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Ministero dell'Università e della Ricerca
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Searching for TeV-emitting candidates among the X-ray bright blazar population

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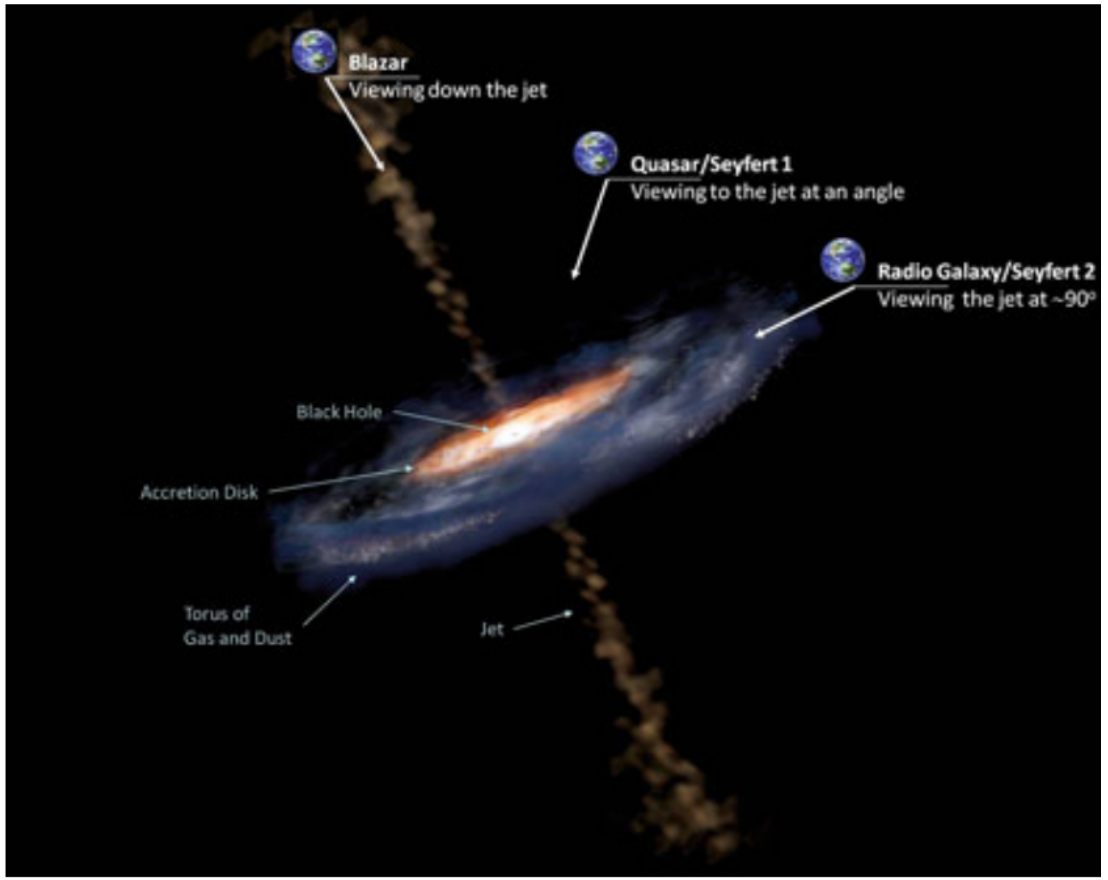
18 Dicembre 2024

Re[Incontri] di Fisica Partenopea, Napoli

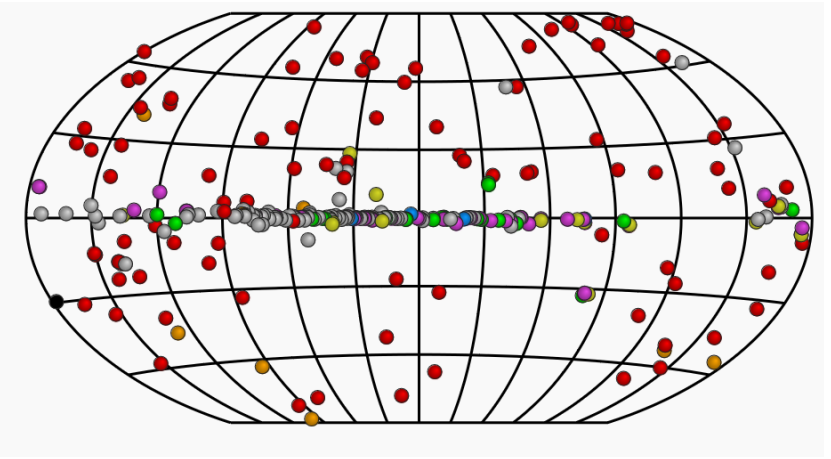
Introduction

- 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



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://tevcat2.uchicago.edu/

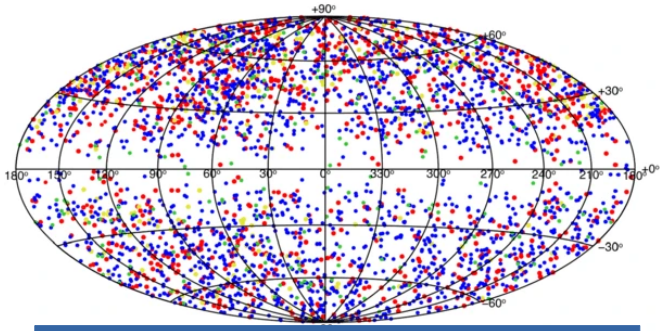
The 5BZCAT catalogue

- 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.ssdc.asi.it/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/

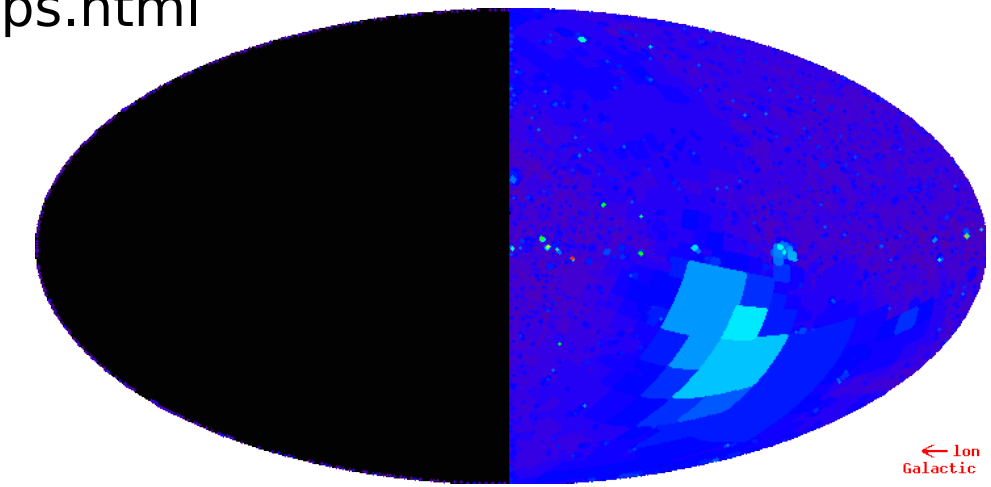


sky distribution in galactic coordinates of the blazars in the 5BZCAT catalogue, from paper Astrophys Space Sci 357, 75 (2015)

List of X-ray catalogs for cross-match

- **XMM-Newton Catalog** (>1300 deg^2; 4XMM-DR13) http://xmm-catalog.irap.omp.eu/)
- **Chandra** (~560 deg^2; CSC 2.0) https://cxc.cfa.harvard.edu/csc/)
- **Swift-XRT** (~3800 deg^2; 2SXPS) https://heasarc.gsfc.nasa.gov/W3Browse/swift/swift2sxps.html
- **NuSTAR** (~6 deg^2; NuBlazar) https://www.ssdc.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



