A New Multiwavelength Census of Blazars

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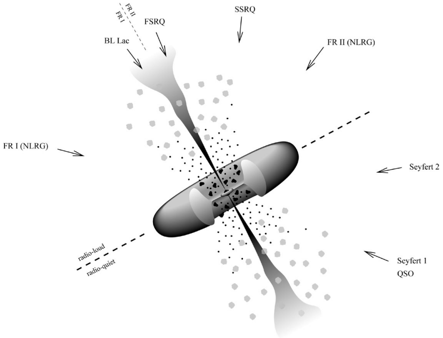
Blazars

Radio-loud sources with emission across whole e.m. spectrum, high and variable polarization, superluminal motion, high luminosities, intense/rapid variability, flat radio spectrum.

Jet aligned with l.o.s. within a few degrees (e.g., Blandford & Rees 1978; Begelman et al. 1984; Königl 1986).



Dominate the γ-ray sky: 80% of extragalactic γ-ray sources, 75% of extragalactic TeV sources.

Blazars Subclasses

BL Lacs:

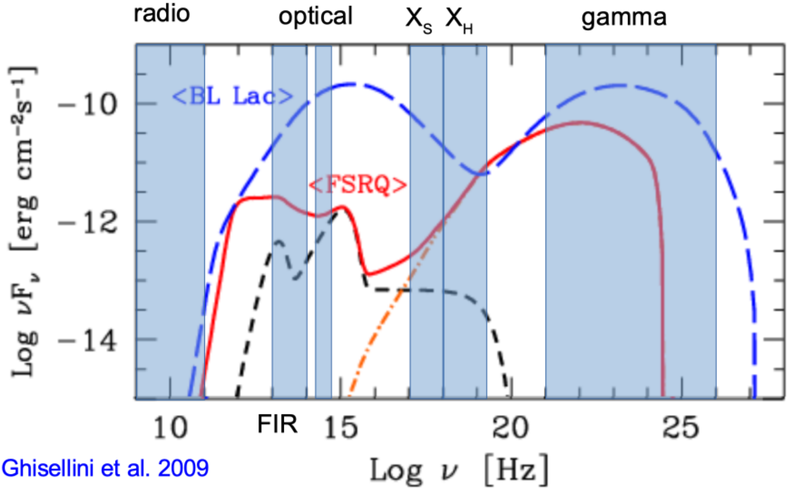
- $L_{\rm iso} \lesssim 10^{46}$
- Spectra with weak em. lines ($EW < 5\,\AA$)
- Pure non-thermal radiation
- $z \lesssim 1.3$ (peak at $z \sim 0.3$)

Flat Spectrum Radio Quasars:

- $L_{\rm iso} \lesssim 10^{48}$
- Spectra with broad em. lines ($EW > 5\,\AA$)
- Thermal emission (BBB)
- $z \lesssim 5.5$ (peak at $z \sim 1.5$)

But recently, γ-ray **BL Lacs** with z up to 2.5 (4LAC, Ajello et al. 2020) and even 3.6 (Paliya et al. 2020).

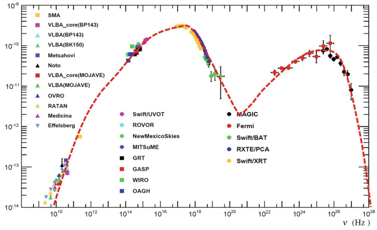
Blazar SED



Ghisellini et al. 2009

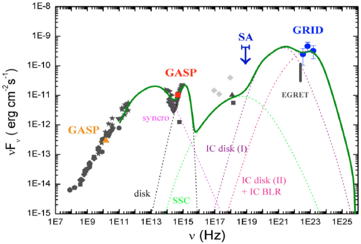
BL Lacs vs. FSRQs

BL Lac: Mrk 501 (Spurio et al. 2018)



Pure non thermal continuum → **SSC**: synch. by electrons in jets + IC on synch. photons (Marscher et al. 2010).

