Elucidating the Nature of Fermi Unassociated Sources using newly discovered Swift Counterparts

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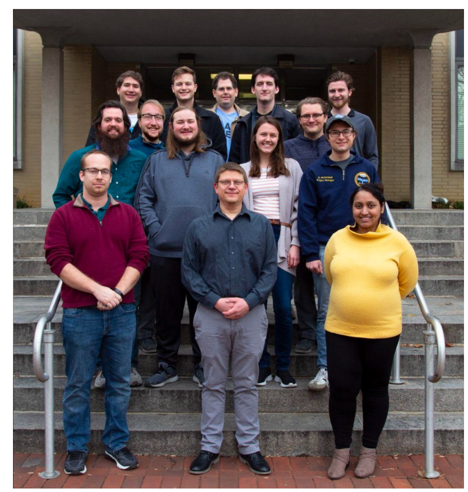
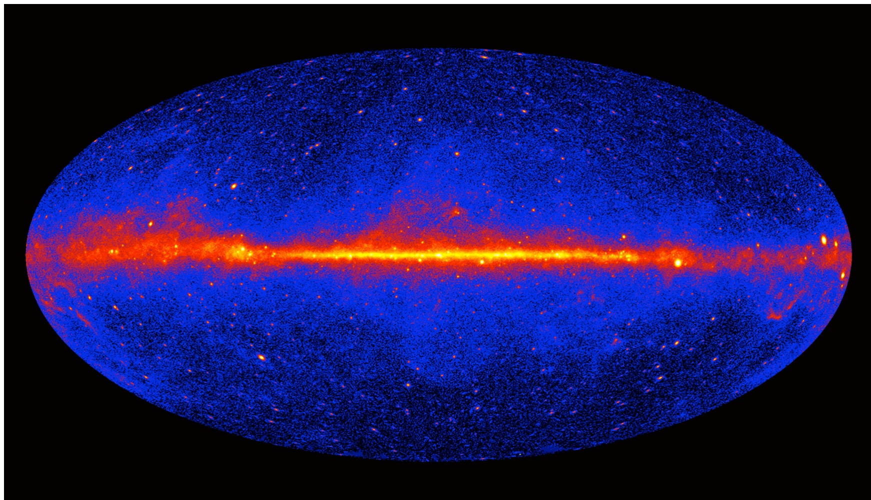
Some collaborators on this long-term project:
S. Kerby, K. Neumann, P. Ray, A. Kaur, B. Cenko, M. Stroh, D. Burrows, F. Hancock, R. Eskenasy, E. Ferrara, E. Grove, J. Kennea, + the Swift-XRT Team

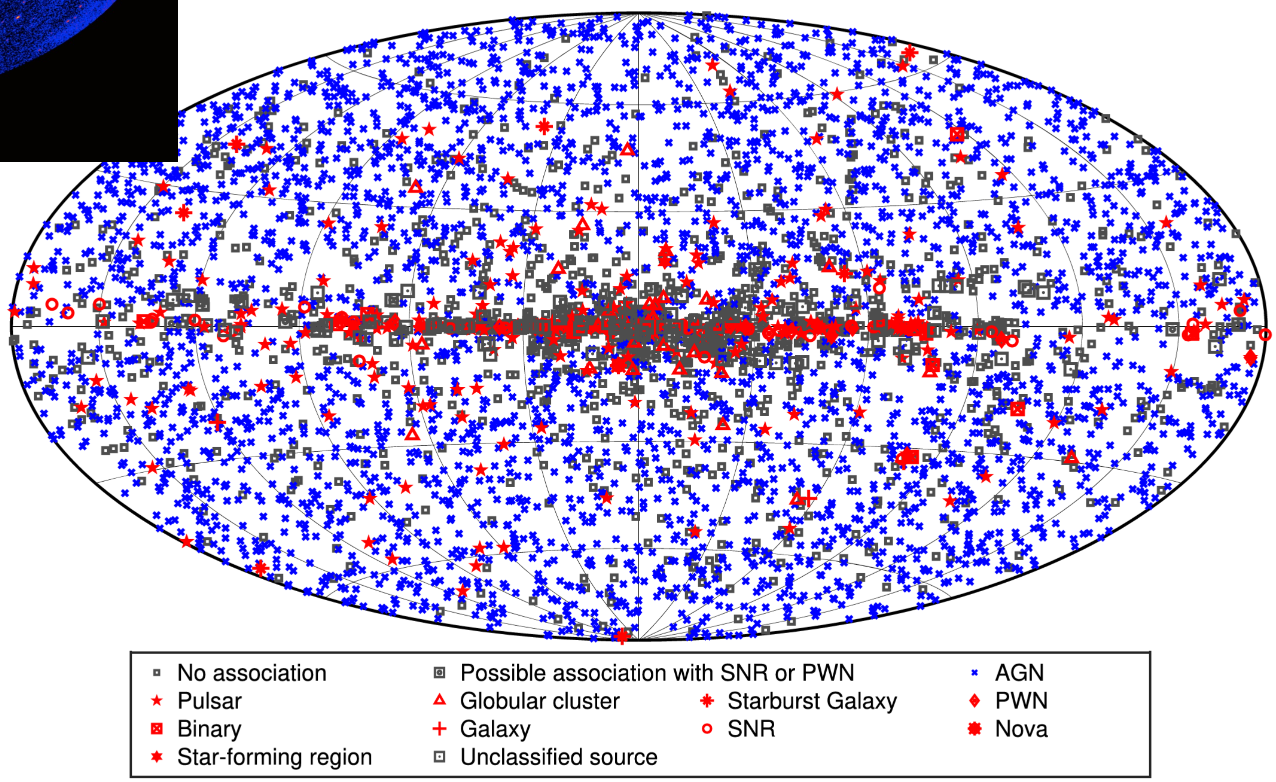


Outline

- **Unassociated Fermi-LAT Gamma Ray Source Follow-Up with Swift**
  - **Some History**
  - **The Observational Campaign**
  - **Some Results**
  - **Some Implications and Conclusions**

Skymap and Gamma-ray Sources (Fermi 4FGL)





The Fermi point source catalog is dominated by blazars and unassociated sources.

LAT Unassociated Source Catalog

- **The 4FGL-DR4 catalog has 7194 sources, more than half of which are associated with blazars and >200 of which are associated with pulsars.**