5BZCAT sources detected in catalogs of X-ray sources

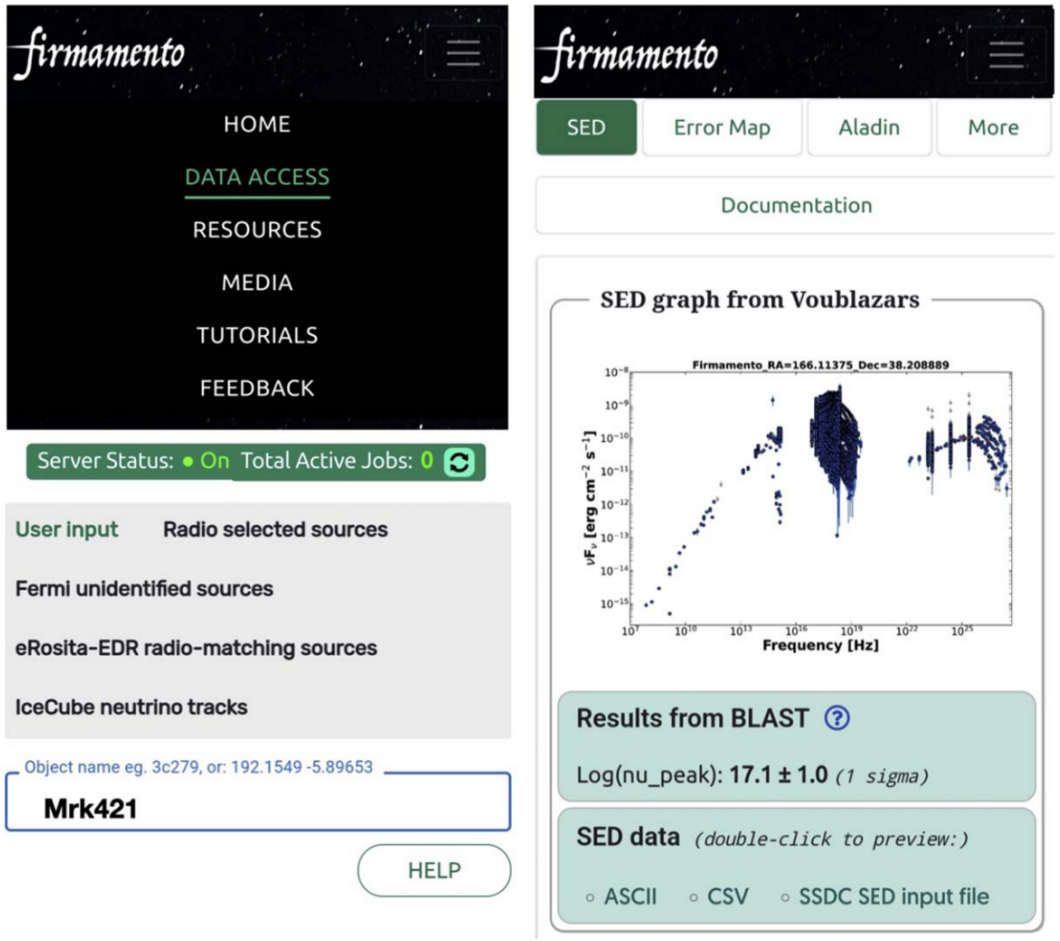
Marchesi S., Iuliano A. et al.
accepted for publication at A&A
https://doi.org/10.1051/0004-6361/202451924

Catalog	X-ray Instrument	Area Covered deg^2	Sources	With *Fermi*-LAT	Without *Fermi*-LAT
4XMM-DR13	XMM-*Newton*	1328	313	181 (58 %)	132 (42 %)
2CSC	*Chandra*	560	218	131 (60 %)	87 (40 %)
2SXPS	*Swift-XRT*	3790	1666	1191 (71 %)	475 (29 %)
eRASS1	eROSITA	20627	1379	726 (52 %)	653 (48 %)
NuBlazar	*NuSTAR*	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 %)

The Firmamento Platform

Tripathi et al. 2024, AJ 167 116

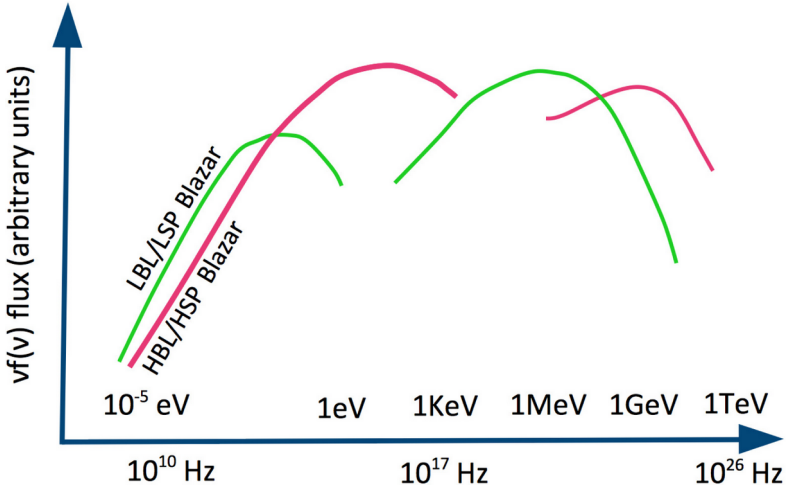
- Web browser tool with an updated version of the **VOU-Blazars** software (Chang+19)
- Available on the web: https://firmamento.hosting.nyu.edu
- Accesses data from catalog at all wavelengths, in order to obtain SED distribution
- Resulting file can be used as input for fitting and extrapolation to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



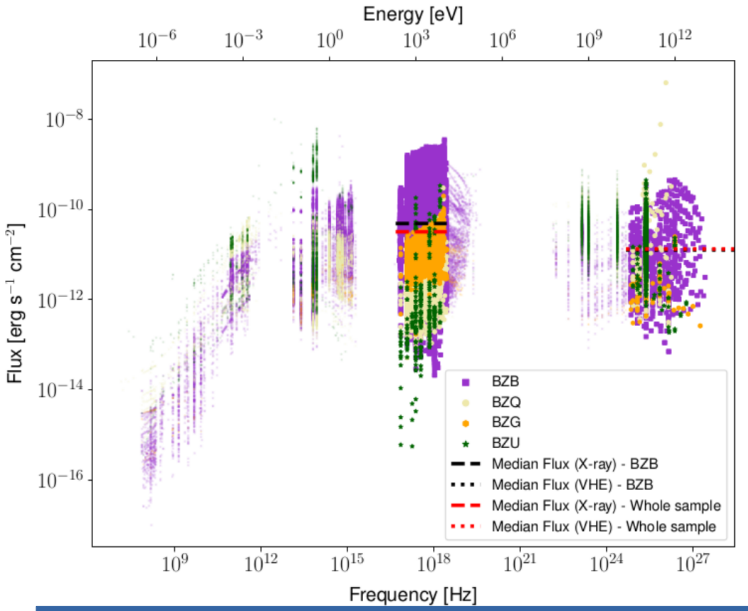
Structure and peaks of a SED

Marchesi S., Iuliano A. et al.
accepted for publication at A&A
https://doi.org/10.1051/0004-6361/202451924

- 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)



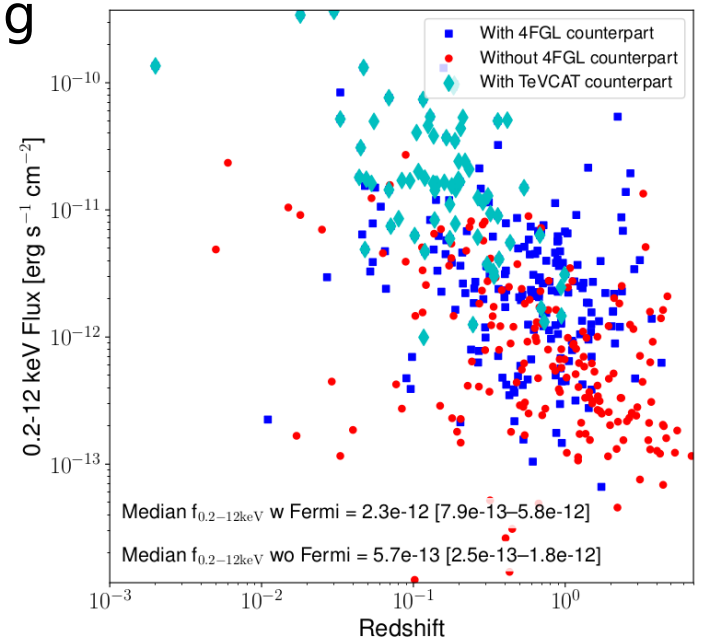
SEDs of TeVCat sources,
divided by class