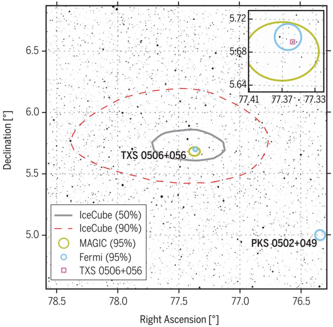
FSRQ: PKS 1510-089 (Pucella et al. 2008)

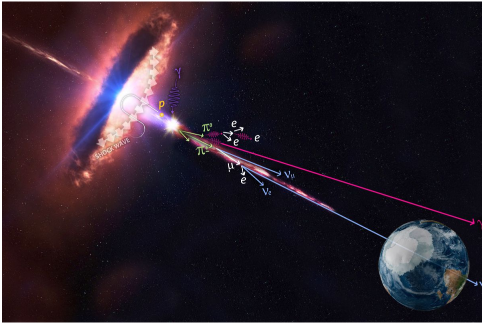


Developed accretion disk (BBB + lines), γ-ray dominance → **EC**: seed photons from disk, torus, BLR (Maraschi et al. 2001).

Blazar Neutrino

TXS 0506+065 (IceCube Collaboration et al. 2018, Garrappa et al. 2019).





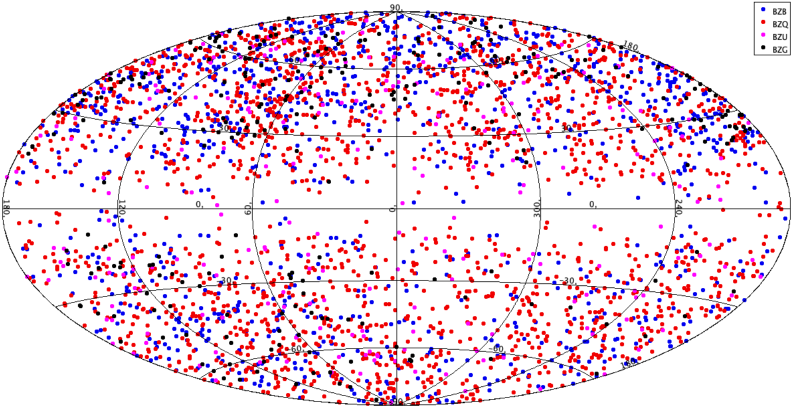
Blazars as multi-messenger sources.

Roma BZCAT

The 5th edition of the Roma-*BZCAT* Multifrequency Catalogue of Blazars (Massaro et al. 2005) represents the most comprehensive list of blazars confirmed by means of available spectra.

- 3561 sources
- Multi-wavelength informations (optical, radio flux, microwave, soft/hard X-ray flux, γ-ray) and redshift
- 1151 **BZBs** (1059 BL Lac objects + 92 BL Lac candidates)
- 1909 **BZQs** (Flat Spectrum Radio Quasars)
- 227 BZUs (blazars of uncertain type)
- 274 BZGs (BL Lacs with dominant galactic emission)

Mind the Gap



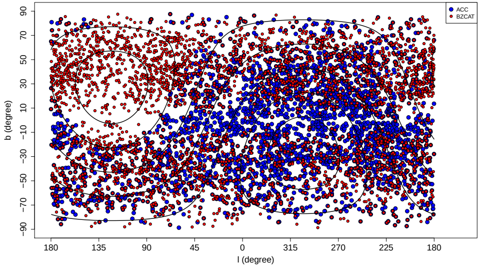
Blazar catalogs as complete as possible are necessary to provide candidate counterparts to unassociated γ-ray sources and to sources of high-energy neutrino emission or UHECRs.

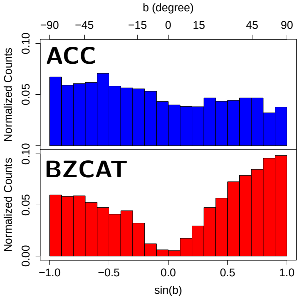
ALMA Calibrators

Combining the ALMACAL (Bonato et al. 2018) with the ALMA Calibrator Source Catalogue, Bonato et al. (2019) built the ALMA Calibrator Catalogue (ACC): 3364 bright, compact radio sources with ALMA flux density measurements, α_{low} between 1 (NVSS, Condon et al. 1998; SUMMS, Mauch et al. 2003) and 5 GHz (GB6, Gregory et al. 1996; PMN, Griffith & Wright 1993).

