



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Searching for TeV-emitting candidates among the X-ray bright blazar population

**Antonio Iuliano (INFN Sezione di Napoli),
Stefano Marchesi,
Paolo Da Vela, Davide Miceli, Chiara Righi,
Elisa Prandini, Michele Doro, Roberta Zanin**

17 June 2024

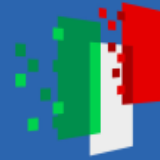
13th CRIS-MAC 2024, Trapani



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

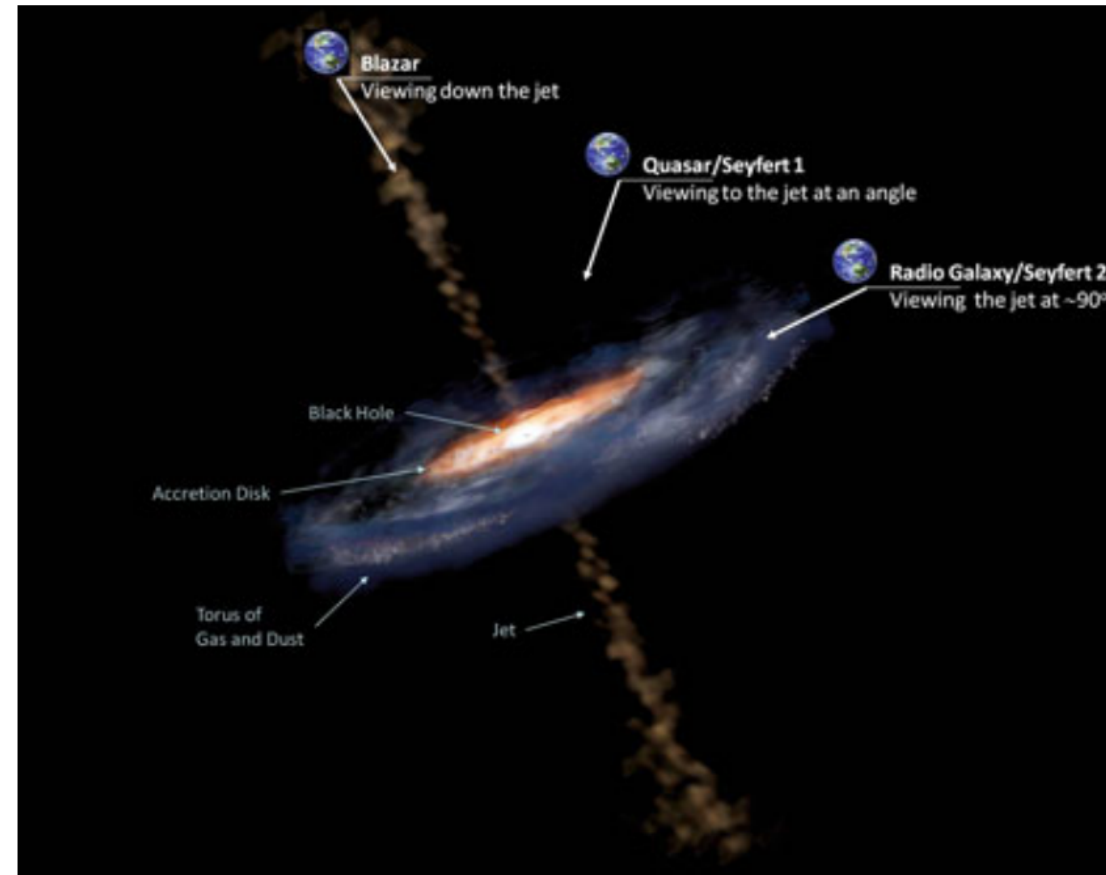


INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Introduction

- Blazars: Active Galactic Nuclei (AGN), with the jet direction closely aligned to the line of sight of the observer
- Emission over a wide range of wavelengths, from radio-waves to gamma-rays
- Important targets for multiwavelength observations, and theoretical modeling of their spectrum distributions





Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

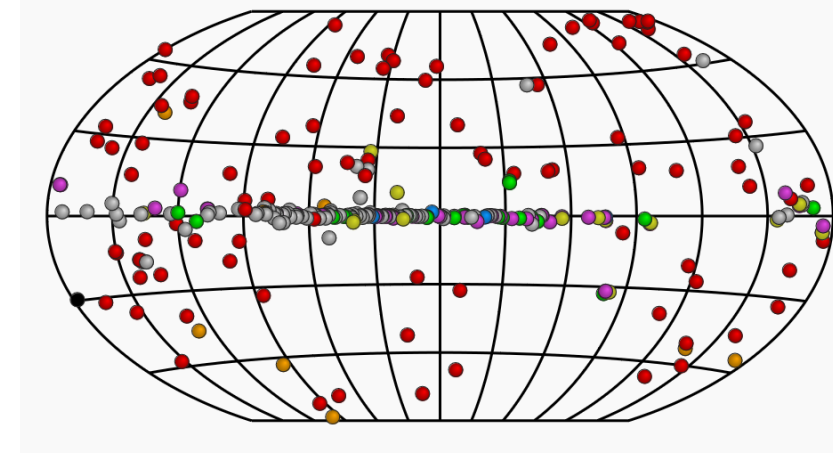


INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Goal of the project

- Investigate currently available observations of known blazars, with a complete and unbiased approach
- TeVCat: an online catalog for TeV Astronomy, listing sources from all available observations
- Due to limited Field of View, input of candidate positions needed for pointing of Cherenkov telescopes, to detect new TeV sources
- Currently, high uncertainty in predicted number of detectable sources. Two main approaches:
 - Extrapolation of Fermi-LAT results (Abdollahi, 2020)
 - Combination of IR and X-ray information (Arsioli, 2015)
- Focusing on the latter approach in this presentation



Map of TeVCat sources
<http://tevcats2.uchicago.edu/>



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

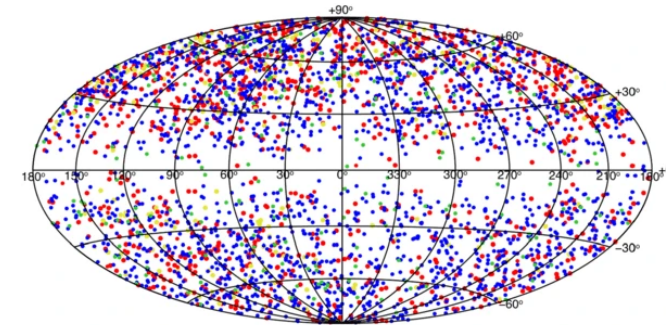


INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



The 5BZCAT catalogue

- Goal: find TeV-emitting candidates from currently available X-ray observations of known blazars
- Starting point: the **Roma Multifrequency catalog of blazars, 5th edition**: <https://www.ssd.cas.ac.cn/bzcat/>
3561 blazars, selected on the basis of their radio emissions
- Four classes, according to multiwavelength properties:
5BZB, **5BZG**, **5BZQ**, **5BZU** (colors as in sky distribution dots)
- Dividing the set of blazars in two groups, according to the presence or not of a counterpart in the Fermi-LAT 4FGL-DR4 catalog
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/14yr_catalog/



sky distribution in galactic
coordinates of the blazars
in the 5BZCAT catalogue,
from paper
Astrophys Space Sci 357, 75
(2015)



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



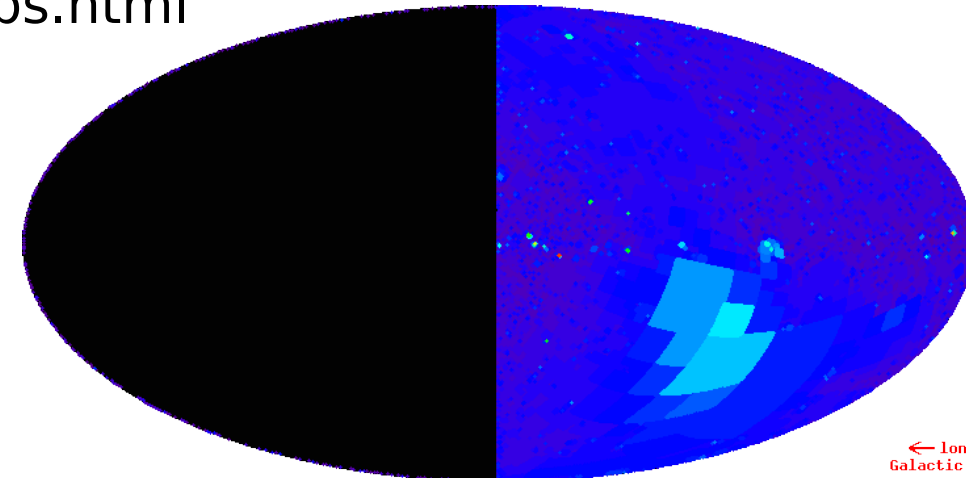
INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