  <u>~2427 of these 4FGL-DR4 sources are cataloged as unassociated sources</u>

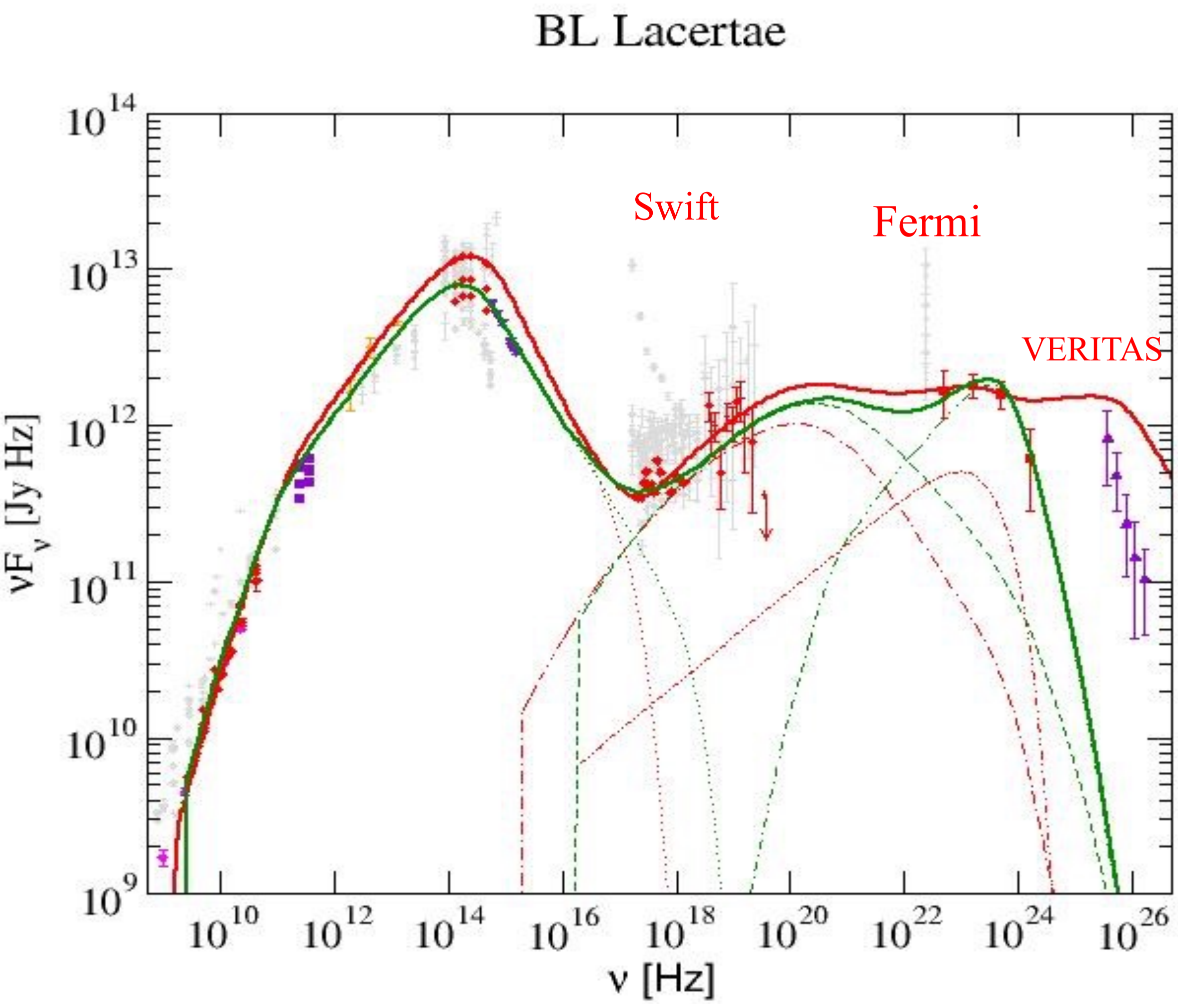
  (Of course, some of these have been associated since the release of the catalog)

- **Large fractions of the LAT catalogs are unassociated**, and the majority of these sources are **probably newly discovered blazars with massive black holes!**

These remaining unassociated Fermi sources are ripe for X-ray emission searches

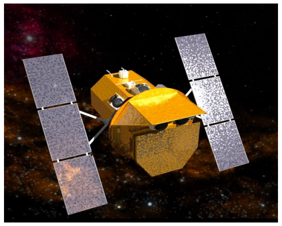
…and Swift is an ideal observatory for this search

Importance of Broadband Coverage



UV/optical & X-ray Spectrum:
Swift,...

15 keV - 150 keV
0.2 keV – 10 keV
650 nm - 170 nm



Gamma ray:
Fermi, AGILE,...

30 MeV – 300 GeV
all sky

VHE:
VERITAS, HESS, MAGIC, ...

100 GeV – 50 TeV

With just a few ksec per source, Swift can detect and localize likely counterparts, with position centroiding of typically <5"

Past Survey Results from 1FGL, 2FGL, and 3FGL

- >430 1FGL & 2FGL sources with ~4 ksec exposures
  - >30 of them have >10 ksec exposures
  - ~30% have a >3σ detection of a new X-ray source within the 95% Fermi confidence region

    ~45% of these candidates had no cataloged radio/optical source
  - ~20% have a >4σ detection of a new X-ray source within the 95% Fermi confidence region

    ~60% of these candidates had no cataloged radio/optical source

- >490 3FGL unassociated source positions have were observed with Swift
  - There are ~125 strong (>4σ) X-ray counterpart candidates in this sample

You can see a large fraction of the reduced results at:
http://www.swift.psu.edu/unassociated/
(was previously automatically updated in nearly real-time, but this has been broken and unfunded for the past ~year)

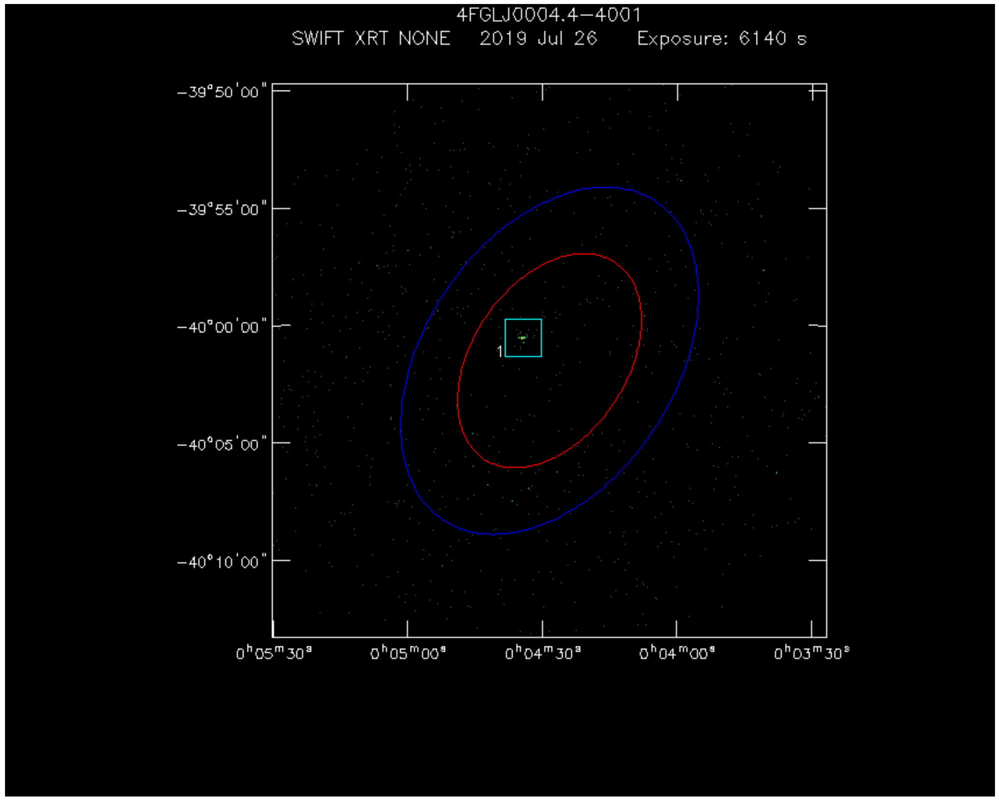
Recent Survey Results: 4FGL-DR4

- 1297 4FGL-DR4 sources have been observed with Swift-XRT and UVOT
    - 246 of these targets have at least 1 X-ray source detected within 4FGL 95% confidence region
        - 219 of these 4FGL 95% confidence regions have newly discovered distinct single X-ray sources
- Analysis is ongoing to characterize the newest of these X-ray sources, while we have performed a classification analysis on many of the likely counterparts that were found in the previous data release (DR3)

You can see a large fraction of the reduced results at:
http://www.swift.psu.edu/unassociated/
(was previously automatically updated in nearly real-time, but this has been broken and unfunded for the past ~year)

An example:

Grabbed image from 4FGL J0004.4-4001:

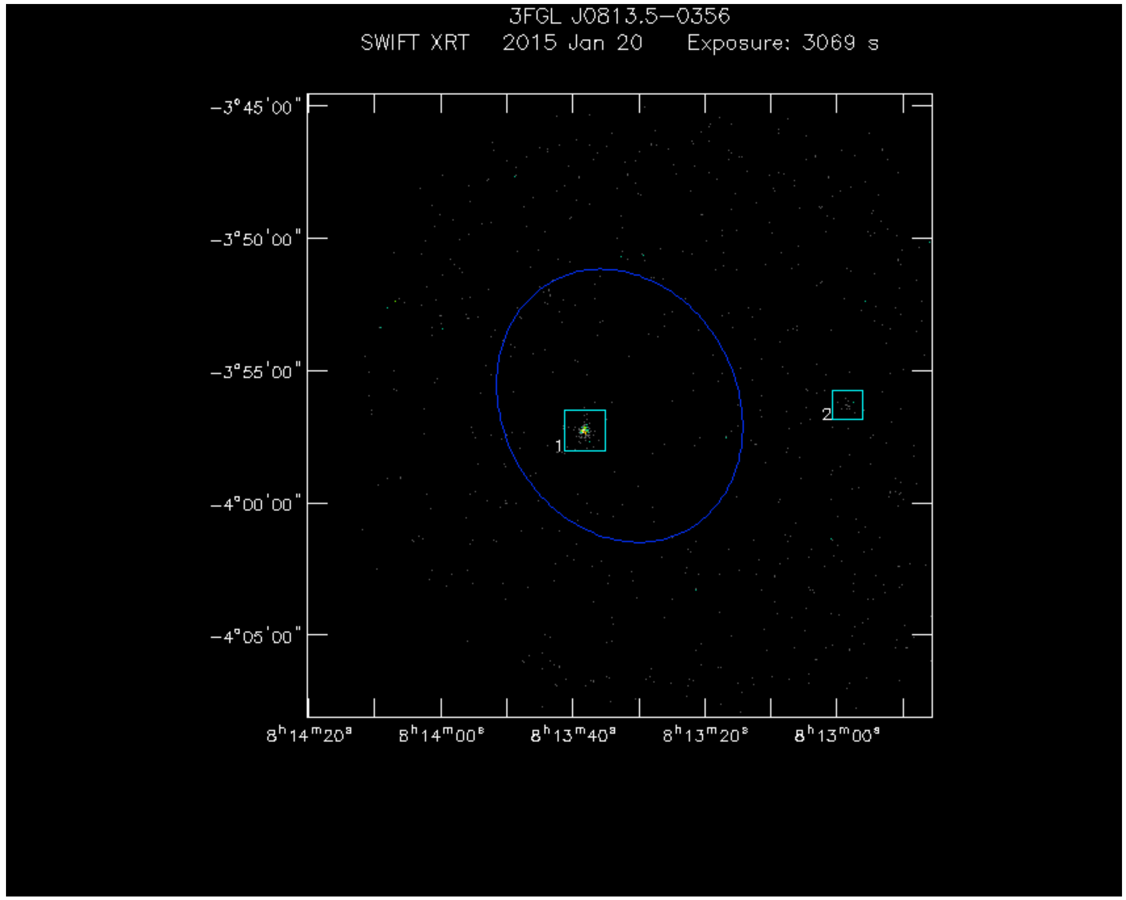


#	R.A. (J2000)	Dec. (J2000)	Pos. Error (")	Rate (cts/s)	Counts	SNR (Detect)	SNR (Sosta)
1	00 04 34.19	-40 00 31.98	4.49	$(1.3 \pm 0.2) \times 10^{-2}$	71	7.506	7.498

A newly discovered X-ray source (7.5σ) is the only known x-ray source within the 95% conf. region at a rate of ~0.013 c/s (0.2-10 keV flux is roughly $\sim 1\times10^{-13}$ erg cm^{-2} s^{-1}).

Another example:

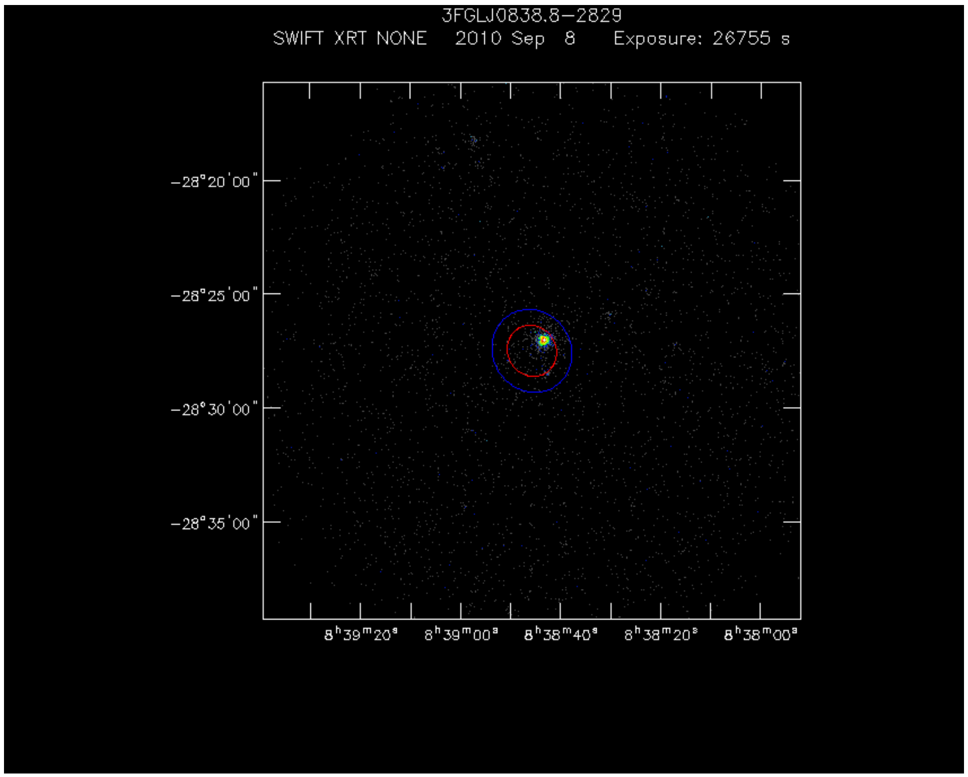
3FGL J0813.5-0356 with 3.1 ksec Swift observation:



Within Fermi 95% confidence region, there is a single newly discovered X-ray source (>13.8σ) at ~0.076 c/s (0.2-10 keV flux is roughly ~$7x10^{-13}$ erg cm^{-2} s^{-1}).

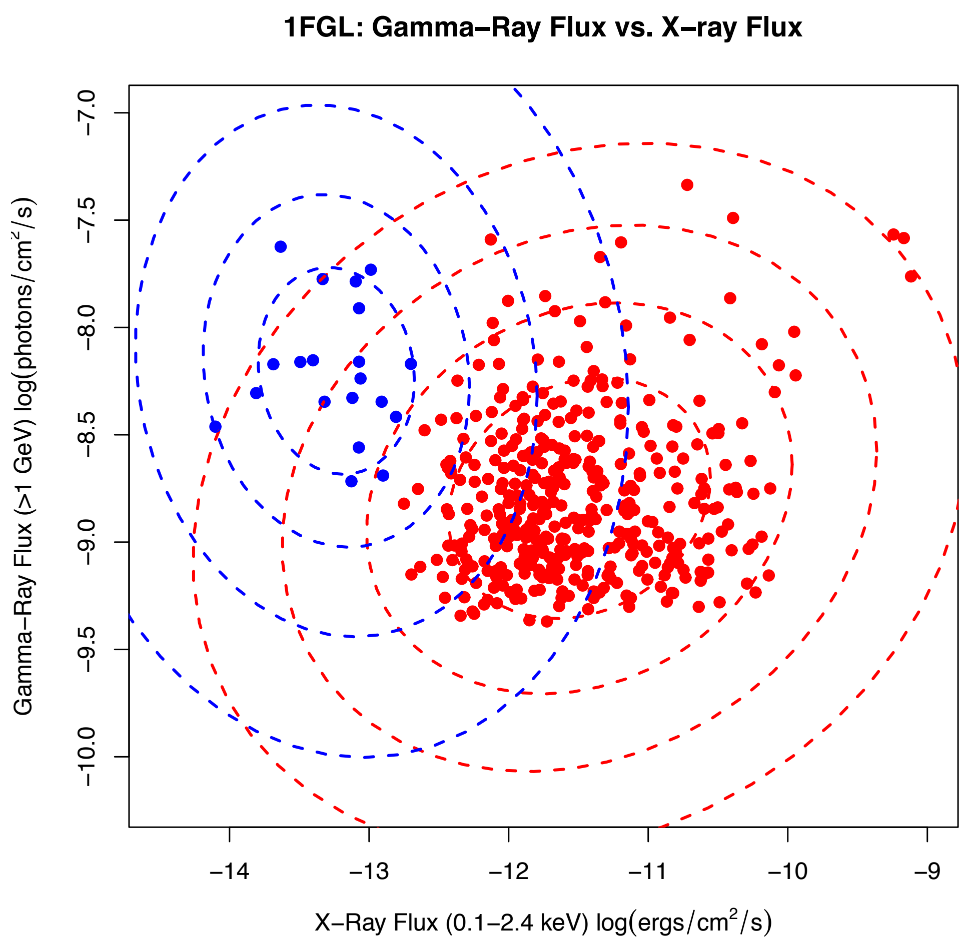
SIDE NOTE: 3FGL J0838.6-2829 → SwXF4 J083843.4-282701 → PSR J0838.7