- 3037 ($\sim$ 90%) blazar candidates: $\alpha_{\text{low}} < 0.5$, evidence of variability, γ-ray emission

BZCAT vs ACC

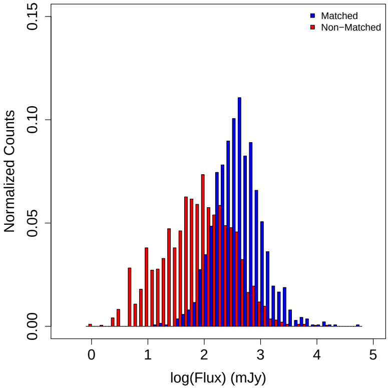




- *BZCAT*: $|b| < 10^\circ \rightarrow 3\%$
- ACC (Dec $\lesssim +60^\circ$): $|b| < 10^\circ \rightarrow 15\%$

ACC Catalog

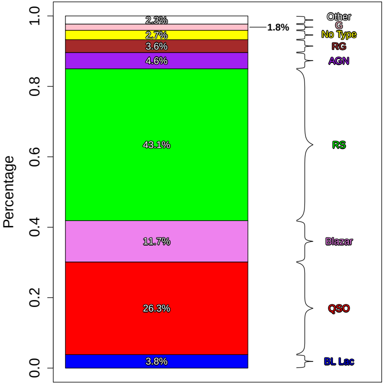
3340 *BZCAT* sources with Dec $< 60^\circ \rightarrow$ 1391/1949 with/without match in ACC: 1.4/0.843 GHz radio flux from *BZCAT*.



We select the brightest radio end of the blazar population.

ABC Catalog

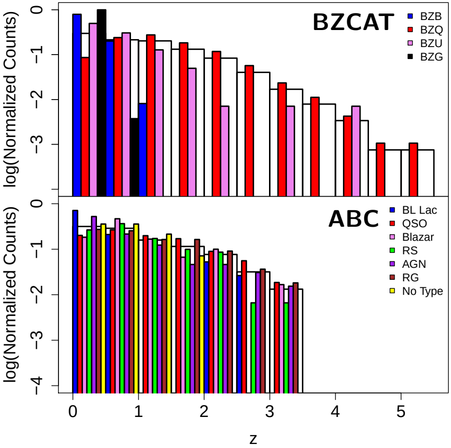
ACC 3037 blazar candidates - 1391 in *BZCAT* $\rightarrow$ 1646 sources. Literature (SIMBAD) classification.



Radio sources (RS, 43%), quasars (QSO, 26%), and Blazars (12%) are the main contributors.
We exclude galaxies (G), galaxies in clusters, stars, etc. (Other) $\rightarrow$ 1580 sources (96%).

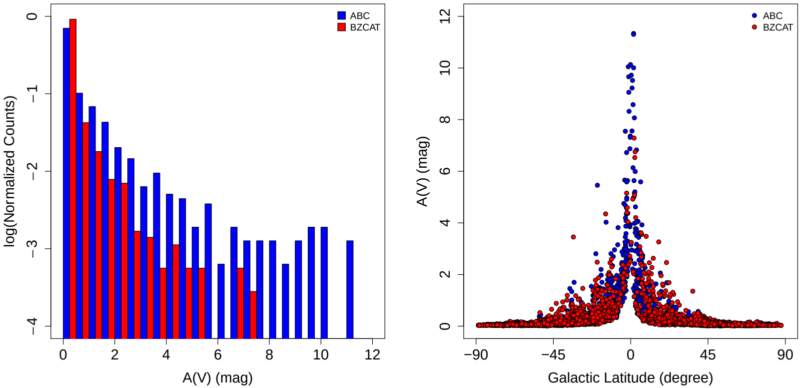
ALMA Blazar Candidates (ABC).

Redshift Distribution



BZCAT $z \leq 5.5$, ABC $z \leq 3.5$.

Absorption Distribution



ABC extends to lower galactic latitudes → stronger absorption.