List of X-ray catalogs for cross-match

- **XMM-Newton Catalog** ($>1300 \text{ deg}^2$; 4XMM-DR13)
<http://xmm-catalog.irap.omp.eu/>
- **Chandra** ($\sim 560 \text{ deg}^2$; CSC 2.0)
<https://cxc.cfa.harvard.edu/csc/>
- **Swift-XRT** ($\sim 3800 \text{ deg}^2$; 2SXPS)
<https://heasarc.gsfc.nasa.gov/W3Browse/swift/swift2sxps.html>
- **NuSTAR** ($\sim 6 \text{ deg}^2$; NuBlazar)
<https://www.ssdsc.asi.it/nustarblaz/>
- **eROSITA-DE** (20627 deg^2 ; eRASS1)
<https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/682/A34>

eRASS1 coverage,
From Vizier page,
Acknowledgement:
Andrea Merloni, am@mpe.mpg.de



← lon
Galactic



Summary of 5BZCAT sources detected in different catalogs of X-ray sources

Marchesi et al. (in prep.)

Catalog	X-ray Instrument	Area Covered deg ²	Sources	With <i>Fermi</i> -LAT	Without <i>Fermi</i> -LAT
4XMM-DR13	<i>XMM-Newton</i>	1328	313	181 (58 %)	132 (42 %)
2CSC	<i>Chandra</i>	560	218	131 (60 %)	87 (40 %)
2SXPS	<i>Swift-XRT</i>	3790	1666	1191 (71 %)	475 (29 %)
eRASS1	eROSITA	20627	1379	726 (52 %)	653 (48 %)
NuBlazar	<i>NuSTAR</i>	6	114	88 (77 %)	26 (23 %)
4XMM-DR13 or 2CSC			464	271 (58 %)	193 (42 %)
2SXPS, no 4XMM or 2CSC			1347	968 (72 %)	379 (28 %)
eRASS1 only			624	189 (30 %)	435 (70 %)
Overall			2435	1428 (59 %)	1007 (41 %)
Of which in TeVCAT			77	77 (100 %)	0 (0 %)



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



The Firmamento Platform

- Web browser tool with an updated version of the **VOU-Blazars** software (Chang+19)
- Available on the web:
<https://firmamento.hosting.nyu.edu>
- Accesses data from catalog at all wavelengths, in order to obtain SED distribution
- Resulting file can be used as input for fitting and extrapolation to TeV emission

Tripathi et al. 2024, AJ 167 116

The screenshot shows the 'firmamento' web interface with a dark theme. A navigation menu is visible with the following items: HOME, DATA ACCESS (highlighted with a green underline), RESOURCES, MEDIA, TUTORIALS, and FEEDBACK. Below the menu, there is a 'Server Status' indicator showing 'On' and 'Total Active Jobs: 0' with a refresh icon. A 'User input' section is present with a text box containing 'Mrk421' and a 'HELP' button.

Server Status: ● On Total Active Jobs: 0

User input Radio selected sources

Fermi unidentified sources

eRosita-EDR radio-matching sources

IceCube neutrino tracks

Object name eg. 3c279, or: 192.1549 -5.89653

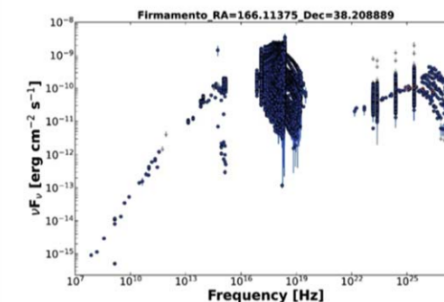
Mrk421

HELP

The screenshot shows the top navigation bar of the 'firmamento' web interface. It includes the 'firmamento' logo and a hamburger menu icon. Below the logo, there are four tabs: 'SED' (highlighted in green), 'Error Map', 'Aladin', and 'More'.

Documentation

SED graph from Voublazars



Results from BLAST ?

Log(ν_{peak}): 17.1 ± 1.0 (1 sigma)

SED data (double-click to preview:)

○ ASCII ○ CSV ○ SSDC SED input file



Finanziato dall'Unione europea
NextGenerationEU



Ministero dell'Università e della Ricerca



Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

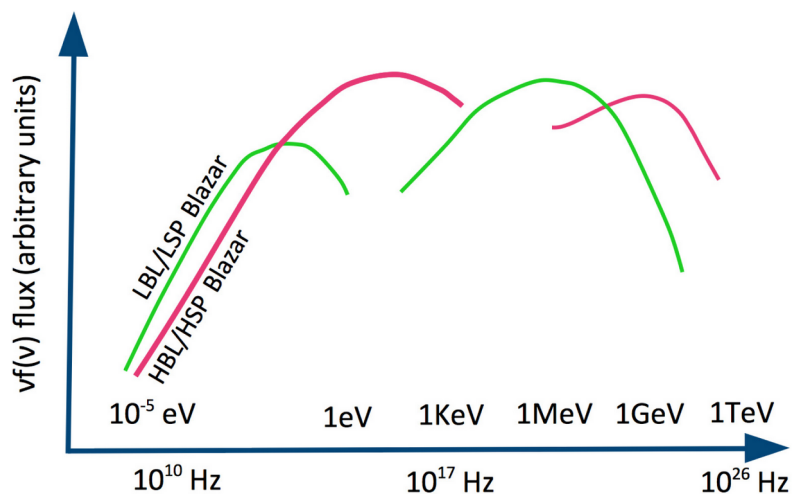


INAF
ISTITUTO NAZIONALE DI ASTROFISICA

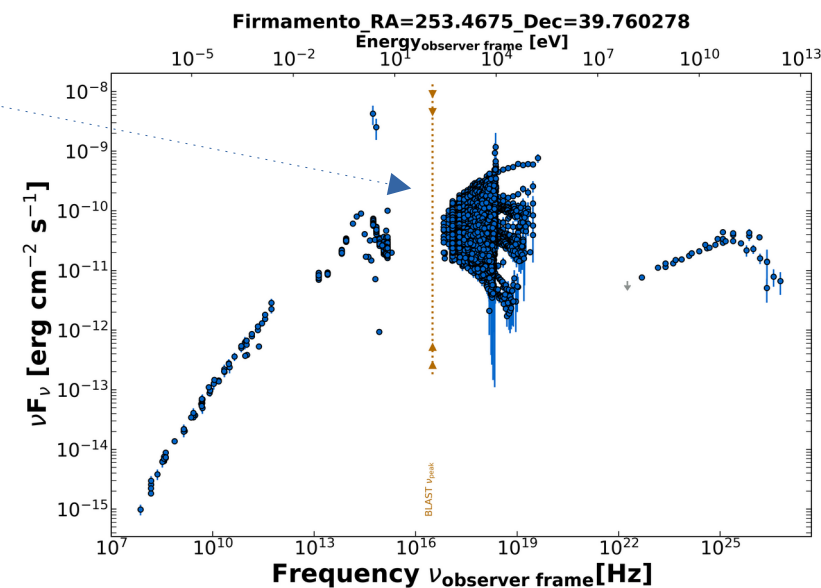


Structure and peaks of a SED

- Presence of two peaks: Self Synchrotron Compton (SSC) and Inverse Compton (IC)
- First peak used for blazar classification, Low or High Synchrotron peaked
- Peak frequency provided with a **BLAST** fit (Glauch et al. 2022)



Typical Blazar SEDs from VOU-Blazars paper (Chang+19)