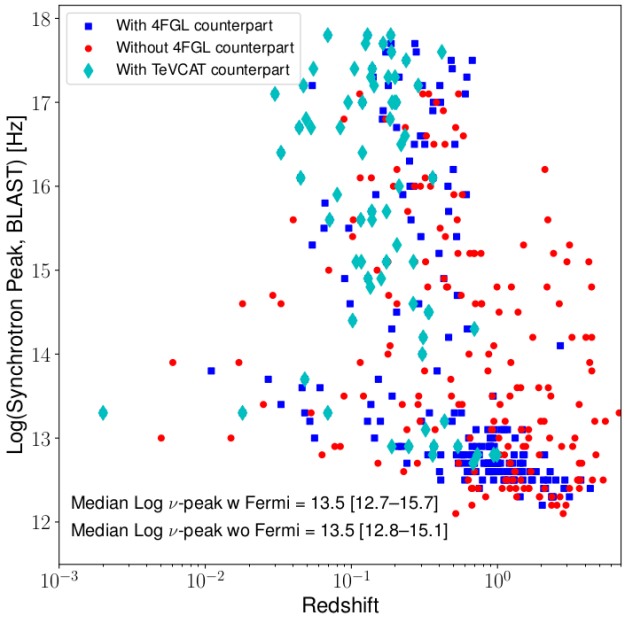
Multiwavelength distributions

- 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 S., Iuliano A. et al.
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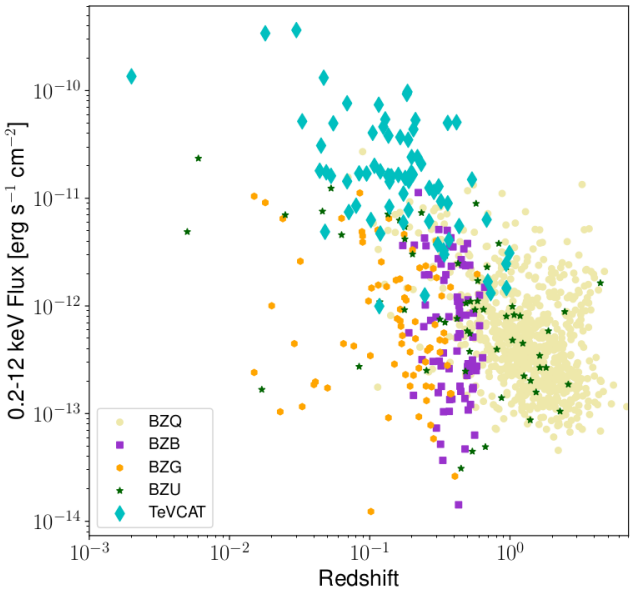
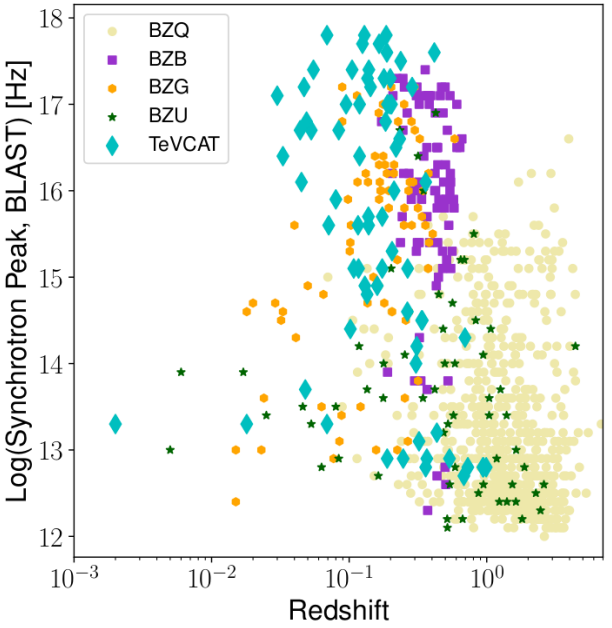
Blazar classes separation

- 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





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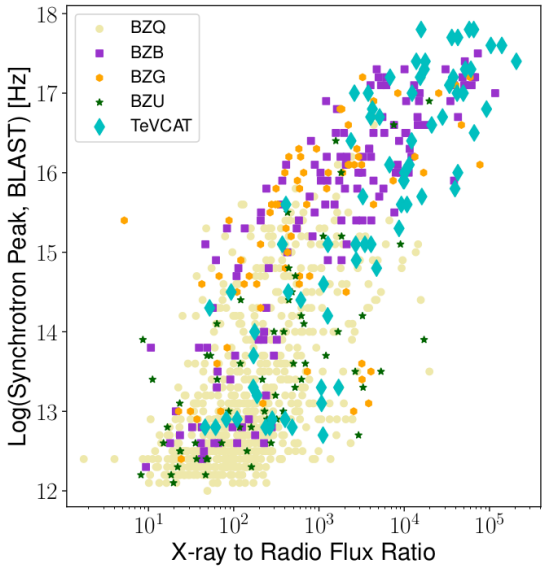
X-ray to radio flux ratio

- 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



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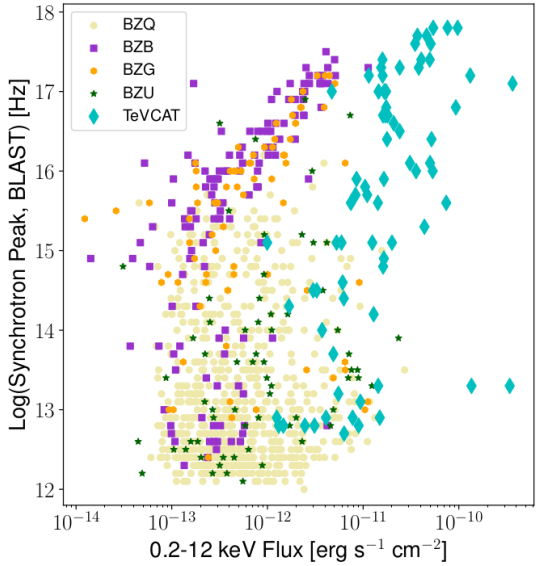
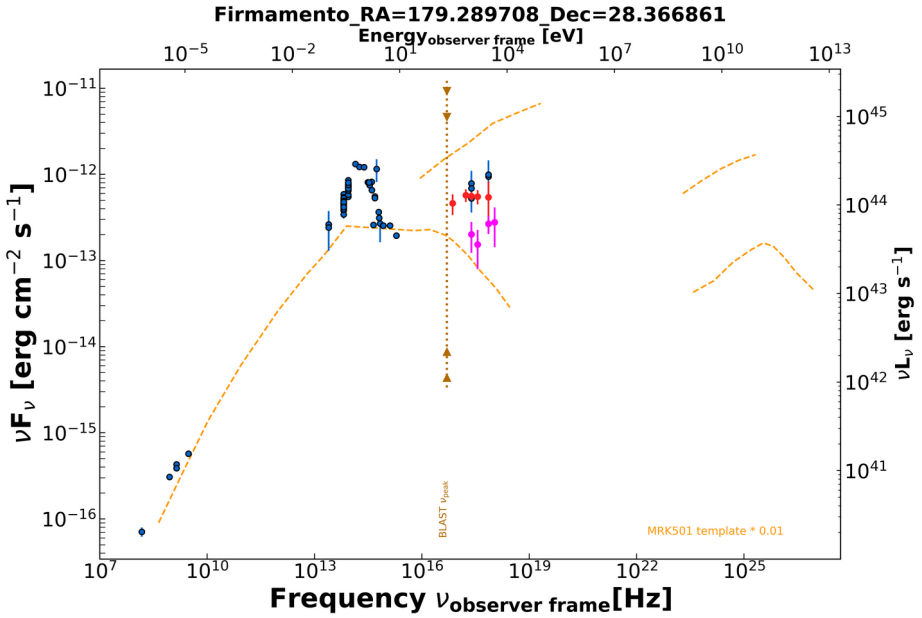