(an example of an ambiguous source in our X-ray sample, later found by MeerKAT and identified as redback MSP with GBT)



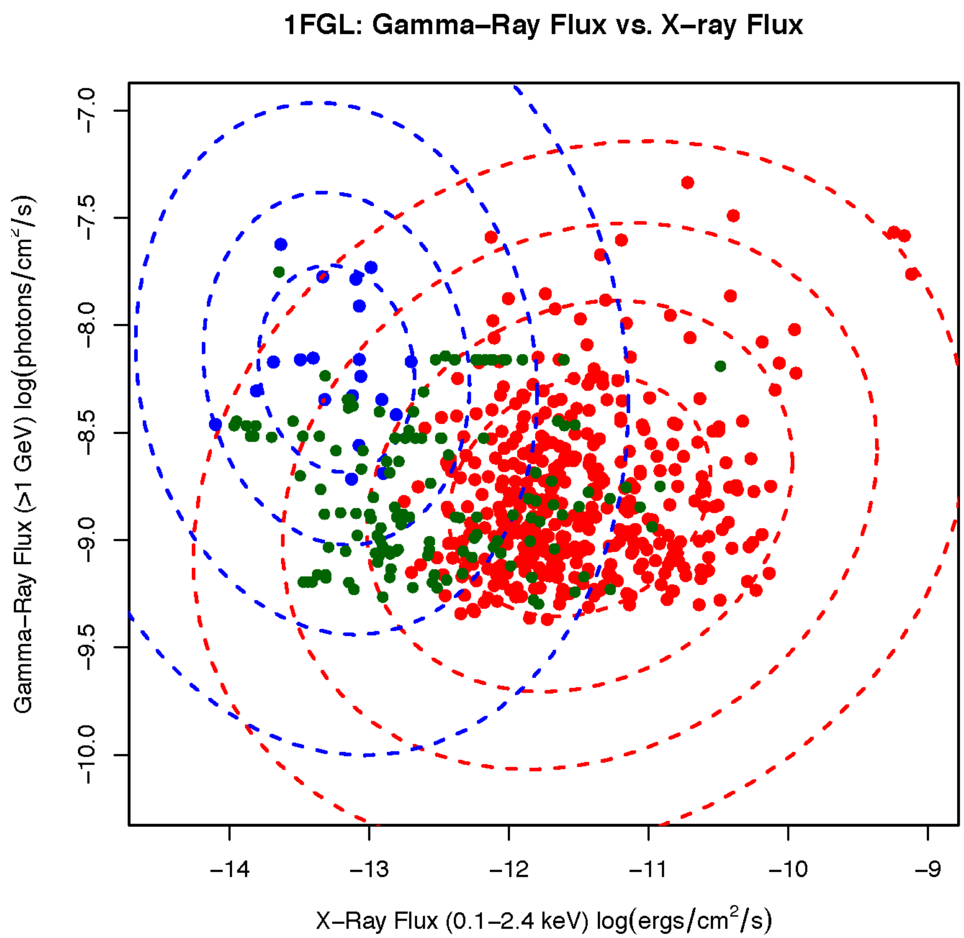
- Swift survey found this source during 3FGL survey
- Initially categorized as ambiguous since it was brighter in UVOT (and a bit brighter in X-ray) than the typical gamma-ray pulsar.
- We did suspect a possible pulsar and triggered some GBT follow-up. However, it was eclipsed during our observation and was then found later by MeerKAT

Discriminating with x-ray flux vs gamma-ray flux: Simplistic Source Classification



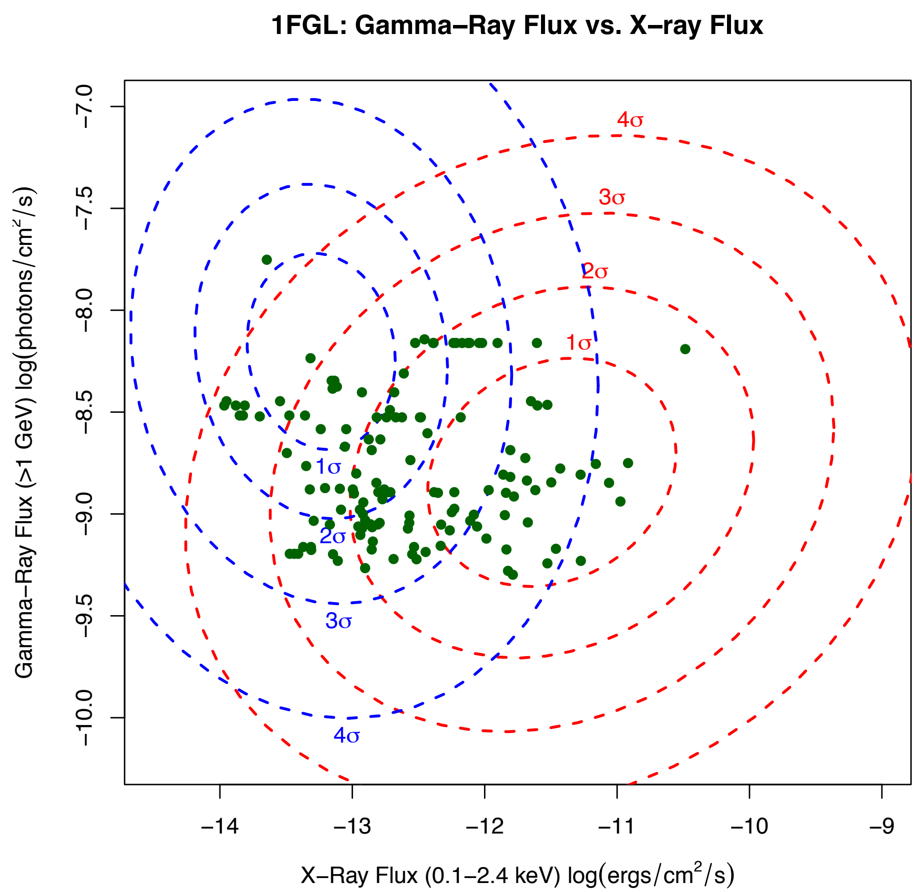
Red = known blazars, blue = known pulsars

Discriminating with x-ray flux vs gamma-ray flux: Simplistic Source Classification



Red = known blazars, blue = known pulsars
green = Fermi Unassociated possible X-ray counterpart

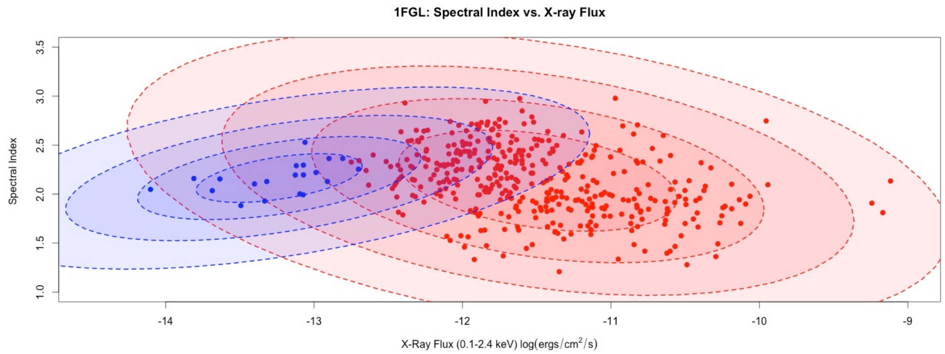
Discriminating with x-ray flux vs gamma-ray flux: Simplistic Version