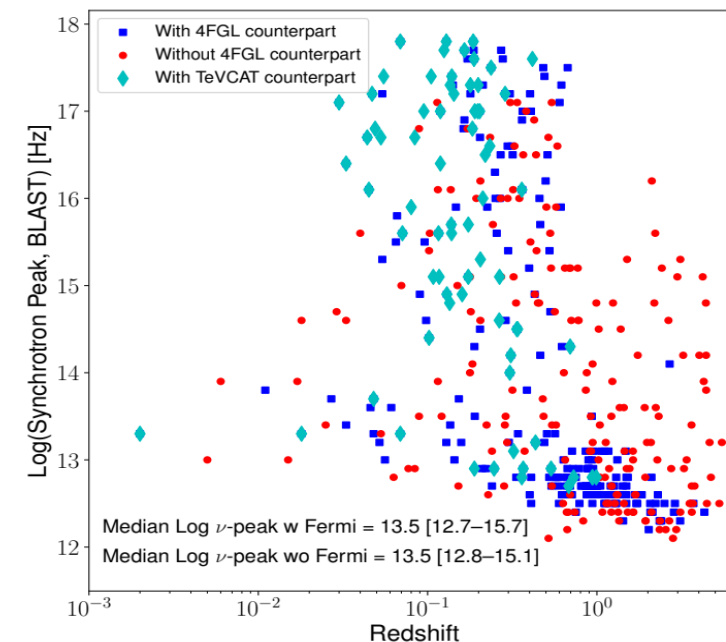
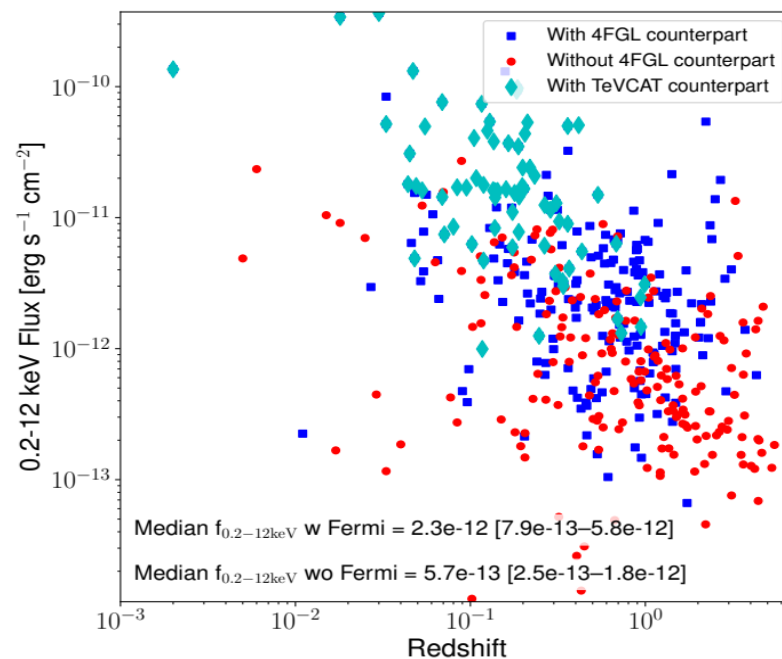
Markarian 501



Multiwavelength distributions

- First, studied the properties of the 464 sources matched by either the XMM-Newton or the Chandra catalog

- Compared multi-wavelength properties of Fermi-detected and not detected sources
- On average, lower x-ray flux and higher redshift for blazars without a Fermi-LAT counterpart



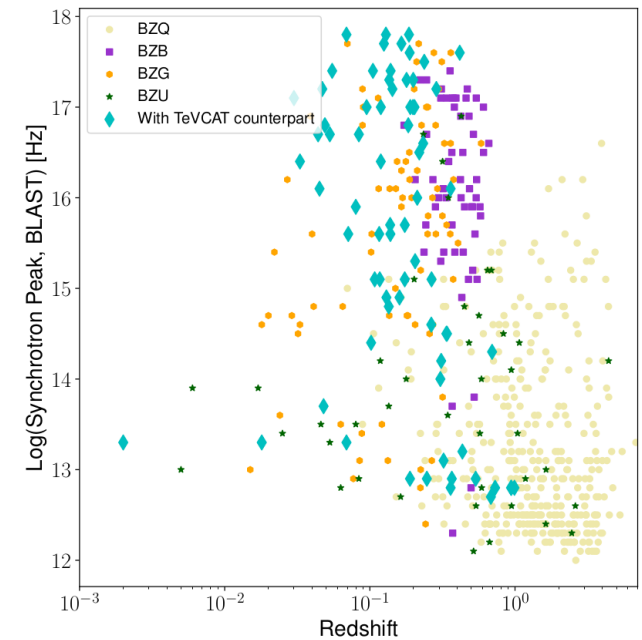
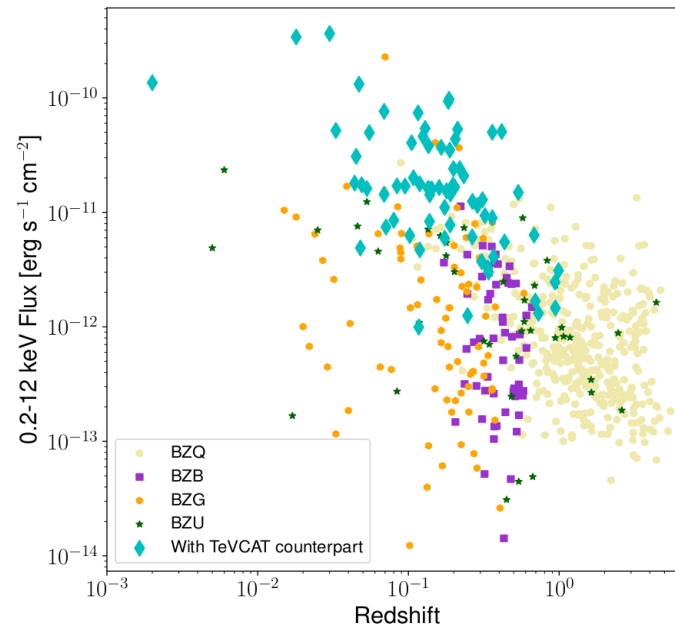
Marchesi et al. (in prep.)



Blazar classes separation

- Adding the information from the 2SXPS catalog
- Breaking down the sample according to the blazar classes (FSQR, BLL, BLL + host, BCU)

- Here, showing sources without a Fermi-LAT counterpart
- Added TeVCAT for comparison reference from detected blazars
- Presence of a Fermi-undetected population overlapping with the TeVCAT region, mostly BL Lac class blazars

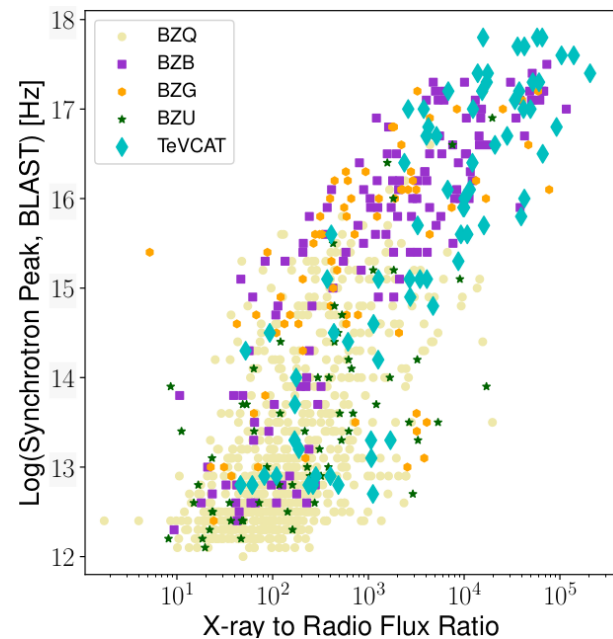


Marchesi et al. (in prep.)

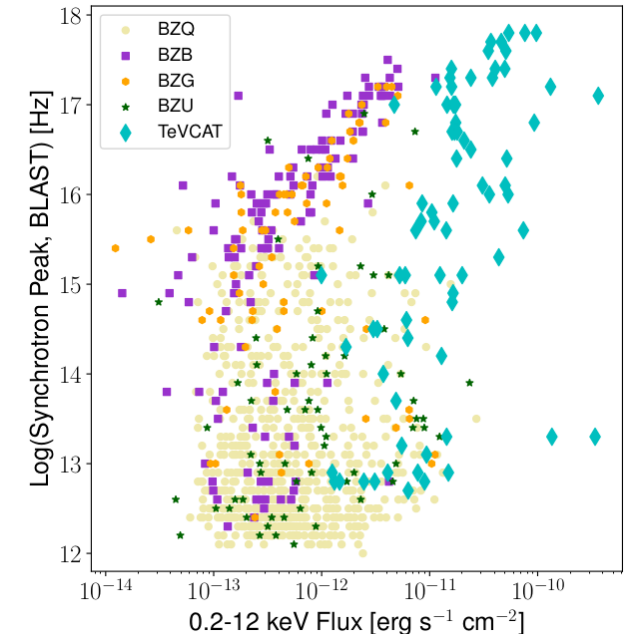


X-ray to radio flux ratio

- Efficient predictor of TeV detectability
- Significant population of sources with high peak, high x-ray to radio flux ratio
- Weaker x-ray flux, not already detected in gamma by Fermi-LAT



Marchesi et al. (in prep.)





Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



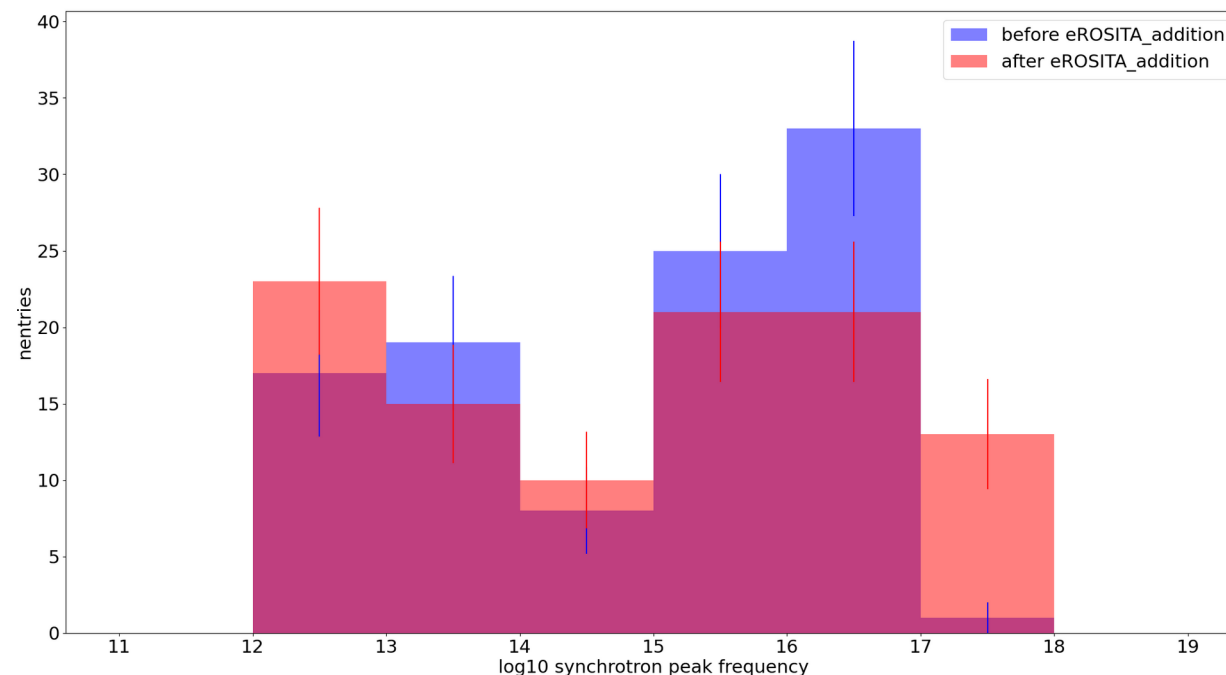
INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Synchrotron peaks with and without eROSITA

- Synchrotron peaks computed by BLAST for eRASS1 counterparts of 5BZCAT, without a Fermi detection and the 5BZQ component
- Comparing the peak before and after the addition of new eROSITA data
- Consistent distributions for most of the data, except for a few high peak sources
- Cross-checking SEDs of outliers

Histogram of Synchrotron peaks from Blast



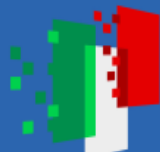
Iuliano et al. (in prep.)



Finanziato dall'Unione europea
NextGenerationEU



Ministero dell'Università e della Ricerca



Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA



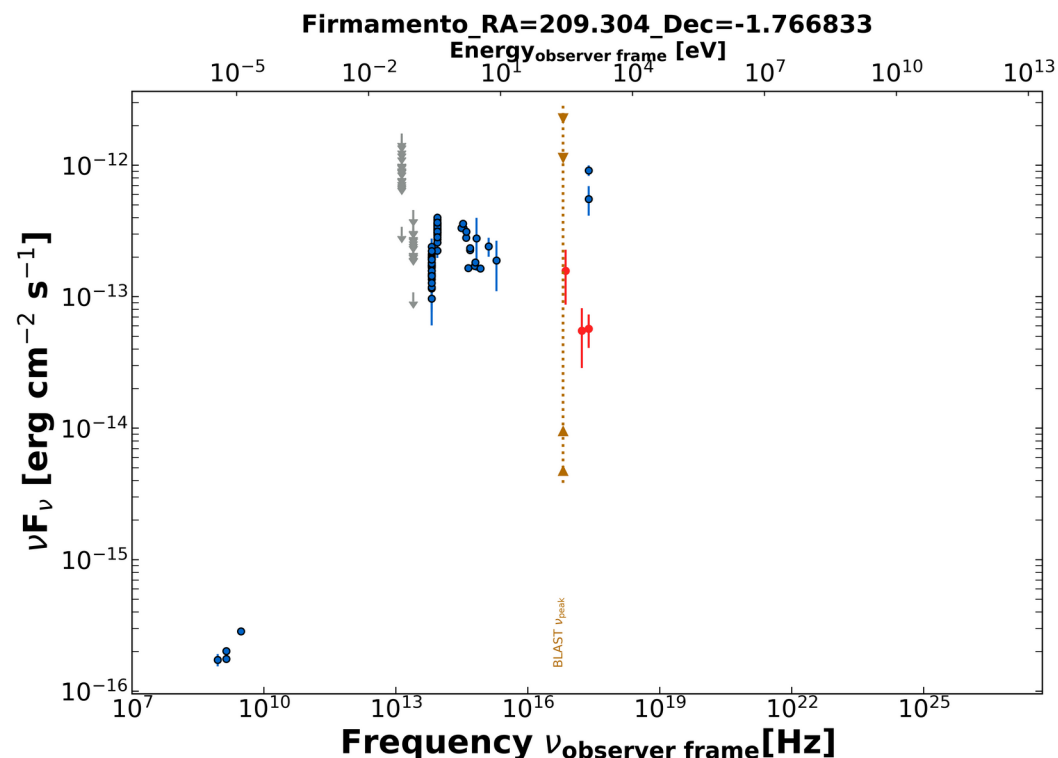
INAF
ISTITUTO NAZIONALE DI ASTROFISICA



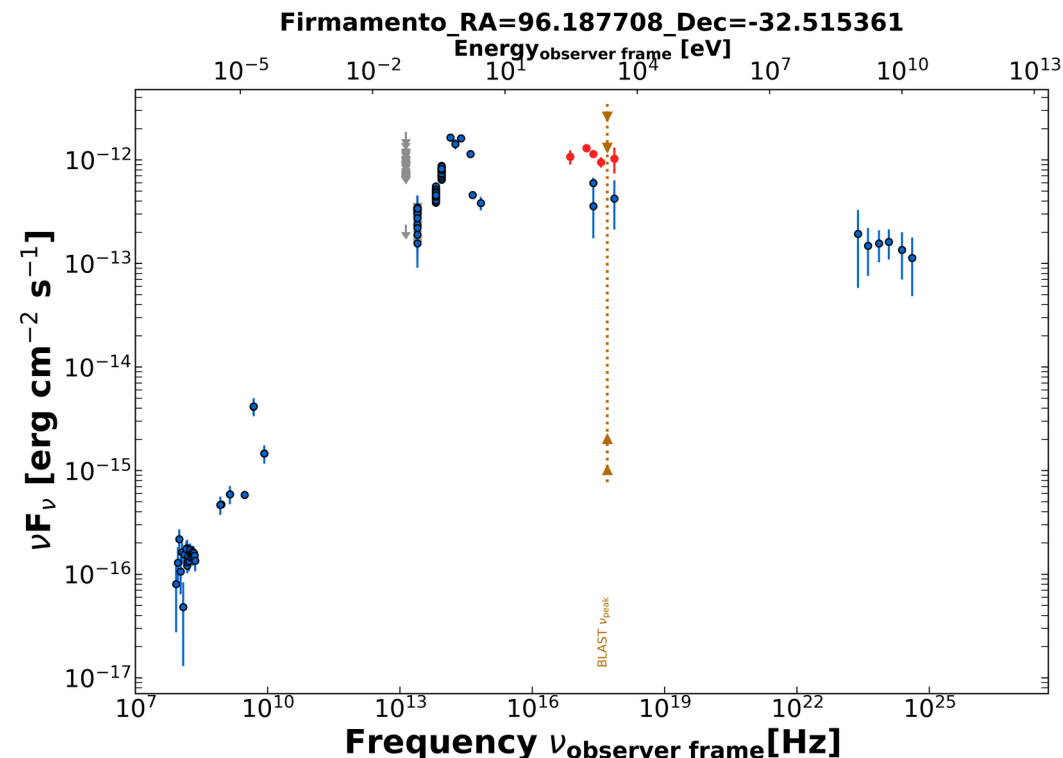
5BZBJ1357-0146

Outlier SEDs and Light Curves

5BZBJ0624-3230



Iuliano et al.
(in prep.)