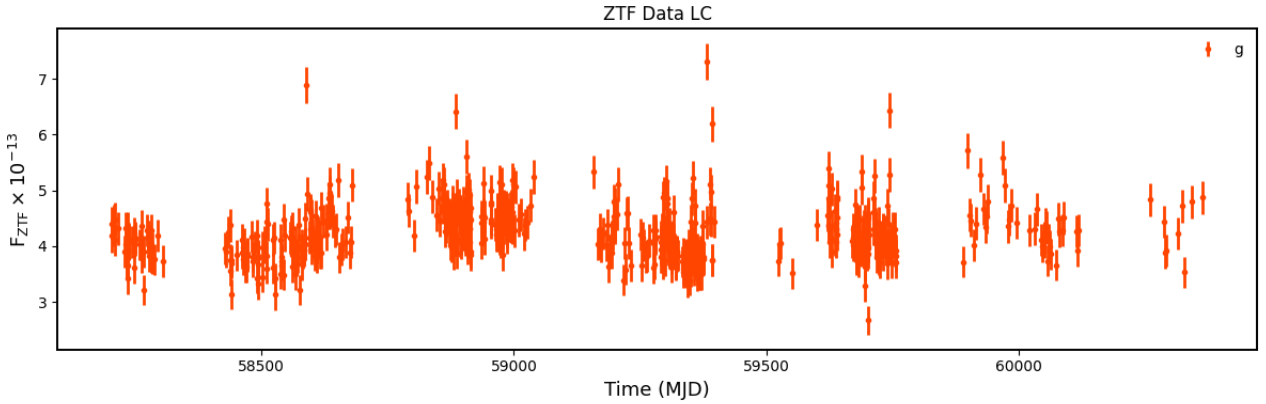
SED selection and analysis

- 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

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





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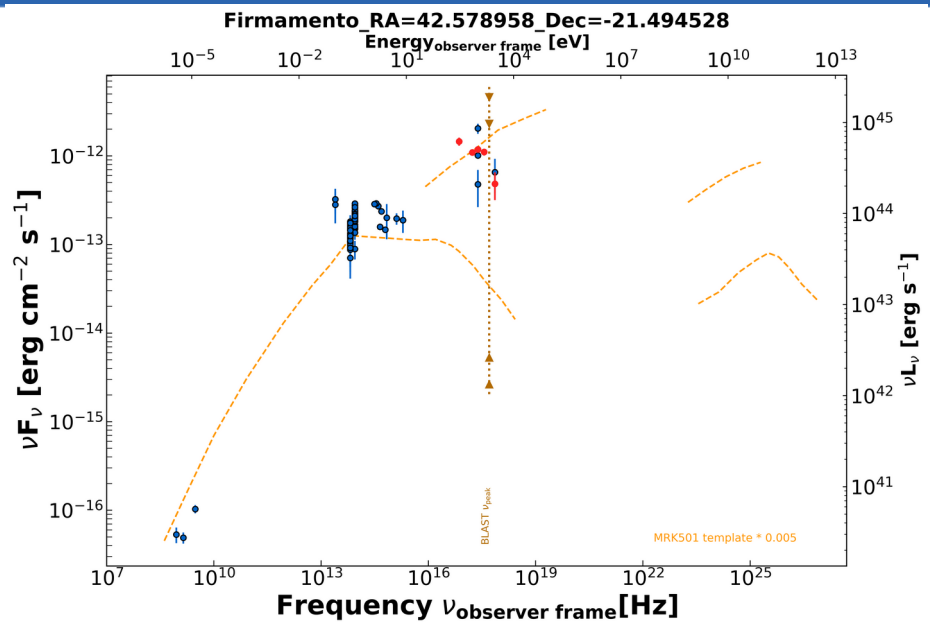
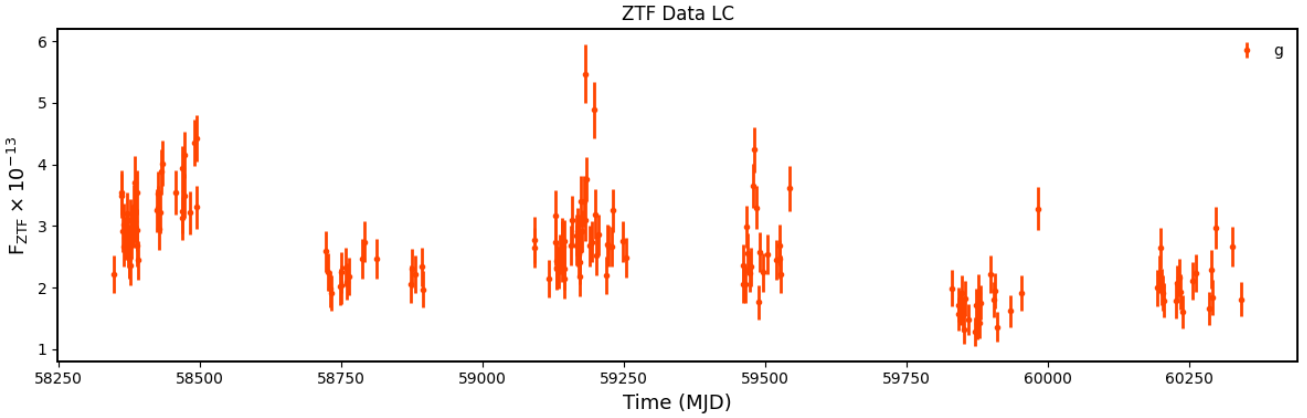




eRASS1 J025018.8-212942

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

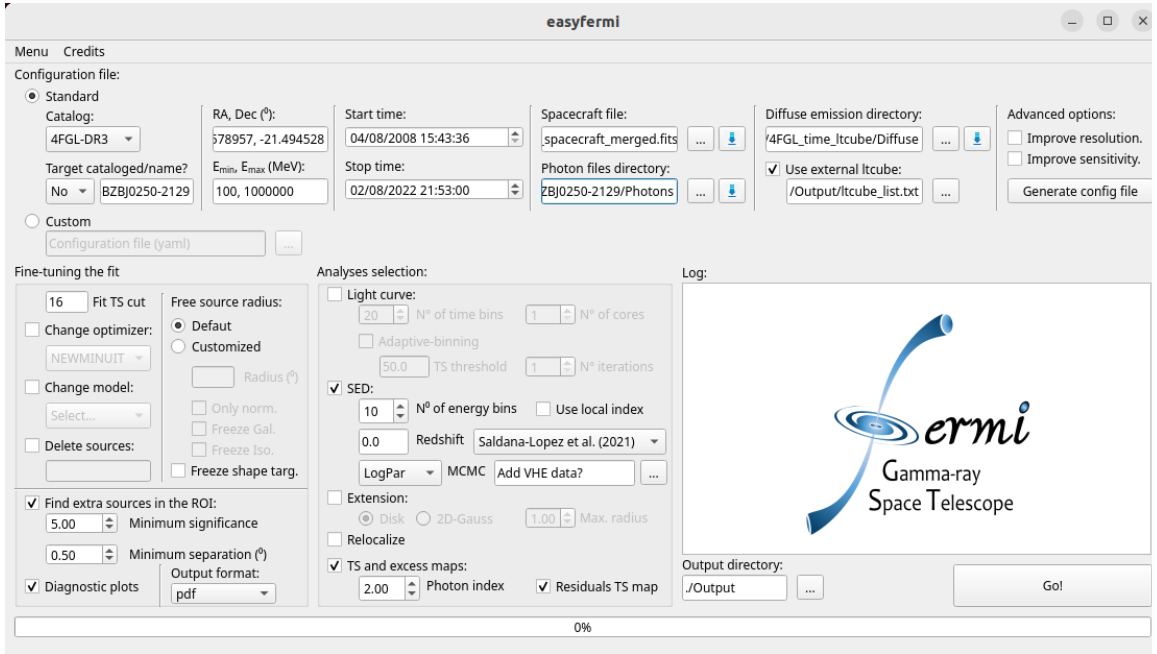
Constraints from Fermi non detection

- A reliable modeling of the Source SED needs to include not only the measured data from the X-ray and other bands, but also the upper limits from the Fermi in the gamma range

- To compute the upper limits, performed analysis with the user-friendly EasyFermi GUI-based tool

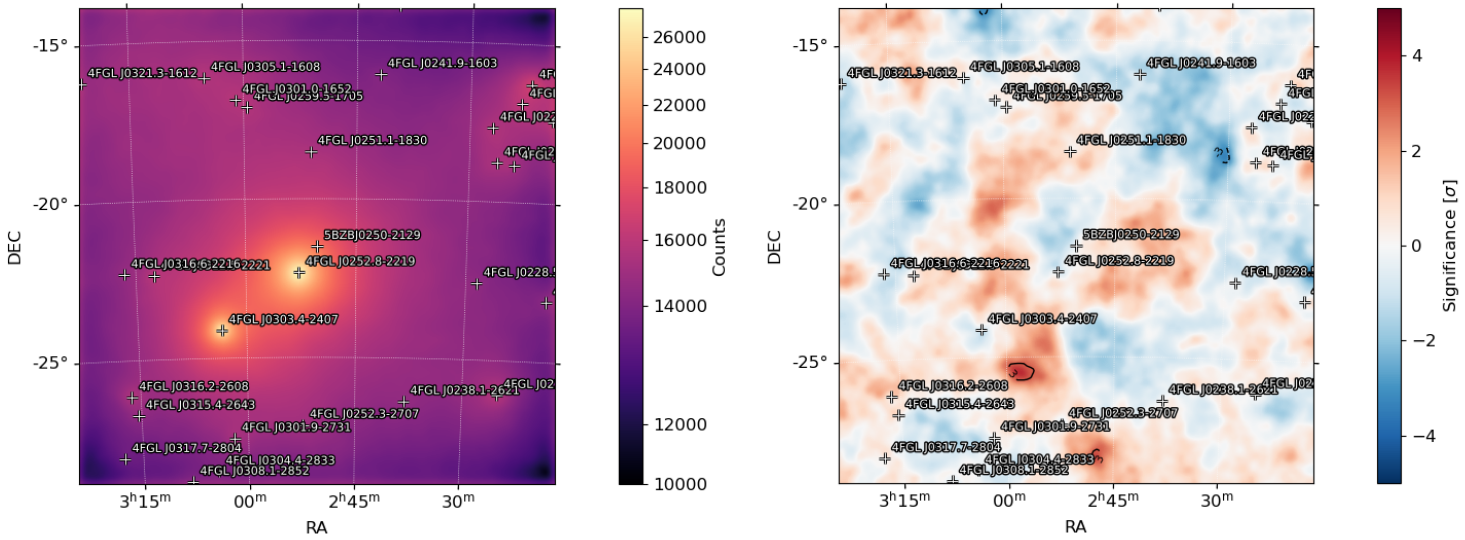
  R. de Mezenes, Astronomy and Computing, (2022) **40**, 10069, doi: 10.1016/j.ascom.2022.100609