Red = known blazars, blue = known pulsars

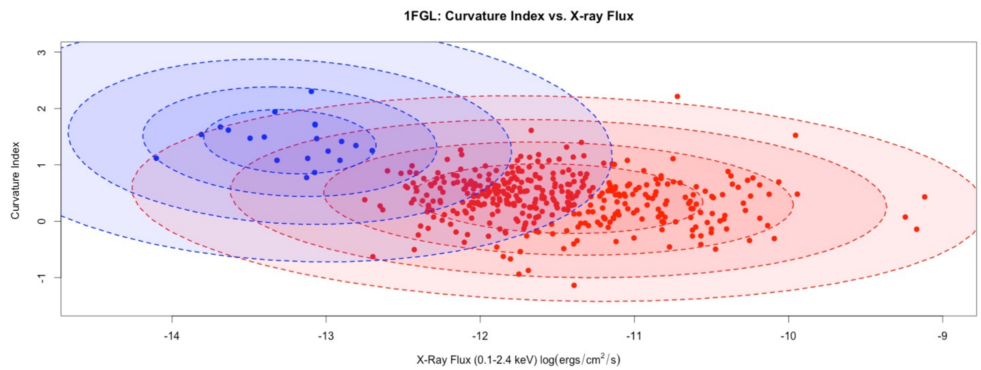
green = Fermi Unassociated possible X-ray counterpart

Discriminating with more variables:
Still simplistic (yet effective with PCA)

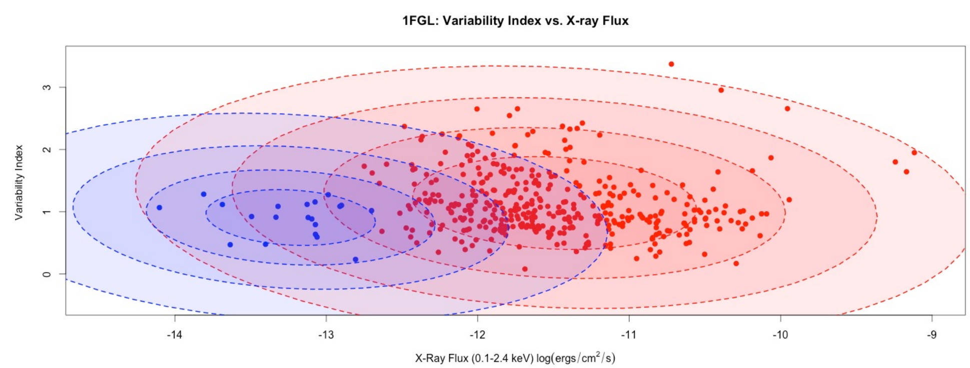


Spectral Index

Curvature



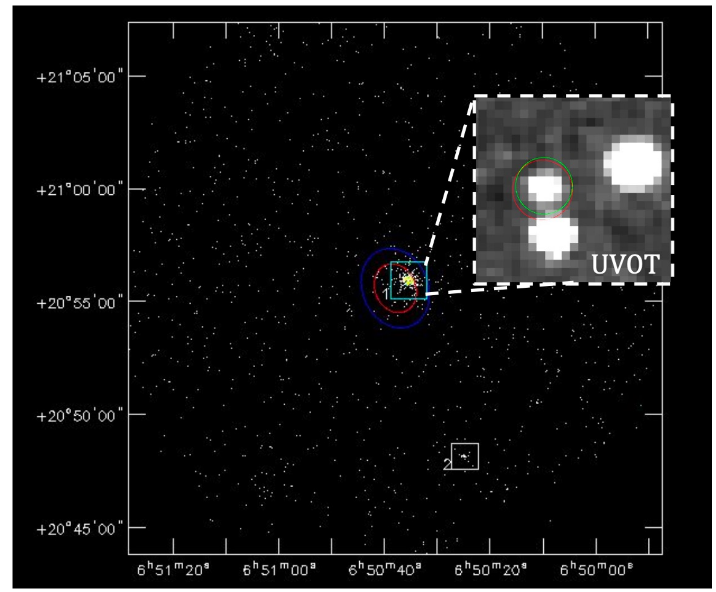
Variability Index



Red = known blazars, blue = known pulsars

Neural Network Classifications of Likely counterparts

- 174 of our single X-ray sources within 4FGL-DR3 also have UVOT counterparts
- For these sources, we trained a neural net with 4 Fermi-LAT variables ($Flux_{0.1\text{-}100GeV}$, Photon Index, Var Index, Sig Curvature), 2 Swift-XRT variables (F_x , Γ_x), and one from UVOT M_V
- Known Fermi blazars (>600) and pulsars (>60 + Smote) were used for training and validation



Led to >99% likelihood of blazar classification for 132 new sources and >99% likelihood of pulsar for 14 sources, with 28 remaining ambiguous; see Kerby et al. 2021

Further Studies of a sample of new blazars

- 106 of the new X-ray sources that are likely blazar counterparts to 4FGL-DR3 sources had WISE data and NVSS radio data
- We used this to perform spectral fitting with agnpy and with a peak fitter to estimate synchrotron peak of SED, as well as comparison of other parameters for this lower-luminosity sample of gamma-ray blazars
- Caveat: different timescales for measurement

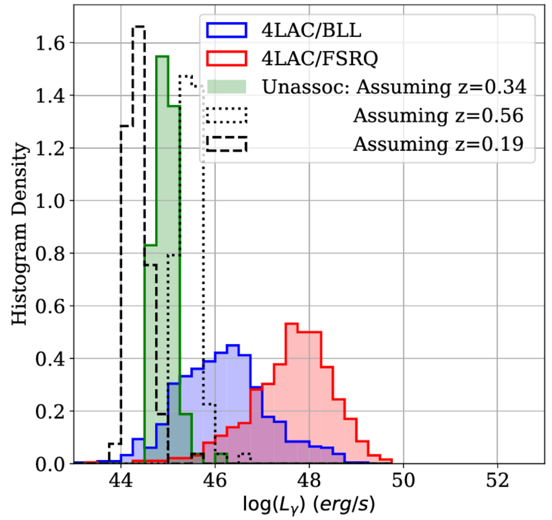
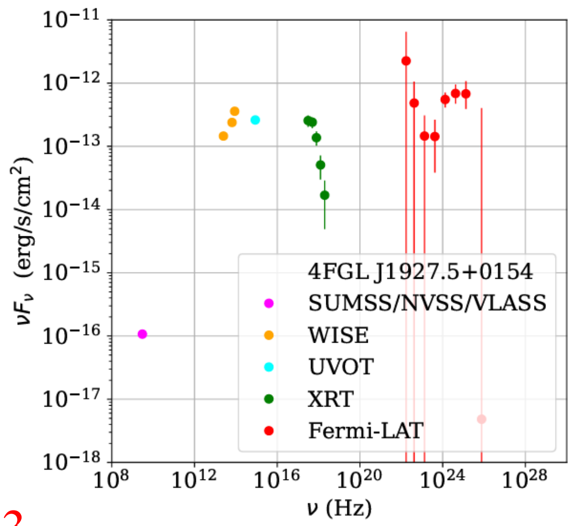


Figure 1. Comparison of the gamma-ray luminosities of 4LAC BL Lacs (blue) and FSRQs (red) with estimated luminosities for the new blazars (green), assuming the same median redshift as the BL Lac sample, $z = 0.34$.