- Different values measured by eROSITA-eRASS1 with respect to other X-ray data

In red: eRASS1
In blue: other catalogs



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

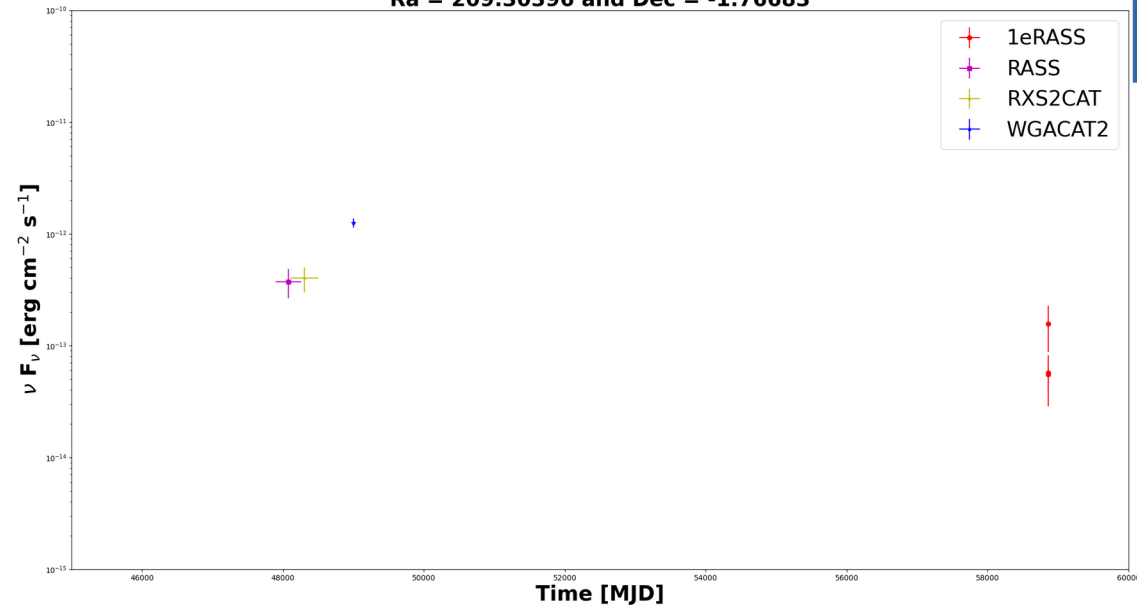


INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Outlier SEDs and Light Curves

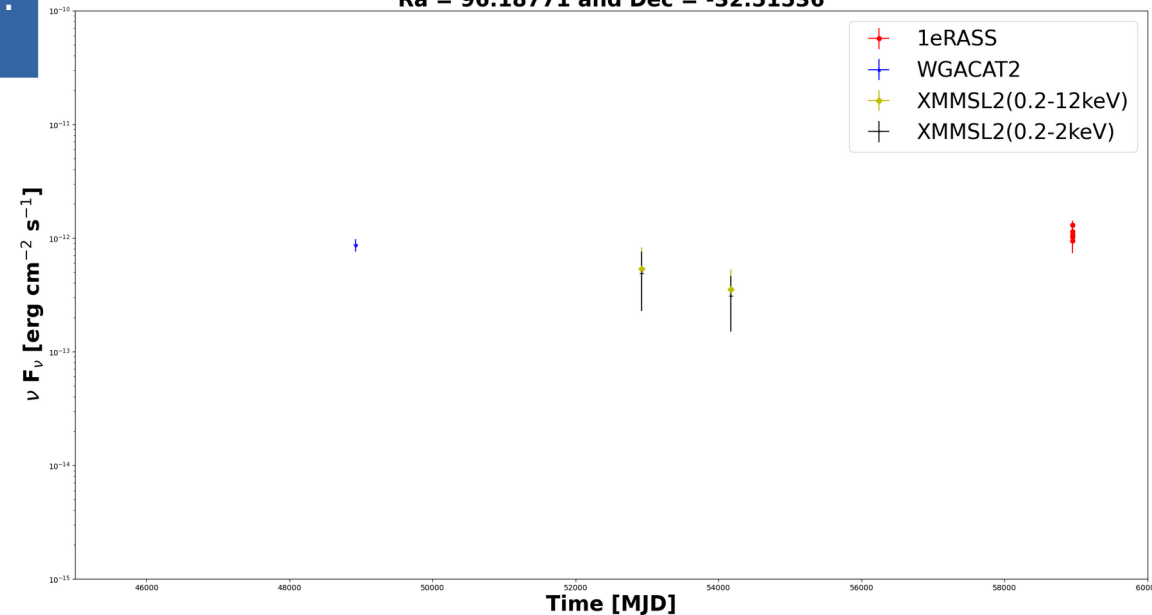
Ra = 209.30396 and Dec = -1.76683



5BZBJ1357-0146

Iuliano et al.
(in prep.)

Ra = 96.18771 and Dec = -32.51536



5BZBJ0624-3230

- Since eRASS1 data are more recent, difference may be explained with blazar variability in the X-ray band
- However, only a few points in the X-ray band, and far in time



Finanziato dall'Unione europea
NextGenerationEU



Ministero dell'Università e della Ricerca



Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA



INAF
ISTITUTO NAZIONALE DI ASTRONOMIA E FISICA SPAZIALE

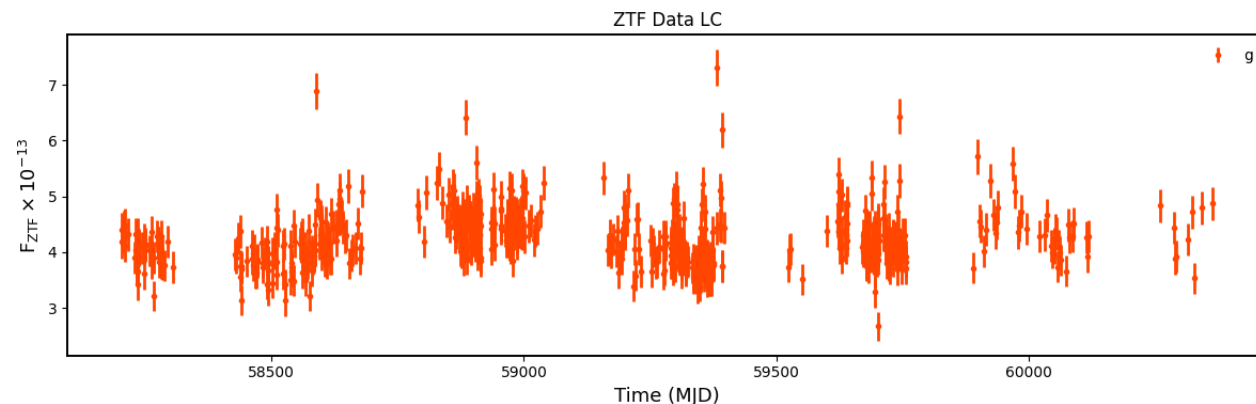
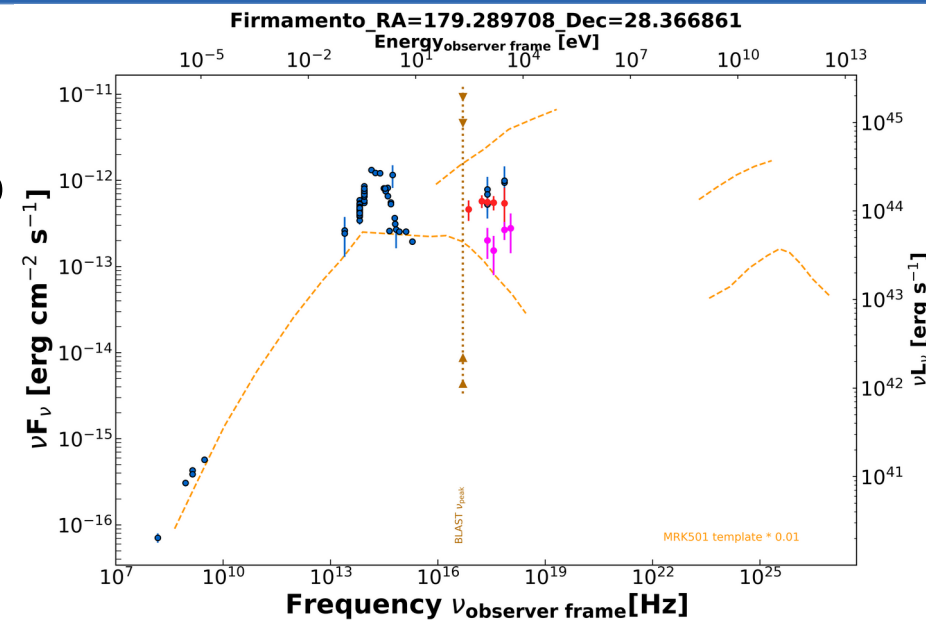