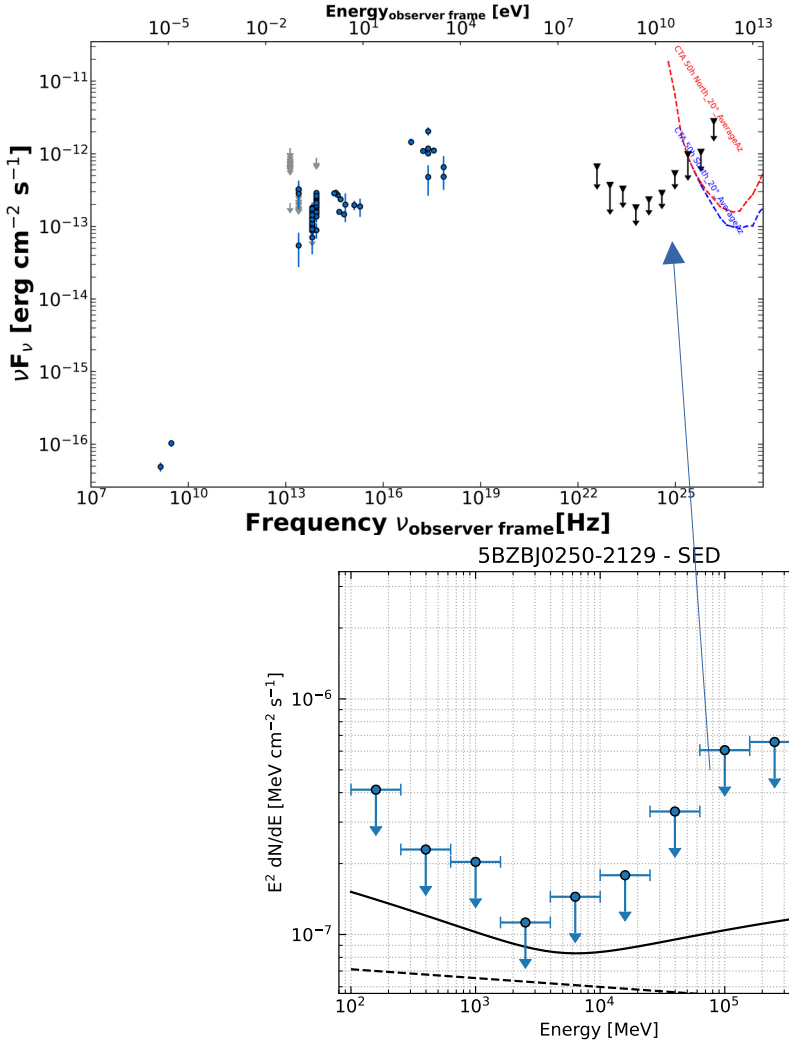
- Allows to perform all the steps of a Fermi-analysis, from data selection up to SED plotting



Example of EasyFermi upperlimits

- For source 5BZBJ0250-2129
- Same time range of the Fermi 4FGL-DR4 catalog
  (4 August 2008 to 2 August 2022)
- Energy range 100 MeV – 1 TeV



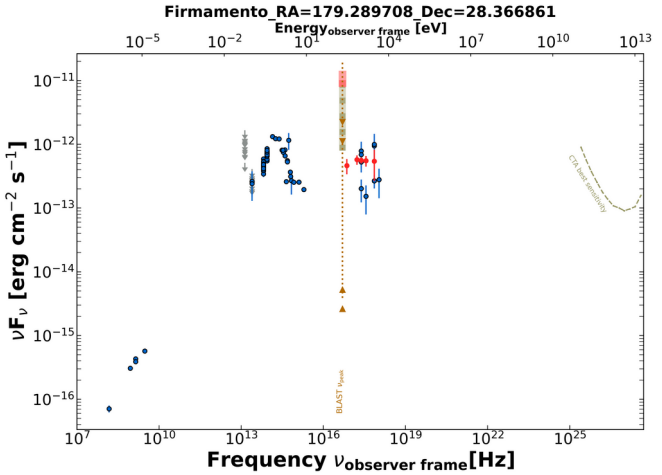


Current data and CTAO sensitivitv

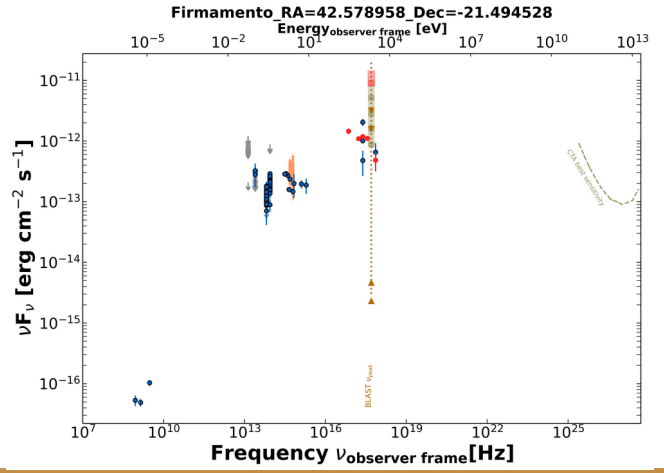
- Public Instrument Response Functions (IRF) from the Cherenkov Telescope Array Observatory (CTAO, prod5 version v0.1):
  - https://www.ctao.org/for-scientists/performance/
  - https://doi.org/10.5281/zenodo.5499840

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

eRASS1 J115709.5+282201



eRASS1 J025018.8-212942



Conclusions

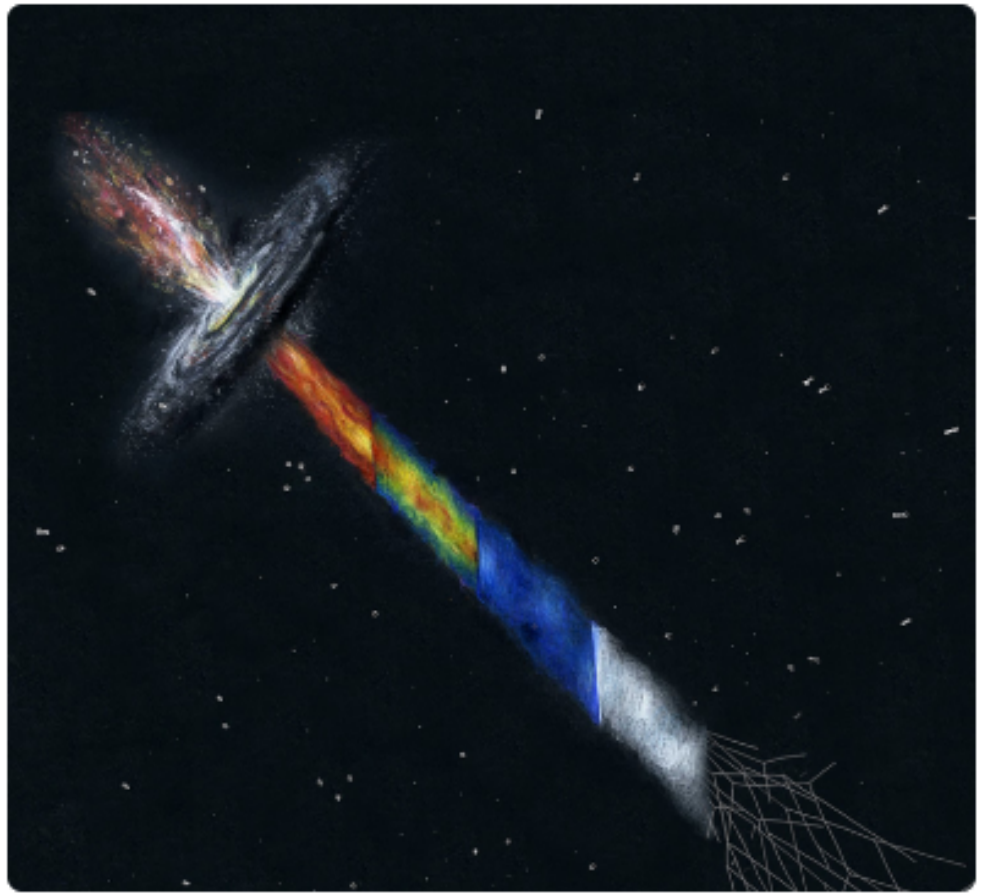
Next steps:

- 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

Thank you for your attention



Backup slides

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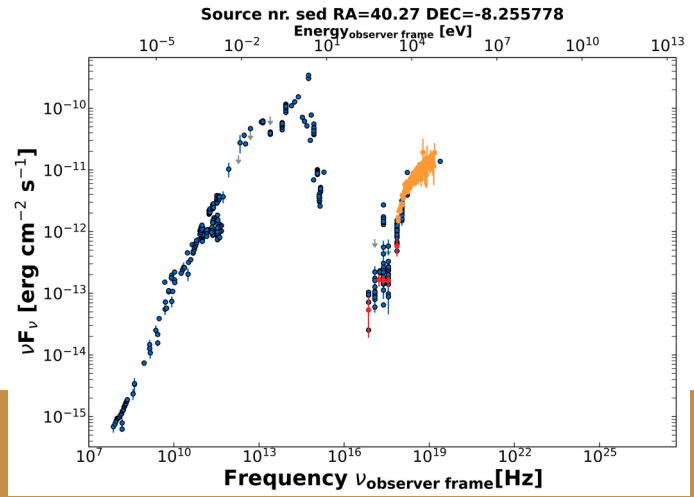
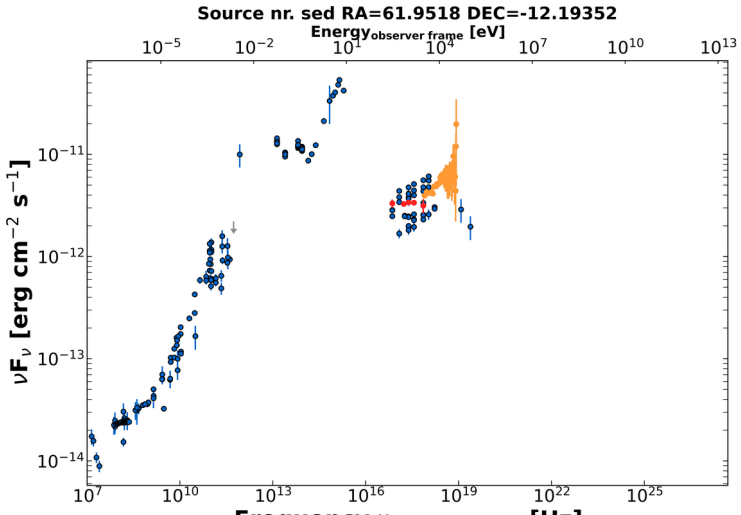
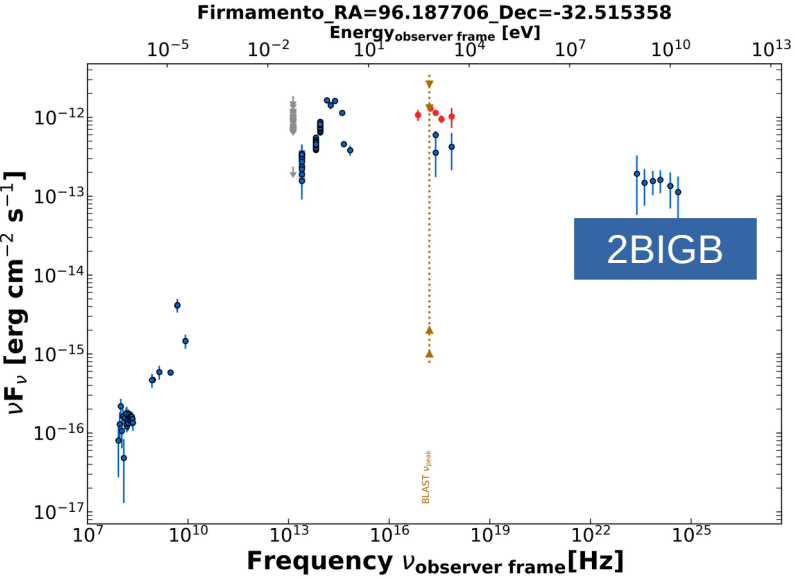
NuBlazar and eRASS1 catalogues

- **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)

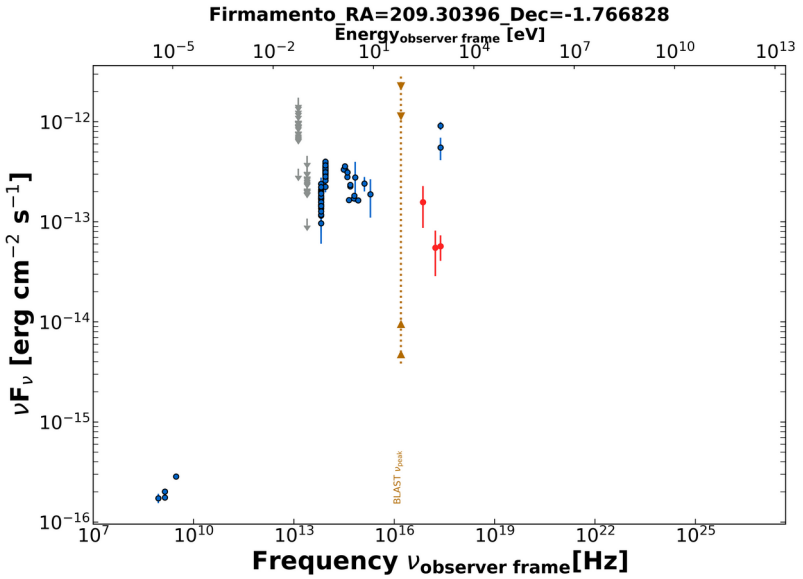




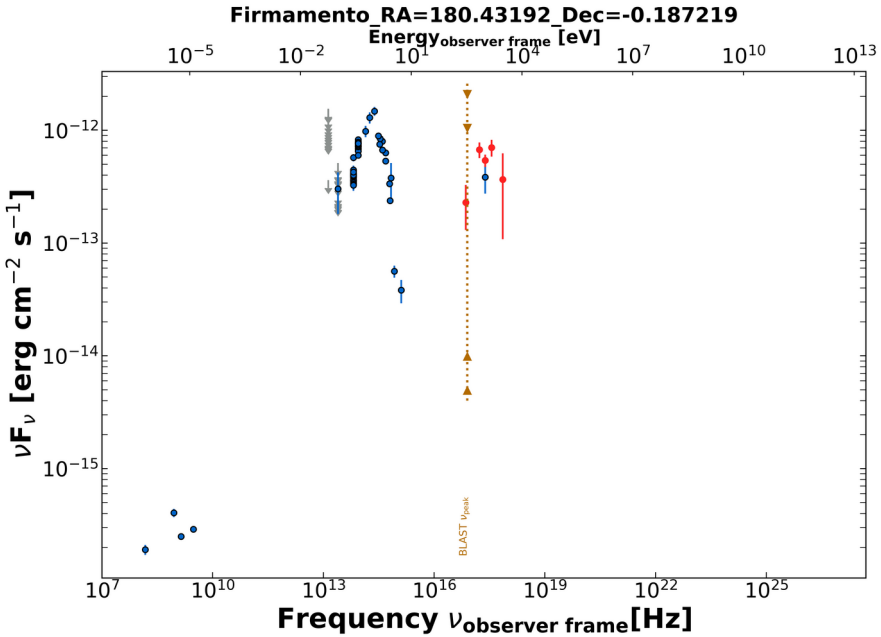
SED of outliers



1.79 σ



1.72 σ



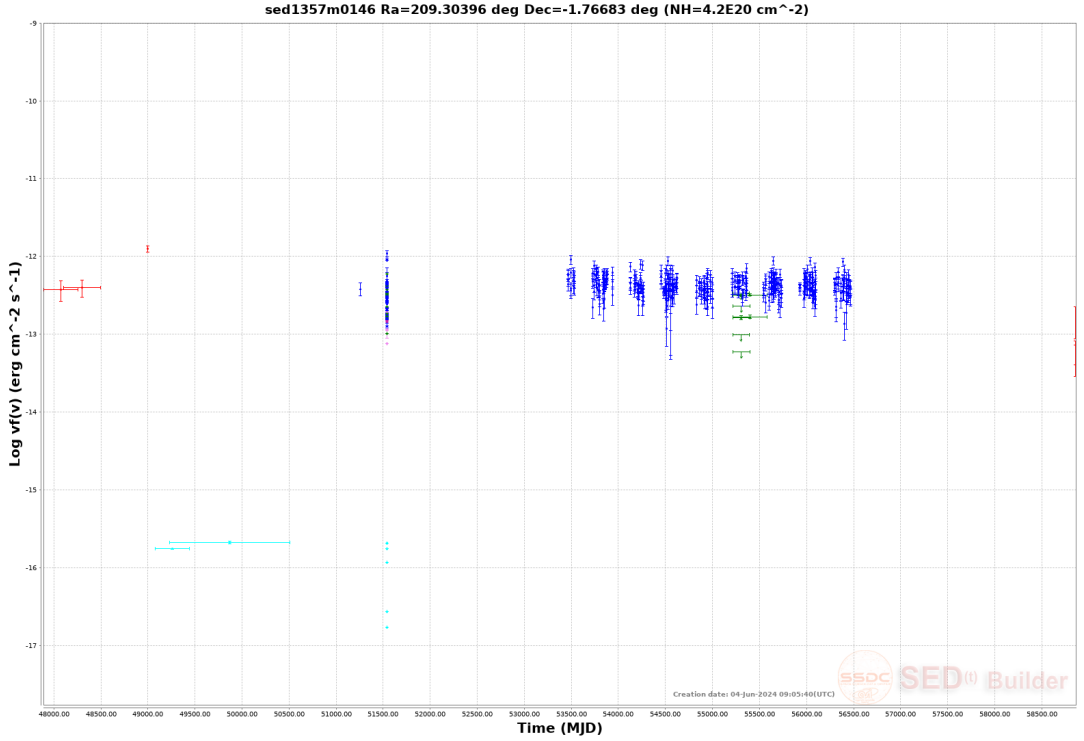
1.88 σ

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

Fit parameters MMDC (Soprano)