Catalog Comparison: 4FGL

4th *Fermi* Large Area Telescope Source Catalog (4FGL, Abdollahi et al. 2020):

- 5064 sources 50 MeV – 1 TeV
- 3474 associated (spatial coincidence) + 359 identified (periodic/correlated variability)
- 3137 blazars (62 % of 4FGL, 82 % of associated/identified): **BLL** (BL Lacs, 36 %), **FSRQ** (22 %), BCU (blazar of uncertain type, 42 %)
- 1231 unassociated (UGS)

259 ABC matches with associated/identified 4FGL sources (no UGSs).

Catalog Comparison: 3HSP

3rd catalogue of extreme and High-Synchrotron Peaked blazars (3HSP, Chang et al. 2019):

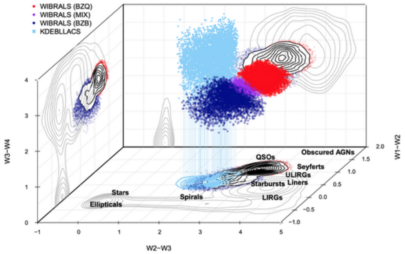
- 2013 high-synchrotron peaked blazars (HSPs), $\nu_p > 10^{15}$ Hz (selected with multi-wavelength analysis)
- 657 in *BZCAT*, similar *b* distribution

9 matches in ABC (7 BL Lacs, 1 RG and 1 No Type).

Catalog Comparison: WIBRaLS2

WISE Blazar-like Radio-Loud Sources (WIBRaLS2) catalog (D'Abrusco et al. 2019), candidate γ-ray blazars:

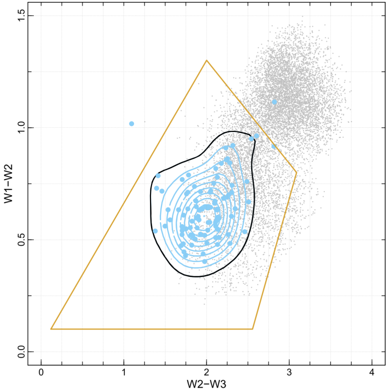
- Radio-loud sources from NVSS and SUMSS (22 μm/radio)
- 9541 sources with WISE colors compatible with γ-ray *BZCAT* blazars (detection in all 4 WISE bands, D'Abrusco et al. 2012)
- Classified depending on how compatible they are with **BZB**, **BZQ**, and **MIXED** regions



381 matches with ABC.

Catalog Comparison: KDEBLLACS

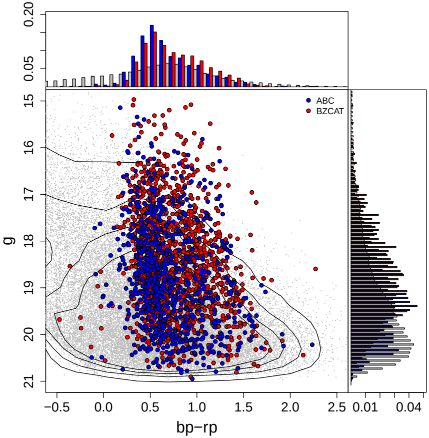
KDEBLLACS (D'Abrusco et al. 2019), candidate γ-ray **BL Lacs** selected using the similar criteria to WIBRaLS2:



- radio-loud (12 μm/radio)
- 5579 sources selected to be compatible with 90% KDE level of *BZCAT* γ-ray BL Lacs (detection in first 3 WISE bands)
- $|b| > 10°$

1 match with ABC (Blazar).

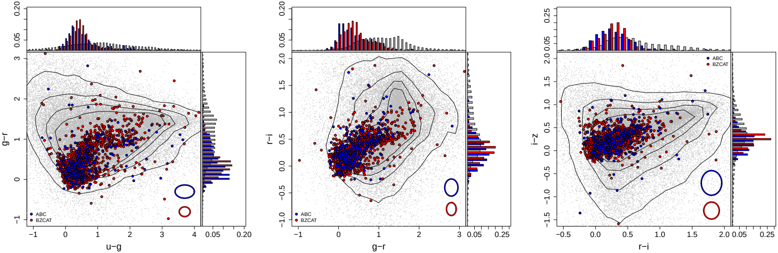
Gaia DR2 (Gaia Collaboration, 2018): **805** matches (null parallaxes and proper motions).