SED selection and analysis

- Selecting sources with high x-ray to radio flux ratio (ratio > 2000)
- Adding:
 - Light curve from the Zwick Transient Facility, a wide field survey of the optical transient sky (<https://irsa.ipac.caltech.edu/Missions/ztf.html>)
 - A template from Markarian 501, rescaled to the data of our source
 - Note: Swift data labelled in pink

eRASS1
J115709.5+282201

$$\frac{X}{radio} = 2311.6$$

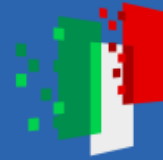




Finanziato dall'Unione europea
NextGenerationEU



Ministero dell'Università e della Ricerca



Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

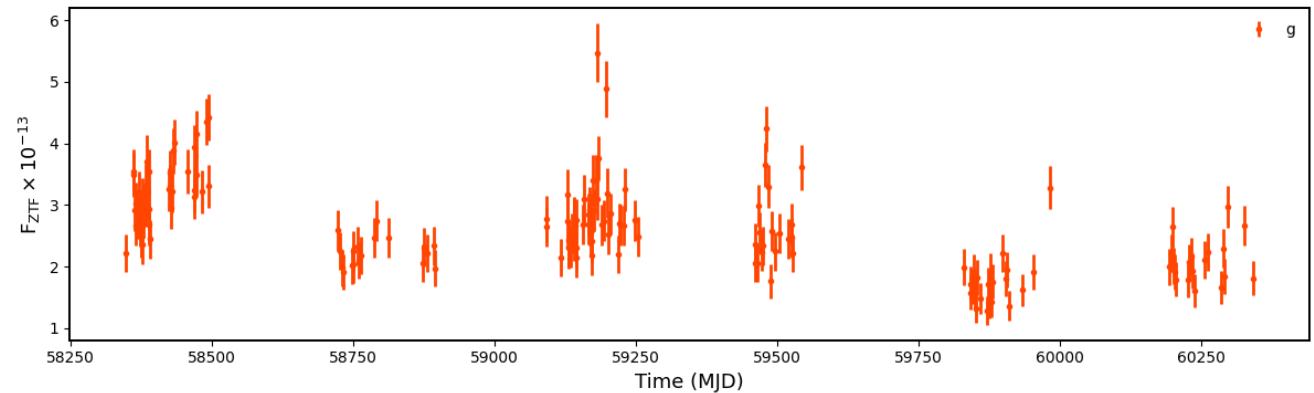
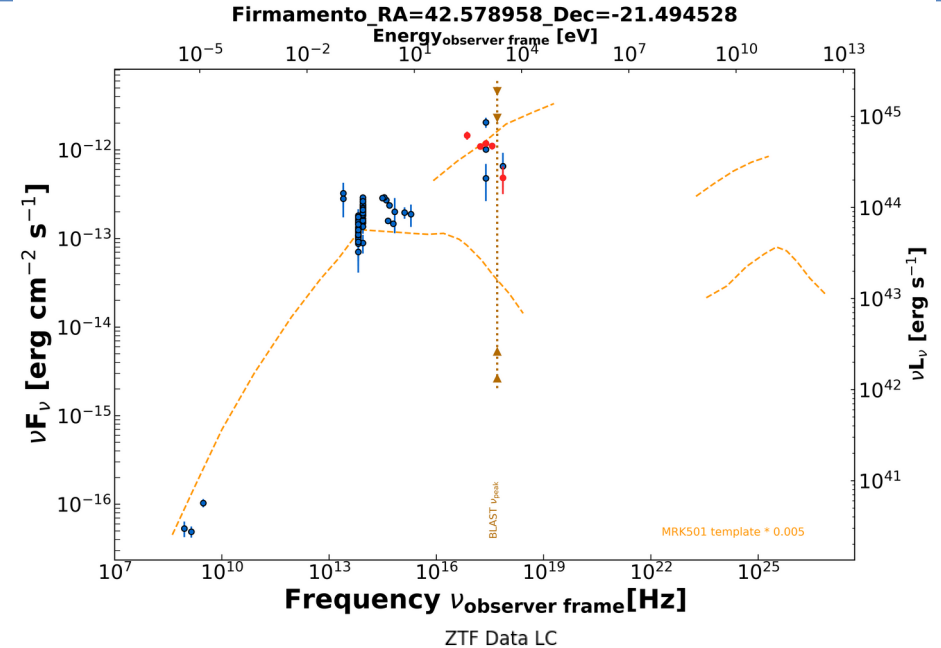


INAF
ISTITUTO NAZIONALE DI ASTROFISICA



SED selection and analysis

- Selecting sources with high x-ray to radio flux ratio (ratio > 2000)
- Adding:
 - Light curve from the Zwicky Transient Facility, a wide field survey of the optical transient sky (<https://irsa.ipac.caltech.edu/Missions/ztf.html>)
 - A template from Markarian 501, rescaled to the data of our source



eRASS1
J025018.8-212942

$$\frac{X}{radio} = 36025.0$$



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Current data and CTAO sensitivity

- Public Instrument Response Functions (IRF) from the Cherenkov Telescope Array Observatory (CTAO, prod5 version v0.1):

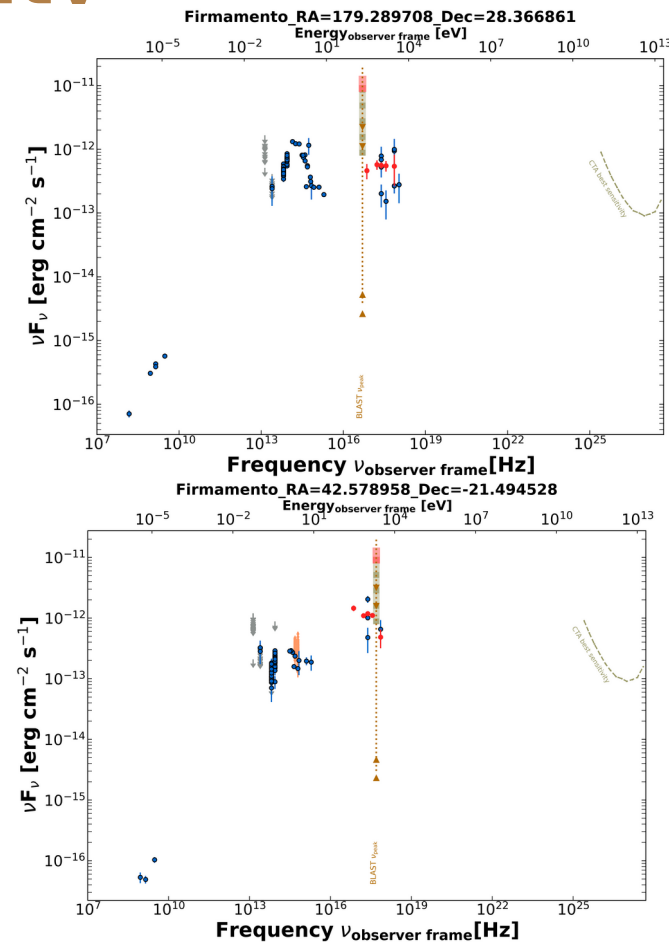
eRASS1
J115709.5+282201

- <https://www.ctao.org/for-scientists/performance/>
- <https://doi.org/10.5281/zenodo.5499840>

- To do:

- Discarding sources with predicted TeV emission below sensitivity
- Identifying possible candidates detectable by CTAO after 50 h of observations

eRASS1
J025018.8-212942





Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Conclusions

Next steps:

- Model spectral distributions of interesting sources
- Possible application of Machine Learning tools
- Provide a catalog of sources with detectable TeV emission

Special thanks:

- CTA+ Project, in particular my local responsible Carla Aramo
- The CTAO EGAL Working Group for their kind suggestions
- Paolo Giommi, for his kind assistance with the VOU-Blazars code and Firmamento