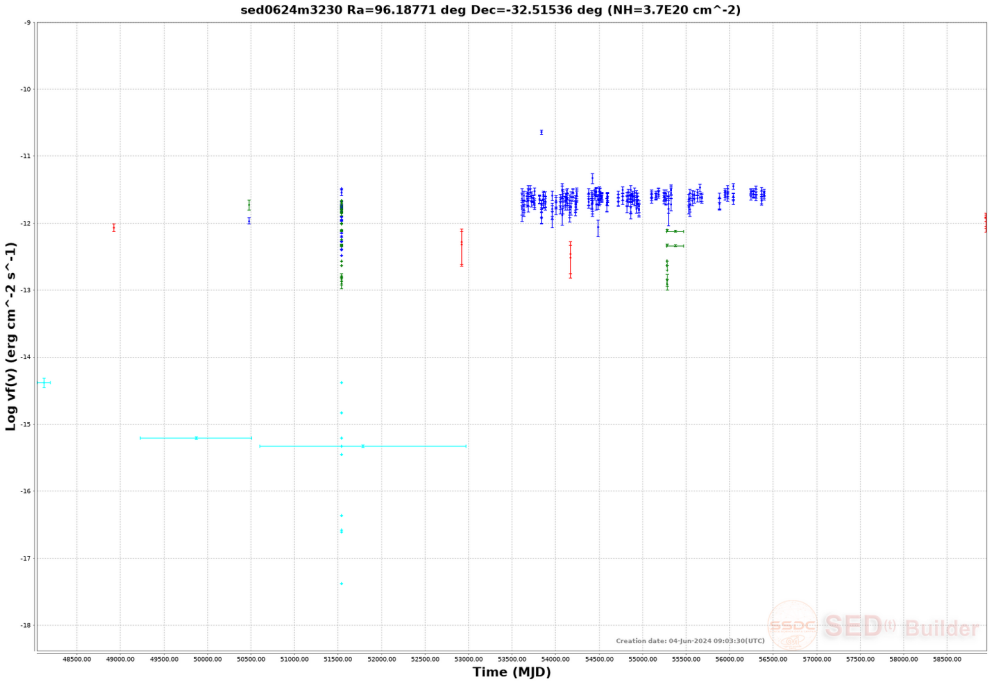
Parameter	Units	Symbol	Minimum	Maximum	Type of distribution
Doppler boost	-	δ	3	50	Linear
Blob radius	cm	R	10^{15}	10^{18}	Logarithmic
Minimum electron injection Lorentz factor	-	$\gamma_{\rm min}$	$10^{1.5}$	10^{5}	Logarithmic
Maximum electron injection Lorentz factor	-	$\gamma_{\rm max}$	10^{2}	10^{8}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

Outlier SEDs and Light Curves



5BZBJ1357-0146

Iuliano et al. (in prep.)



5BZBJ0624-3230

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

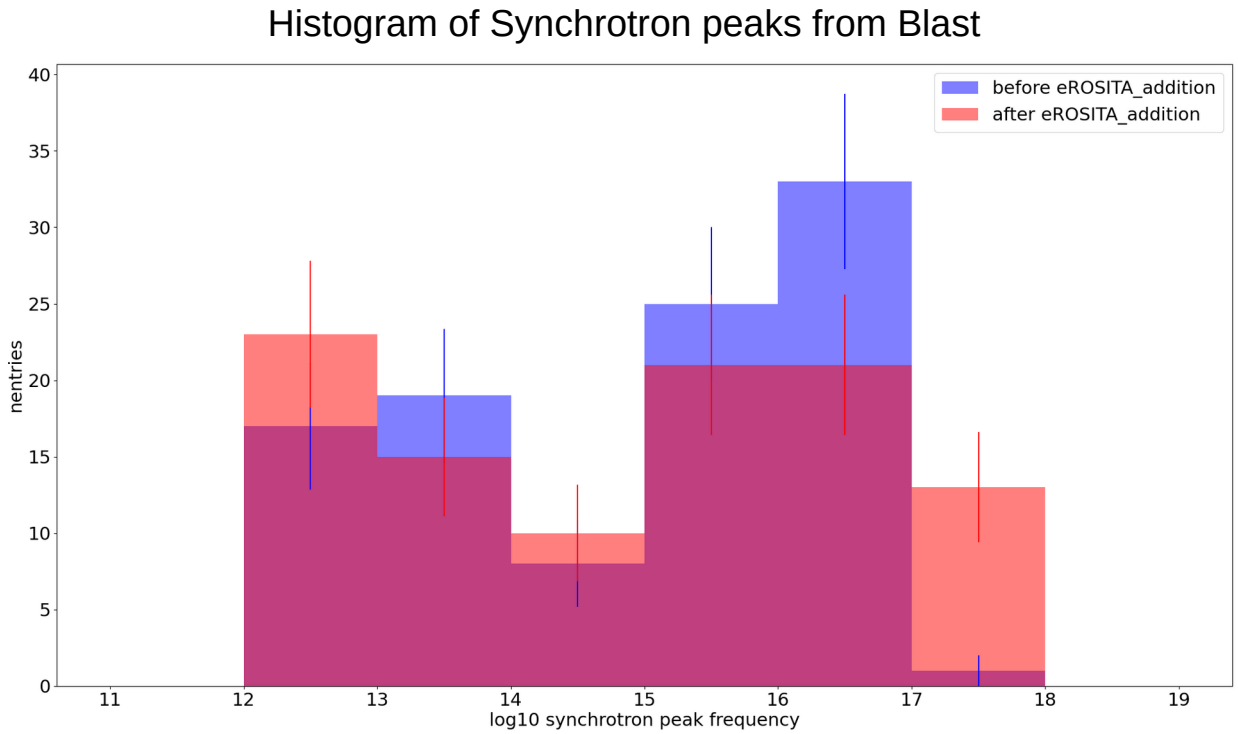
Modeling of blazar SEDs

- 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

Synchroton peaks with and without eROSITA

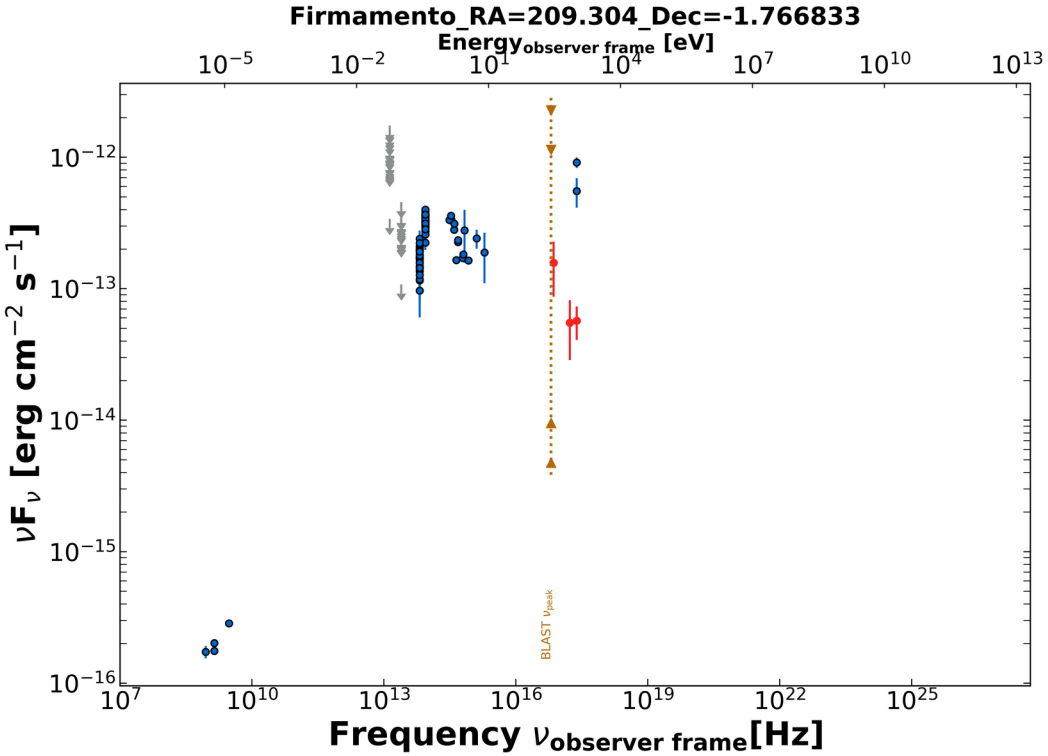
- Synchrotron peaks computed by BLAST for eRASS1 counterparts of 5BZCAT, without a Fermi detection and the 5BZQ component
- Comparing the peak before and after the addition of new eROSITA data
- Consistent distributions for most of the data, except for a few high peak sources
- Cross-checking SEDs of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



Iuliano et al. (in prep.)