- ABC sources are less bright than BZCAT sources ($p = 3 \times 10^{-11}$) although spanning similar ranges of magnitudes
- ABC sources are redder than BZCAT sources ($p = 1 \times 10^{-5}$)

SDSS Cross-match

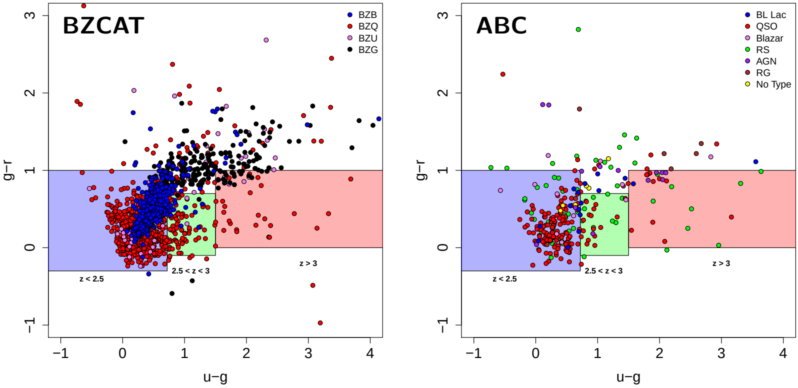
SDSS DR12 (Alam et al., 2015): **295** matches.



ABC sources are bluer than *BZCAT* sources, although with low significance (u-g: $p = 6 \times 10^{-3}$, g-r: $p = 6 \times 10^{-3}$, r-i: $p = 4 \times 10^{-3}$, i-z: $p = 9 \times 10^{-5}$).

SDSS Cross-match

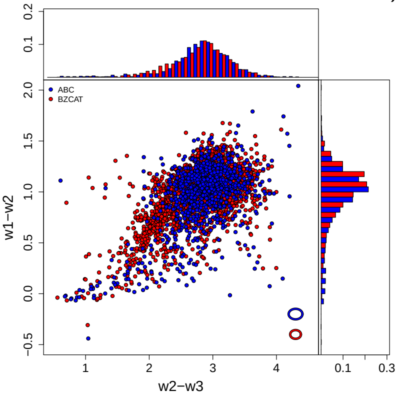
Butler & Bloom (2011): three regions to select low ($z < 2.5$), intermediate ($2.5 < z < 3$), and high ($z > 3$) redshift quasars.



Most most **BZQs/QSOs** and **BZBs/BL Lacs** fall into the region of low z quasars, BZGs outside.

WISE Cross-match

AllWISE (Cutri et al., 2013): **1311** matches (906 detected in all four WISE bands, 739 with $SNR > 3$).



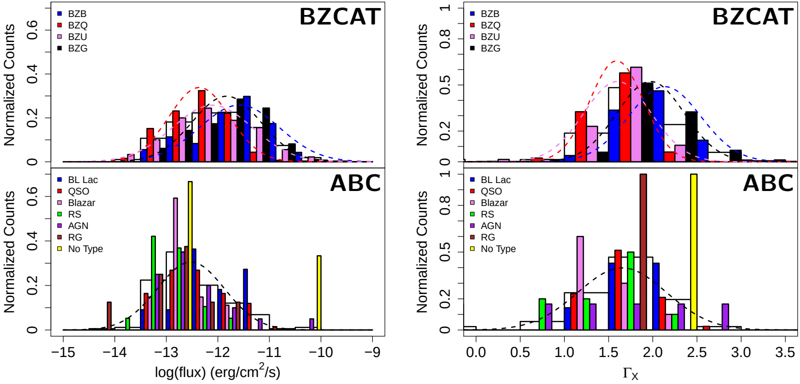
ABC sources have similar w1-w2 colors to *BZCAT* sources ($p = 4 \times 10^{-2}$), while they appear bluer in the w2-w3 ($p = 4 \times 10^{-4}$) and w3-w4 ($p = 9 \times 10^{-11}$) colors.