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



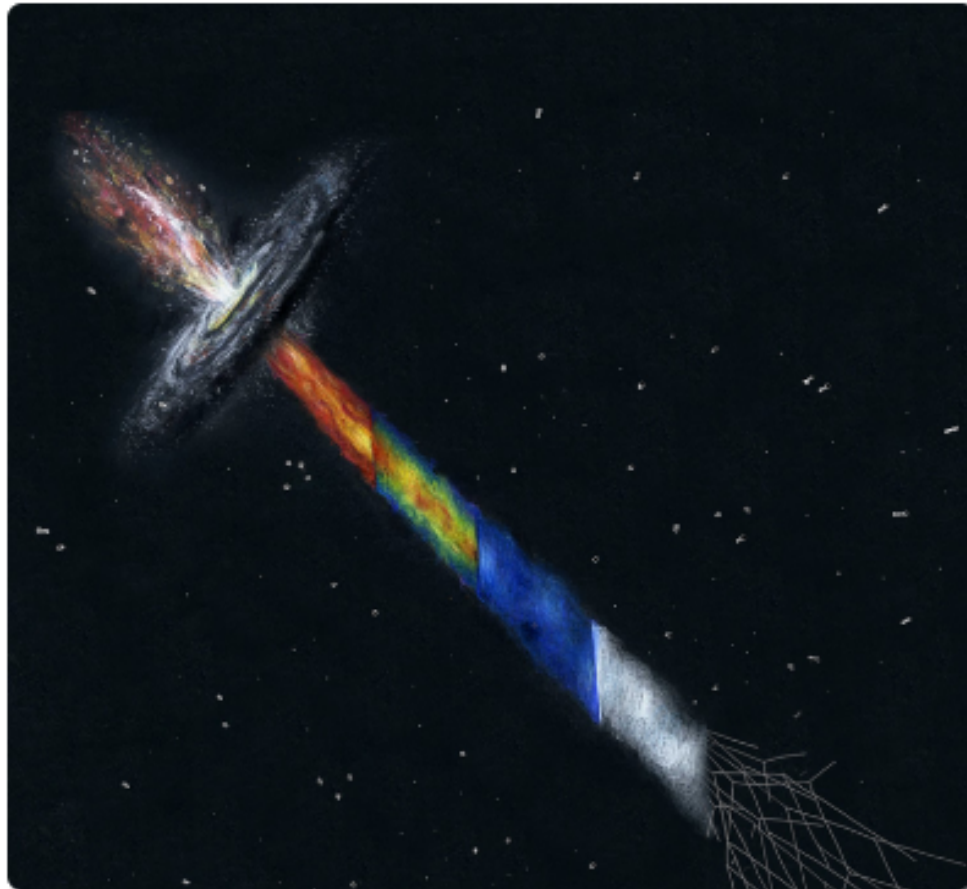
Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Thank you for your attention





Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Backup slides





Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

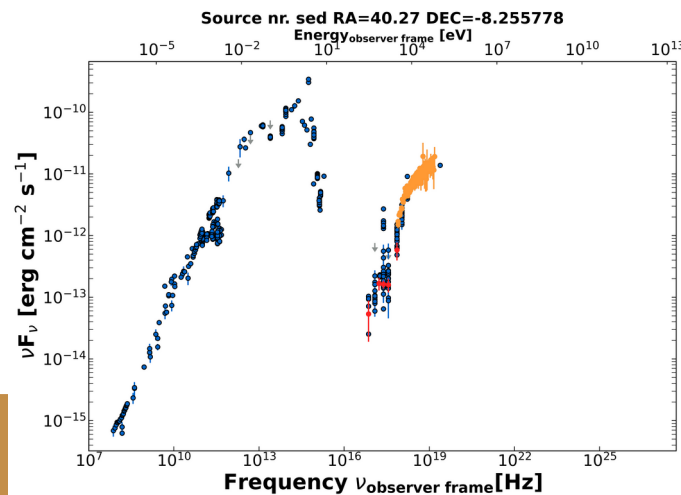


INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

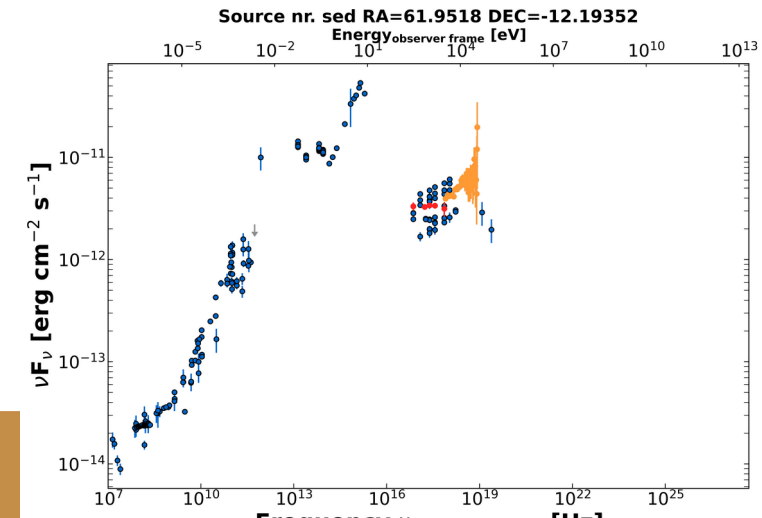


NuBlazar and eRASS1 catalogues

- **NuBlazar** (MNRAS 514, 2022): catalog of 124 sources from NuStar measurements
- Already included in VOU-Blazars catalog lists used in our analysis
- Making an independent check of building SEDs directly from NuBlazar list
- From NuBlazar (**orange**) list, returned 54 sources with eRASS1 data (**red**)



Iuliano - VHE Blazars



e Ricerca



Finanziato dall'Unione europea
NextGenerationEU



Ministero dell'Università e della Ricerca



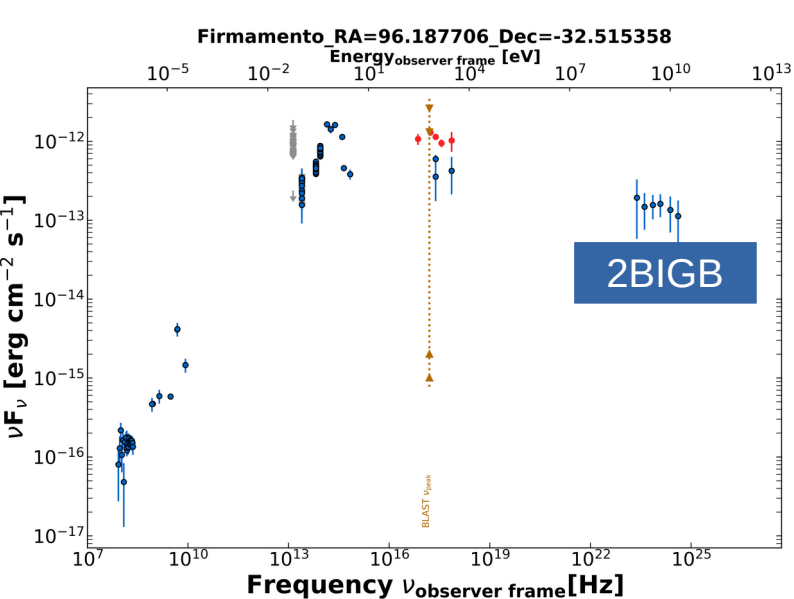
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA



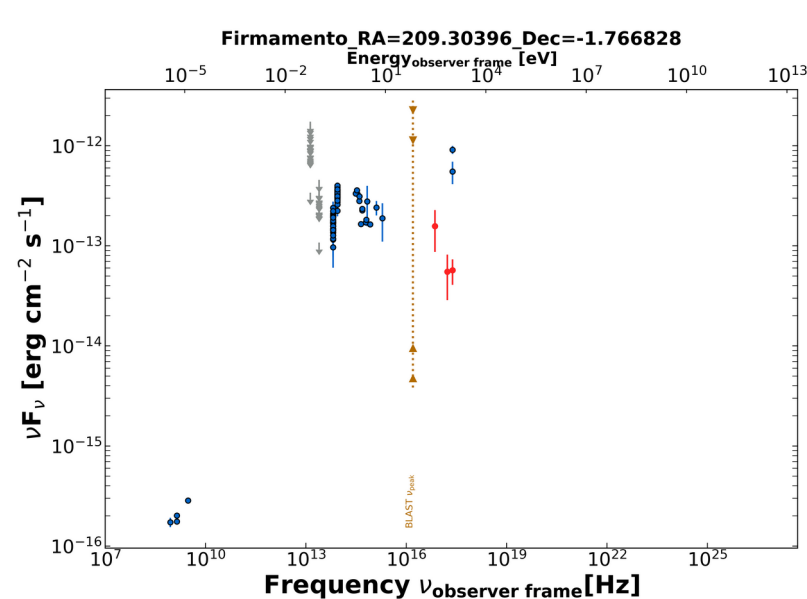
INAF
ISTITUTO NAZIONALE DI ASTROFISICA



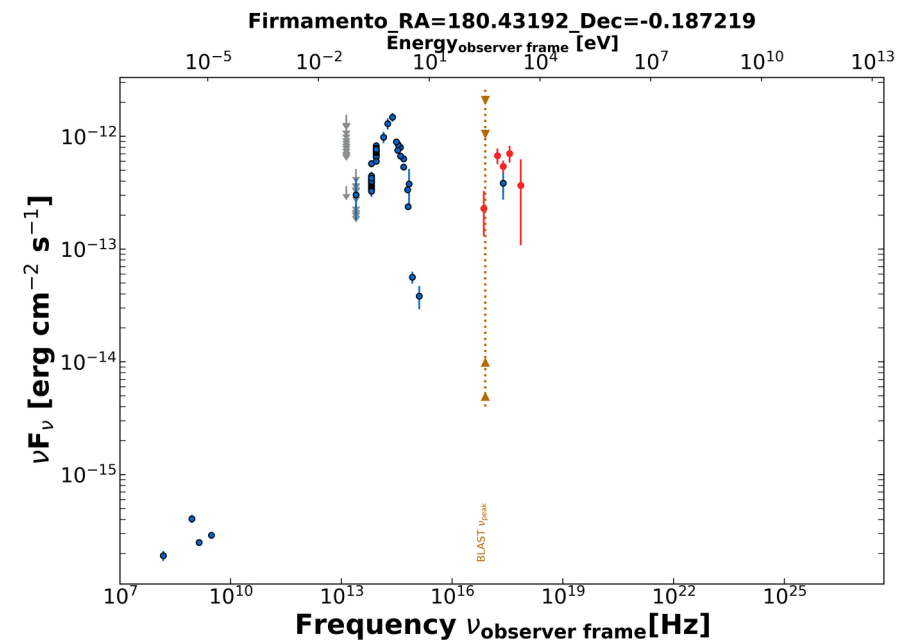
SED of outliers



1.79 σ



1.72 σ



1.88 σ

In red: data from the eROSITA eRASS1 catalogue
In blue: data from other catalogues



Fit parameters MMDC (Soprano)

Parameter	Units	Symbol	Minimum	Maximum	Type of distribution
Doppler boost	-	δ	3	50	Linear
Blob radius	cm	R	10^{15}	10^{18}	Logarithmic
Minimum electron injection Lorentz factor	-	γ_{\min}	$10^{1.5}$	10^5	Logarithmic
Maximum electron injection Lorentz factor	-	γ_{\max}	10^2	10^8	Logarithmic
Injection index	-	p	1.8	5	Linear
Electron luminosity	$\text{erg}\cdot\text{s}^{-1}$	L_e	10^{42}	10^{48}	Logarithmic
Magnetic field	G	B	10^{-3}	10^2	Logarithmic



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

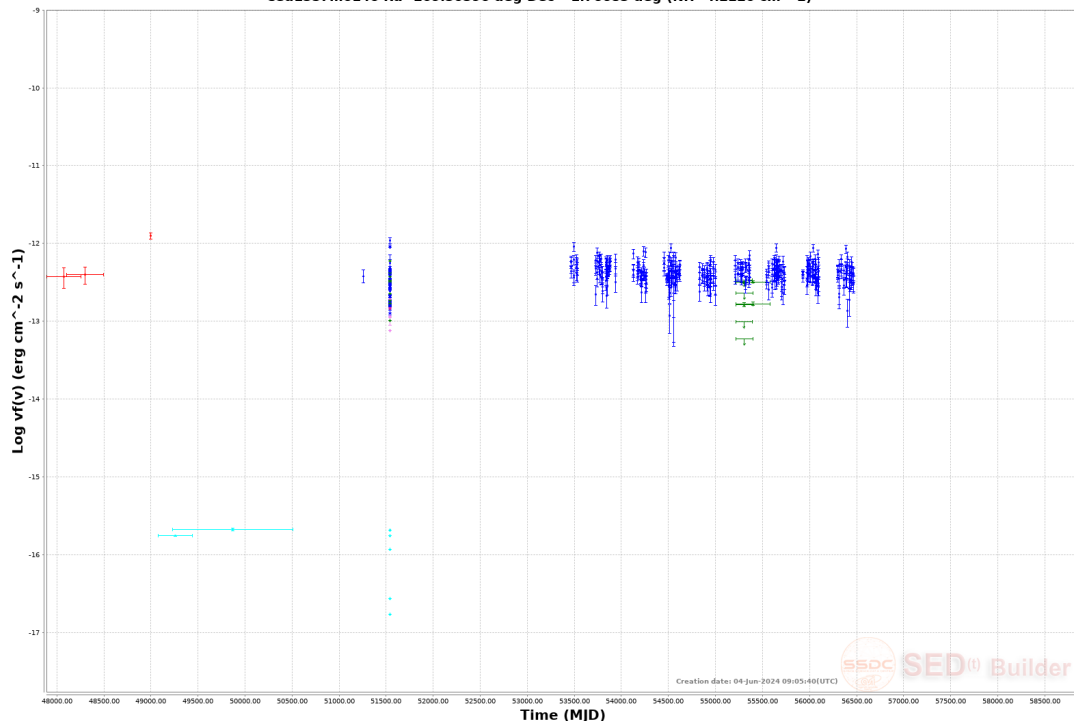


INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Outlier SEDs and Light Curves

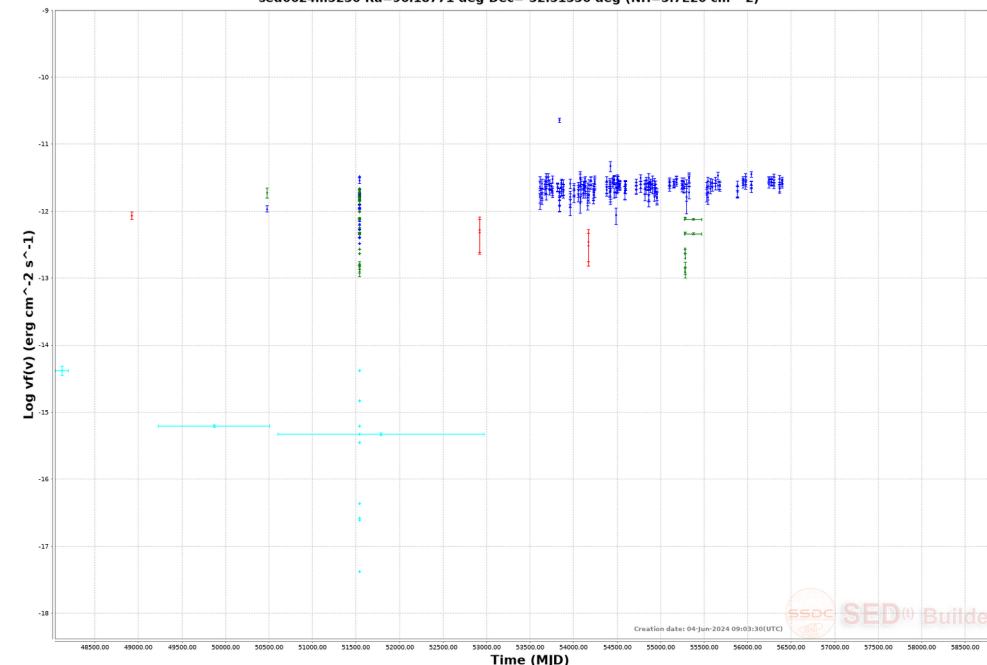
sed1357m0146 Ra=209.30396 deg Dec=-1.76683 deg (NH=4.2E20 cm⁻²)



5BZBJ1357-0146

Iuliano et al.
(in prep.)

sed0624m3230 Ra=96.18771 deg Dec=-32.51536 deg (NH=3.7E20 cm⁻²)



5BZBJ0624-3230

Colors according to energy band:
Red: x-ray Blue: Optical Green: Infrared Cyan: Radio Violet: UV



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



INAF
ISTITUTO NAZIONALE
DI ASTROFISICA



Modeling of blazar SEDs

- Selected a subsample of blazar candidates with high X/radio ratio
- In order to estimate TeV emissions, modelling the SED with the online platform Markarian Multiwavelength Data Center (MMDC): <https://mmdc.am/>
- Publicly available tool, employing Convolutional Neural Networks
- Employing the Self Synchrotron Compton (SSC) model to perform a fit with seven free parameters, provided the SED and the redshift



D. Bégué et al 2024 ApJ 963 71