Kerby & Falcone 2023, ApJ, 951, 133

The Astrophysical Journal, 951:133 (17pp), 2023 July 10 https://doi.org/10.3847/1538-4357/acd4c0

Testing the Blazar Sequence with Spectra of Recently Discovered Dim Blazars from the Fermi Unassociated Catalog

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Received 2023 March 14; revised 2023 May 2; accepted 2023 May 2; published 2023 July 10

Abstract

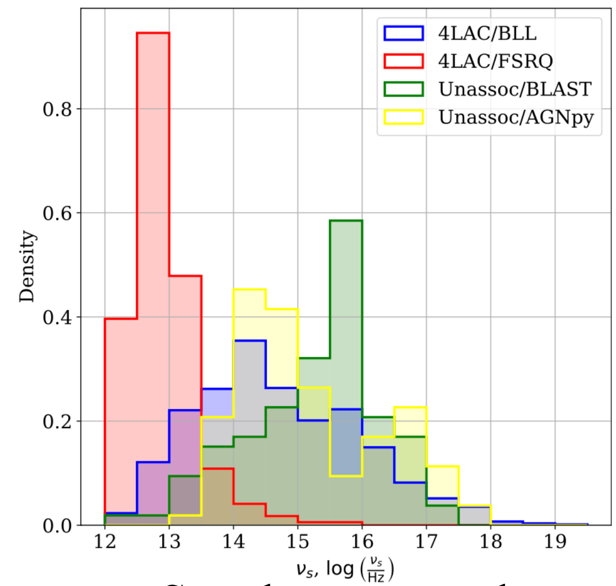
Recent works have developed samples of blazars from among the Fermi Large Area Telescope unassociated sources via machine-learning comparisons with known blazar samples. Continued analysis of these new blazars tests the predictions of the blazar sequence and enables more flux-complete samples of blazars as a population. Using Fermi, Swift, Wide-field Infrared Survey Explorer, and archival radio data, we construct broadband spectral energy distributions for 106 recently identified blazars. Drawn from the unassociated 4FGL source sample, this new sample has a lower median flux than the overall sample of gamma-ray blazars. By measuring the synchrotron peak frequency, we compare our sample of new blazars with known blazars from the 4LAC catalog. We find that the bulk of the new blazars are similar to high-synchrotron-peaked BL Lac objects, with a higher median synchrotron peak; the sample has a median $\log(\nu_{syn}/\mathrm{Hz}) = 15.5$ via BLaST peak estimation, compared to $\log(\nu_{syn}/\mathrm{Hz}) = 14.2$ for the 4LAC BL Lacs. Finally, we conduct synchrotron self-Compton leptonic modeling, comparing fitted physical and phenomenological properties to brighter blazars. We find that the new blazars have smaller characteristic Lorentz factors γ_{boost} and fitted magnetic fields B, in agreement with blazar sequence predictions. The new blazars have slightly higher Compton dominance ratios than expected, which may point to alternative emission models for these dim blazars. Our results extend the predictions of the blazar sequence to a sample of dimmer blazars, confirming the broad predictions of that theory.

Unified Astronomy Thesaurus concepts: Blazars (164); Catalogs (205)
Supporting material: data behind figure, machine-readable tables

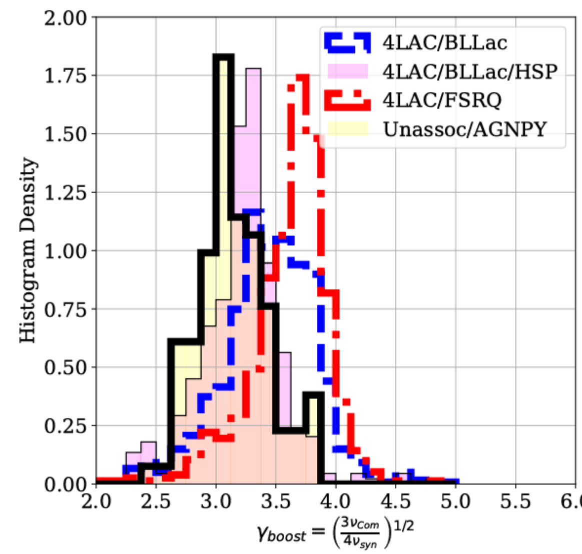
1. Introduction

In the unified scheme of active galactic nuclei (AGNs; Blandford & Rees 1978; Urry & Padovani 1995), blazars are radio-loud AGNs with a jet viewed almost directly on-axis.

flaring states; at different times, these changes make them appear alternatively as BL Lacs or FSRQs, blurring the lines between the two categories (Tavecchio et al. 1998; Bianchin et al. 2009; Abdo et al. 2010b). In general, FSRQs tend to dominate at higher redshifts and have lower synchrotron peak



Synchrotron peaks



Characteristic Doppler Boost

We find that these dimmer blazars appear to extend the blazar sequence, that they have synchrotron peaks consistent with BLLacs, possibly with a slightly higher peak than the mean of that of 4LAC BLLs. They also seem to have smaller characteristic Doppler boost factors and magnetic fields, within the context of a simple SSC model

Conclusions

- Swift provides an ideal multiwavelength observatory for follow-up of enigmatic unassociated gamma-ray sources, and has detected hundreds of new x-ray and UV/optical counterparts:
  - ~30% of the 1FGL/2FGL/3FGL fields have a firm detection of a possible X-ray counterpart (~half of these are new sources), and ~20% of the 4FGL-DR4 fields that we've surveyed (>1200) have an X-ray counterpart
  - Most of these are likely to be blazars

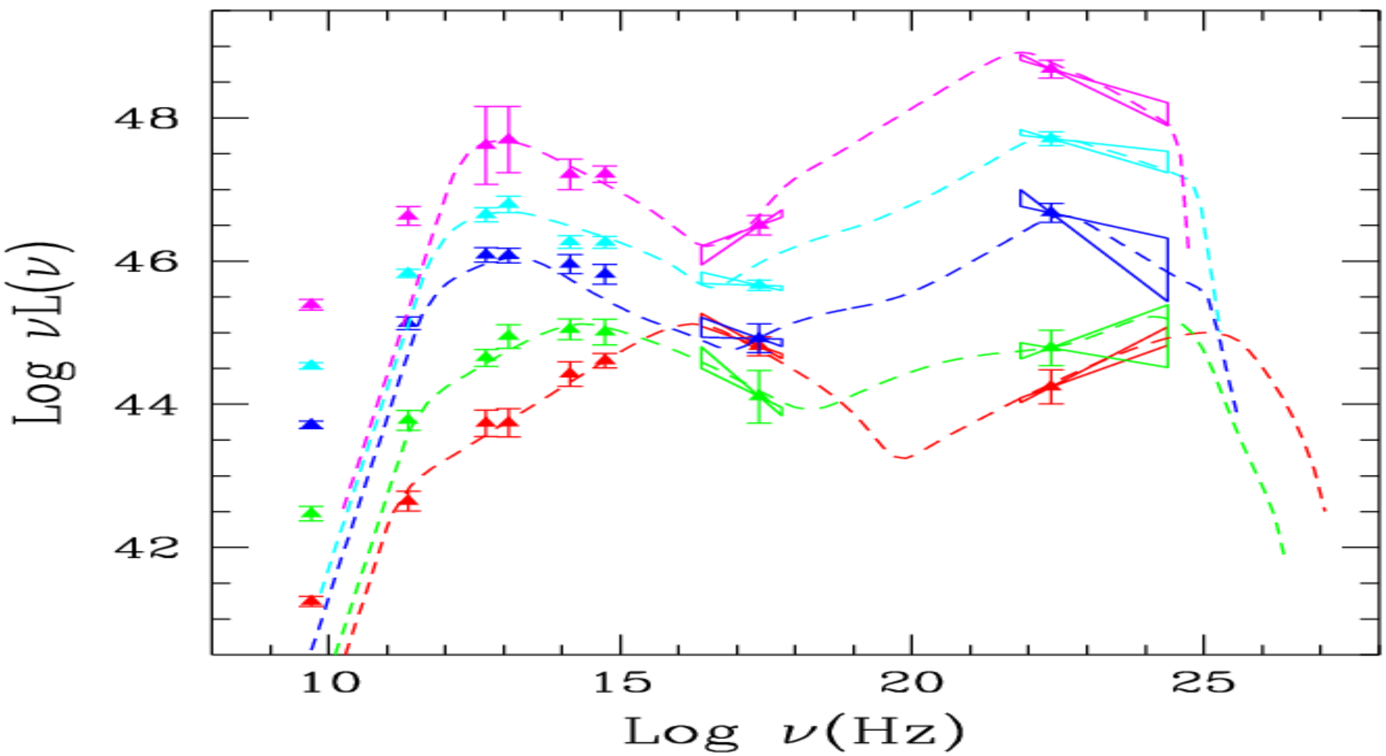
- Classification: From 4FGL-DR3, We have classified 132 likely counterparts as >99% likely to be new blazars and 14 as>99% likely to be pulsars
  - We are now moving on to 4FGL-DR4
- Blazar Characteristics and Blazar Sequence: this dimmer sample of Fermi blazars seems to extend the blazar sequence, with lower luminosities leading to higher synchrotron peaks, challenging attempts to explain the sequence as arising due to selection effects (for the 106 new blazars studied in a SSC context with limited temporal coverage)
- Swift results (including images and new source positions) are posted to for the older observations: http://www.swift.psu.edu/unassociated/