X-rays

Swift/XRT, *Chandra*/ACIS and *XMM-Newton*/EPIC observations:

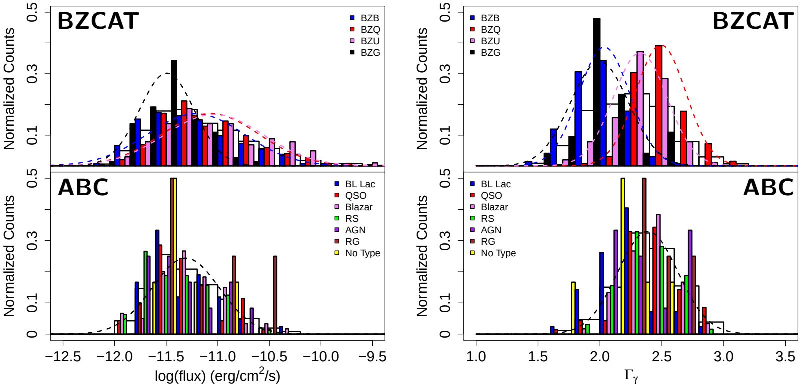
- X-ray counterparts for 173 ABC sources
- 140 spectra for 92 sources
- 109 power-law spectra → spectral slope Γ_X
- 31 "complex" spectra for 24 sources (1 Blazar, 11 **AGNs**, 9 **QSOs**, 1 RS, 1 RG, 1 No Type)
- Fluxes: from spectra or from count-rates assuming $\Gamma_X = 1.8$

X-rays: Fluxes and Slopes



- ABC sources are dimmer ($p = 3 \times 10^{-16}$) in X-rays compared to *BZCAT* sources
- ABC sources show similar Γ_X to *BZCAT* sources ($p = 0.1$) and differ significantly from **BZBs** ($p = 2 \times 10^{-13}$) and BZGs ($p = 6 \times 10^{-5}$)

Gamma-rays: Fluxes and Slopes

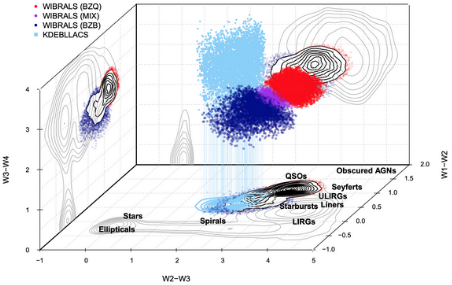


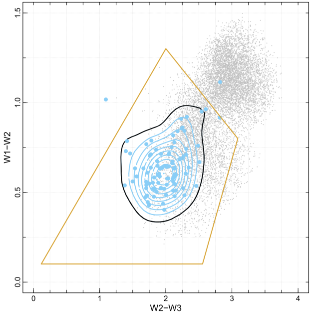
- ABC sources are dimmer ($p = 1 \times 10^{-5}$) in γ-rays compared to *BZCAT* sources
- ABC are softer than *BZCAT* sources ($p = 4 \times 10^{-13}$) and show Γ_γ similar to BZUs ($p = 4 \times 10^{-2}$)

WISE Selection of γ-ray Blazar Candidates

WIBRaLS2: WISE counterparts to γ-ray *BZCAT* blazars detected in all 4 bands, 3D locus.

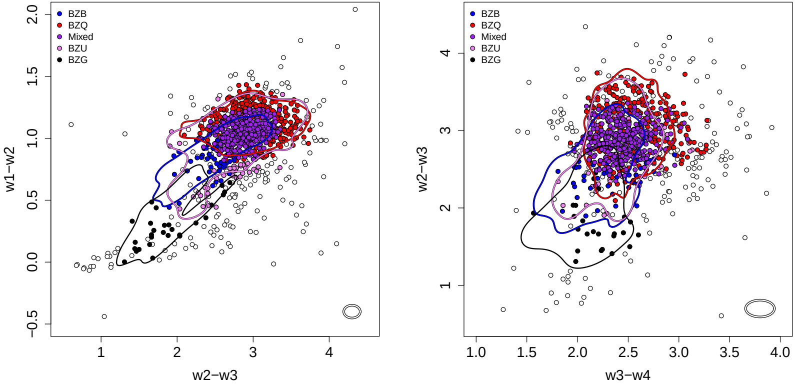
KDEBLLACS: WISE counterparts to γ-ray *BZCAT* **BZB** detected in first 3 bands, 2D KDE.