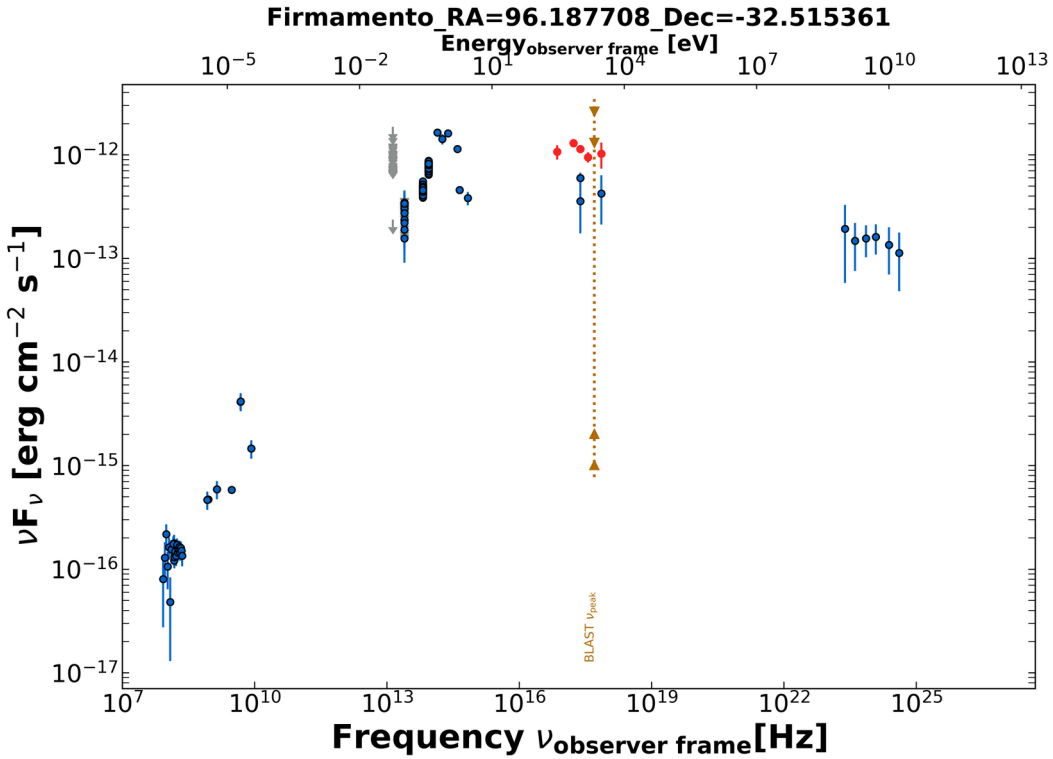
Outlier SEDs and Light Curves

5BZBJ1357-0146



Iuliano et al. (in prep.)

5BZBJ0624-3230

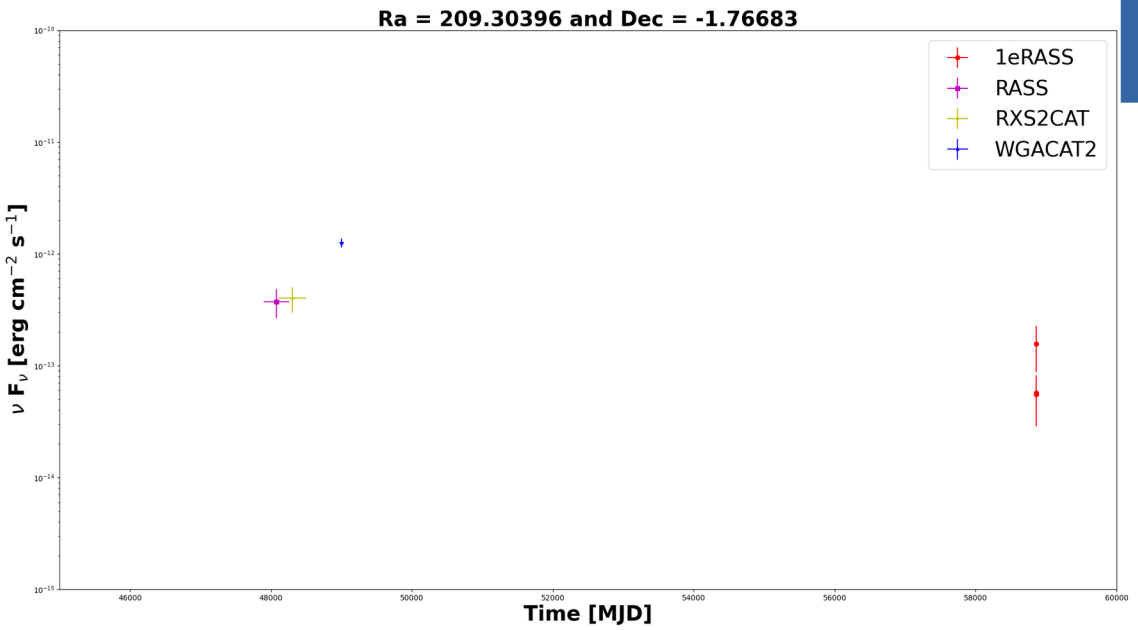


- Different values measured by eROSITA-eRASS1 with respect to other X-ray data

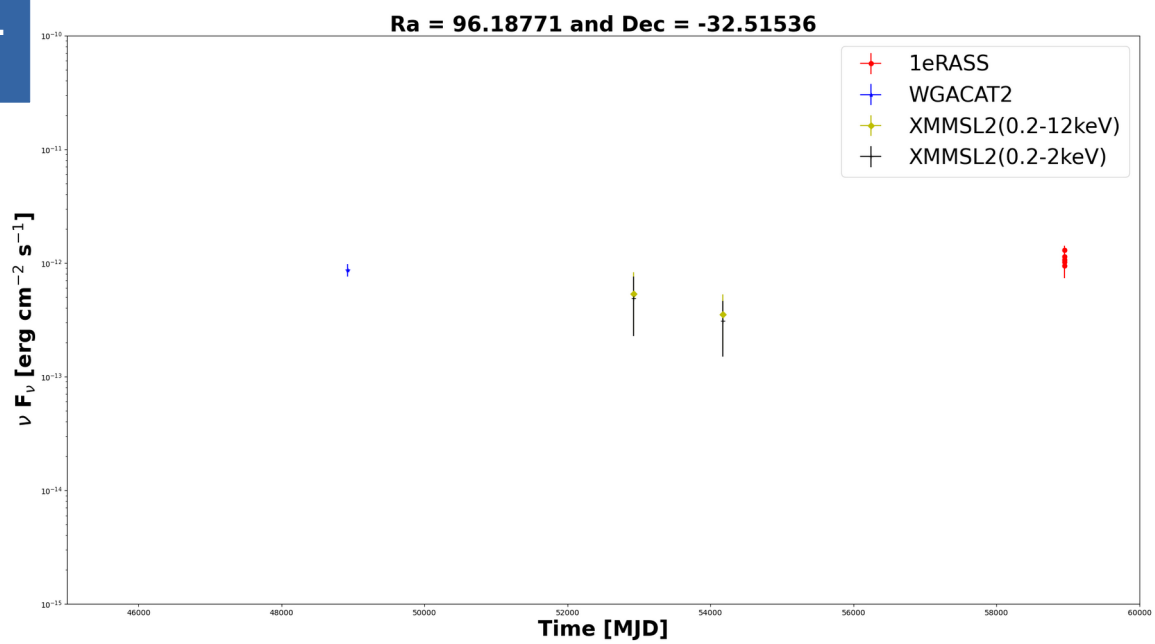
In red: eRASS1
In blue: other catalogs

Outlier SEDs and Light Curves

Iuliano et al. (in prep.)



5BZBJ1357-0146



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