(we're trying to get this system up and running again for recent observations)

Extra Slides

Blazar Categories

- FSRQ Vs. BL Lac
  - High power w/broad lines Vs. low power with no broad lines
- Low Peaked Vs. High Peaked
  - Variable peak energy for synchrotron emission, along with other parts of SED



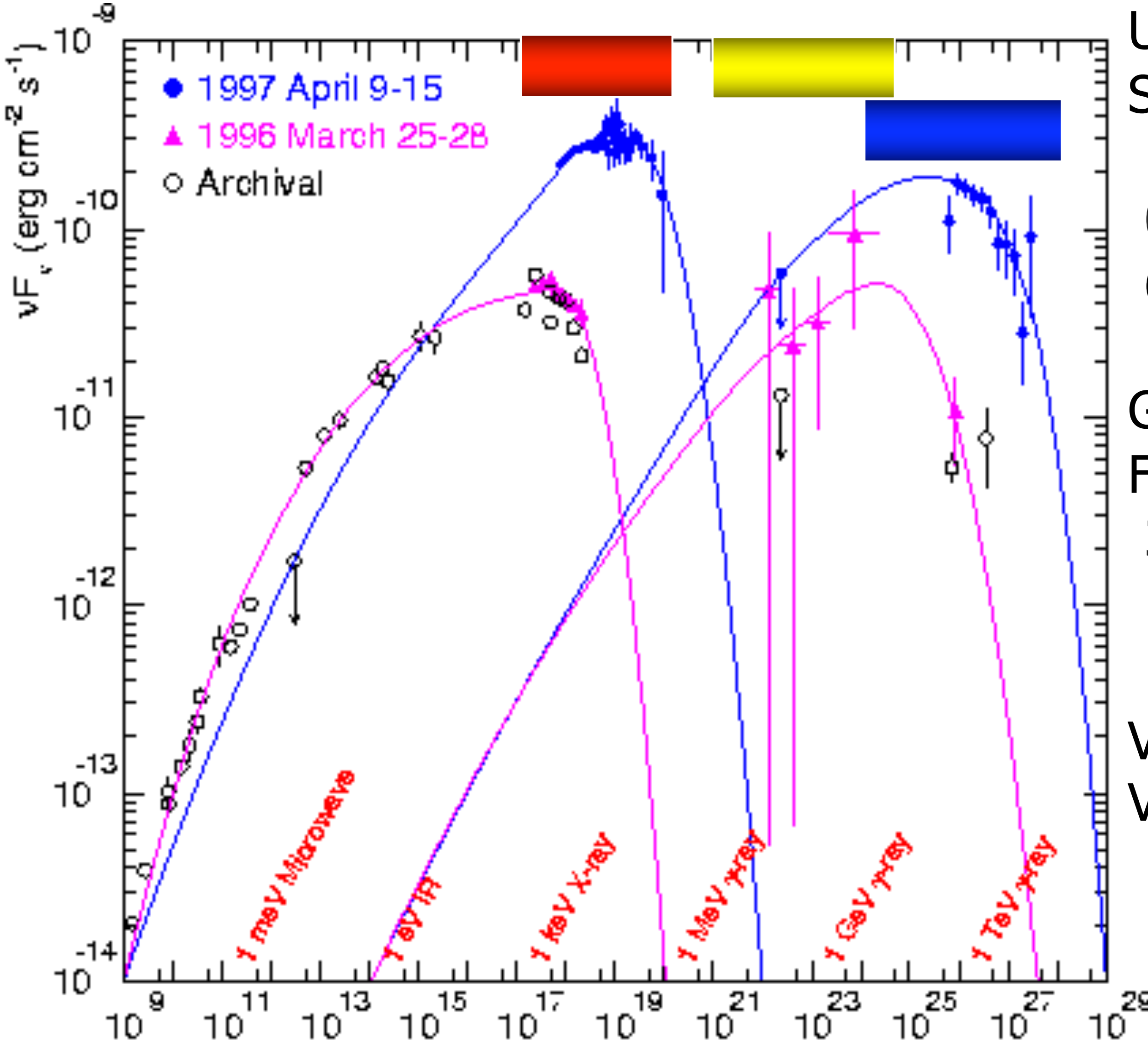
Fossati et al. 1998, Ghisselini et al. 1998, Abdo et al. 2010

- Note: FR I & FR 2 are off-axis jet cousins of BL Lac & FSRQ blazars

Unidentified Gamma-ray Sources: A VERY brief History

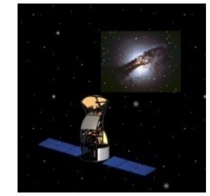
- First Unidentified γ-ray source was γ 195+5, found by SAS-2 in 1972 (Fichtel et al. 1975). Radio pulsar is theorized (Thompson et al. 1977), but VLA can't find it.
- In 1975, COS-B was launched and it detected 21 unidentified sources (+ 4 identified) in a 3 year catalog, one of which corresponded to γ 195+5 (Swanenburg et al. 1981).
- Einstein satellite finds X-ray counterpart (Bignami et al. 1983), and ROSAT finds X-ray pulsations (Halpern & Holt 1992), from γ 195+5. ***It is now known as Geminga***, an incredibly interesting radio-quiet pulsar still widely studied today.
- EGRET (20 MeV – 30 GeV) on CGRO (1991-2000) uses leap in sensitivity to detect 271 point sources in the 3EG (Hartman et al. 1999), of which more than half were unidentified (74 UnIDs at $|b| < 10^o$, 96 UnIDs at $|b| > 10^o$). More recent analysis, using revised interstellar emission models, has resulted in only 87 unidentified EGRET sources (Casandjian & Greiner 2008).
- Through m-wave follow-up, ***particularly though X-rays***, some counterparts have been found, but many unidentified γ-ray sources remain unidentified
- Fermi ….

Importance of Broadband Coverage



Mrk501 SED taken from Catanese & Weekes 1999

UV/optical & X-ray Spectrum:
Swift,...



15 keV - 150 keV
0.2 keV – 10 keV
650 nm - 170 nm

Gamma ray:
Fermi, AGILE,...