WISE Selection of γ-ray Blazar Candidates

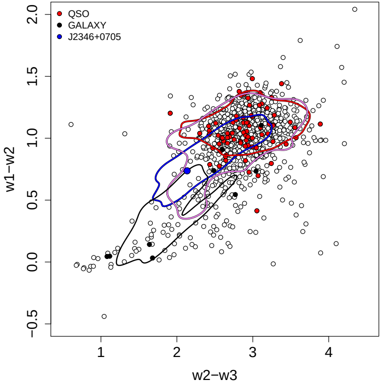
WISE counterparts to γ-ray *BZCAT* blazars detected in all 4 bands, 2D KDE contours in *both* color-color projection.



697 γ-ray blazar candidates.

WISE Selection of γ-ray Blazar Candidates

Optical spectra: 98 SDSS DR12 + 28 LAMOST DR5 (15 already in SDSS) $\rightarrow$ 111 optical spectra, 99 **QSO** + 12 GALAXY.

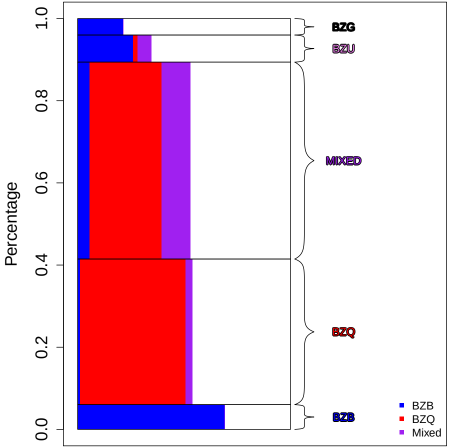


Most spectroscopic **QSO** are classified as **BZQ** and **MIXED**. Spectroscopic GALAXY are classified as **BZB**, BZU and BZG.

J2346+0705 (z=2.62): GALAXY + **BZB**: $EW < 1\,\AA$.

Comparison with WIBRaLS2

ABC γ-ray blazar candidates as WIBRaLS2 candidates:



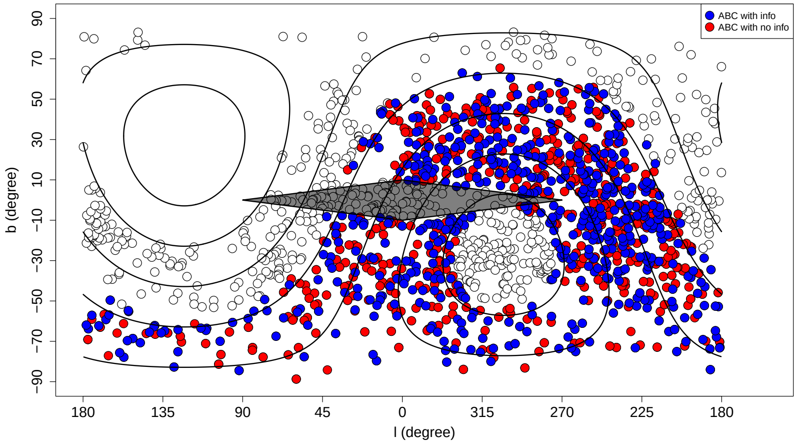
Not equivalent and complementary selections.

Conclusions

- ABC contains 1580 blazar candidates, filling the lack of $|b| < 10^\circ$ blazars in current catalogs
- Multi-wavelength informations *Gaia* DR2, SDSS DR12, LAMOST DR5, AllWISE, and 4FGL catalogs. X-ray data from *Swift*, *Chandra* and *XMM-Newton* archives
- ABC sources are brighter in the radio than *BZCAT* blazars by selection, while they appear dimmer in *Gaia*, X-rays and γ-rays
- ABC sources appear bluer than *BZCAT* blazars in SDSS and WISE
- ABC sources show similar X-ray spectral slopes to *BZCAT* blazars, while they appear softer in γ-rays
- We classified 697 ABC WISE-detected sources as candidate γ-ray blazar
- Future work: investigate multi-wavelength correlations, optical spectral observations

http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/641/A62

Future Prospective: LSST @ Vera C. Rubin Observatory



WFD survey area: 556/529 ABC sources with/without additional info. 125 ABC sources in WFD survey area with SDSS DR12 counterpart: 114 ($> 90\%$) with $24.16 > r > 16$ (planned WFD median single-visit 5σ point sources depth and nominal LSST saturation limit for 15 s exposures).