.5	CXO J182352.2+431452	—	SDSS J182352.34+431452.7
	18:23:52.34, +43:14:52.6	18:23:52.28, +43:14:52.2	—	18:23:52.34, +43:14:52.7
Positional uncertainty	0.13	0.88 $''$	—	—
Distances from IR position	—	0.77 $''$	—	0.10 $''$
	WISE J182409.25+431404.7	CXO J182409.1+431404	NVSS J182409+431407	SDSS J182409.13+431404.8
	18:24:09.25, +43:14:04.8	18:24:09.10, +43:14:04.5	18:24:09.06, +43:14:07.2	18:24:09.13, +43:14:04.9
Positional uncertainty	0.19	1.54 $''$	15.9 $''$	—
Distances from IR position	—	1.68 $''$	3.18 $''$	1.32 $''$
	WISE J182419.04+430949.6$^{(*)}$	CXO J182419.0+430948	NVSS J182419+430949	SDSS J182419.05+430949.5
	18:24:19.04, +43:09:49.7	18:24:19.02, +43:09:48.9	18:24:19.21, +43:09:49.6	18:24:19.05, +43:09:49.5
Positional uncertainty	0.15	0.41 $''$	0.7 $''$	—
Distances from IR position	—	0.83 $''$	1.86 $''$	0.23 $''$

$^{(*)}$ The source WISE J182419.04+430949.6 is in the direction of the galaxy cluster 1RXS J182418.7+430954 (R.A.(J2000): 18h24m18.7s, Dec.(J2000): +43d09m54s; see § 2.2 for details).