30 MeV – 300 GeV
all sky

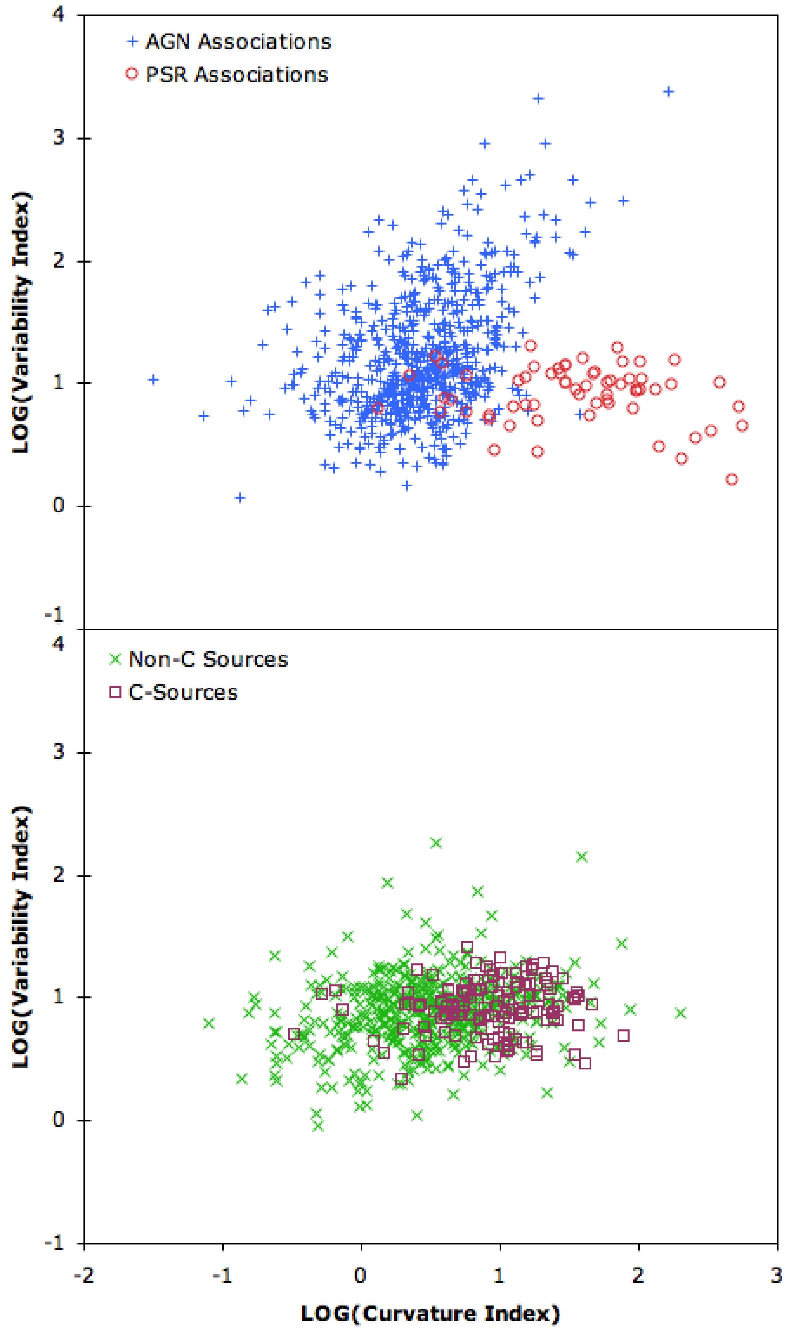
VHE:
VERITAS, HESS, MAGIC, ...
100 GeV – 50 TeV

Initial Survey Sample Selection & Strategy

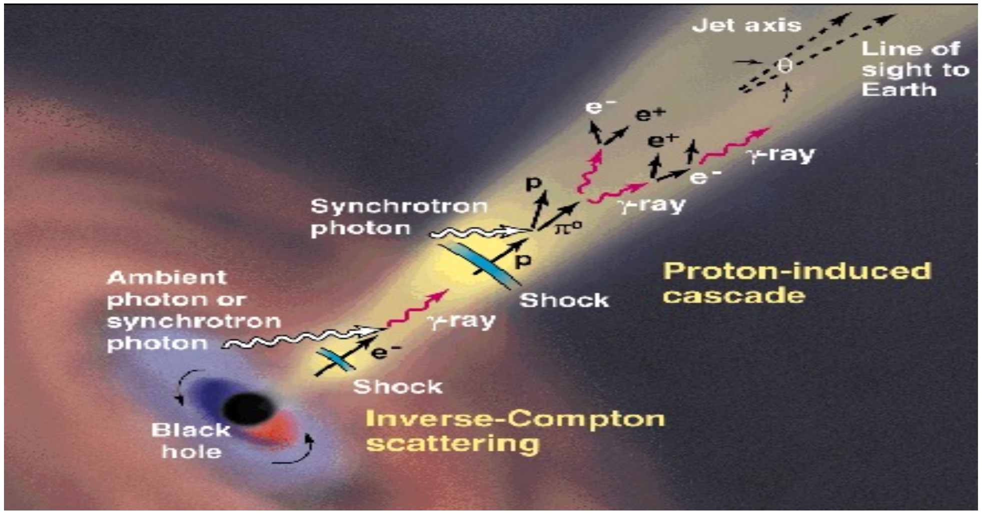
Many of the Unassociated sources fall within the region of parameter space that is overlapping with both Fermi AGN and Fermi pulsars.

This makes initial screening difficult and necessitates large counterpart search programs

See: Ackermann et al. 2011; arXiV 1108.1202



Why Monitor Blazars (and other jet sources) with X-rays?

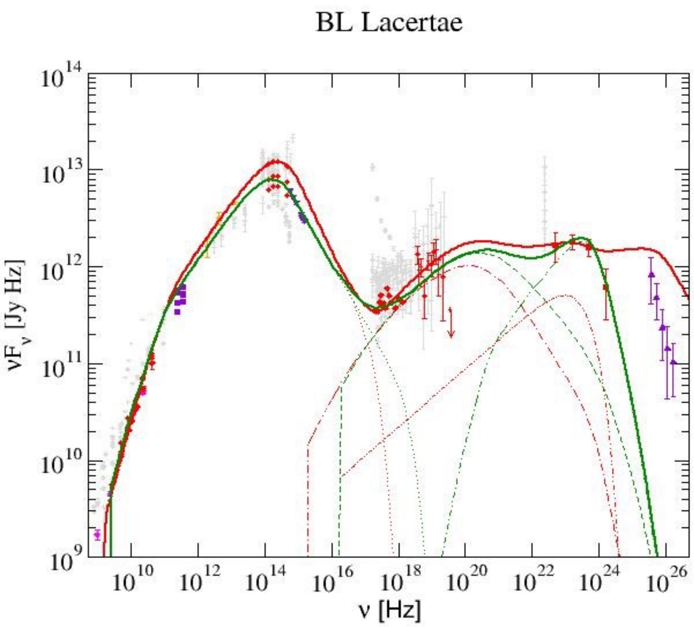


- ***Jets typically produce variable synchrotron emission in X-ray band. This is a required input for modeling the higher energy emission.***

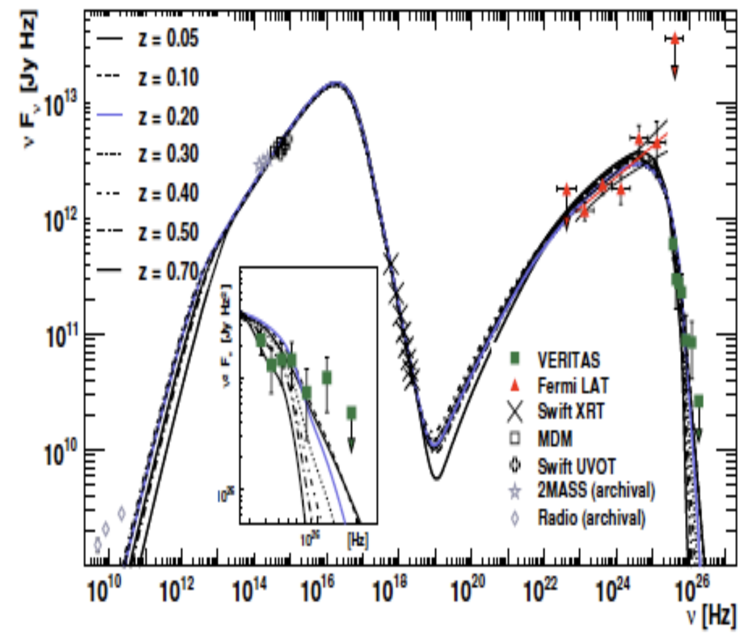
Figure from J.Buckley 1998

- Need to understand acceleration mechanisms capable of producing large luminosity at very high energies and below:
  - SSC? (Maraschi et al. 92, Tavecchio et al 98, …)
  - External IC? (Dermer & Schlickeiser 2002, …)
  - Proton cascades? (Mannheim 93, …)
  - Proton synchrotron? (Muecke & Protheroe 2000, Aharonian 2000, …)
- Constrain blazar environment characteristics: Doppler factor, seed populations, photon vs. magnetic energy density, accel. and cooling timescales, …
- Need to understand blazar development and evolution
- Potential sources of cosmic ray acceleration
- Constrain models of extragalactic infrared background
- Potentially enable studies of Lorentz Invariance and quantum Gravity

Two Blazar Campaigns with critical x-ray and multiwavelength data



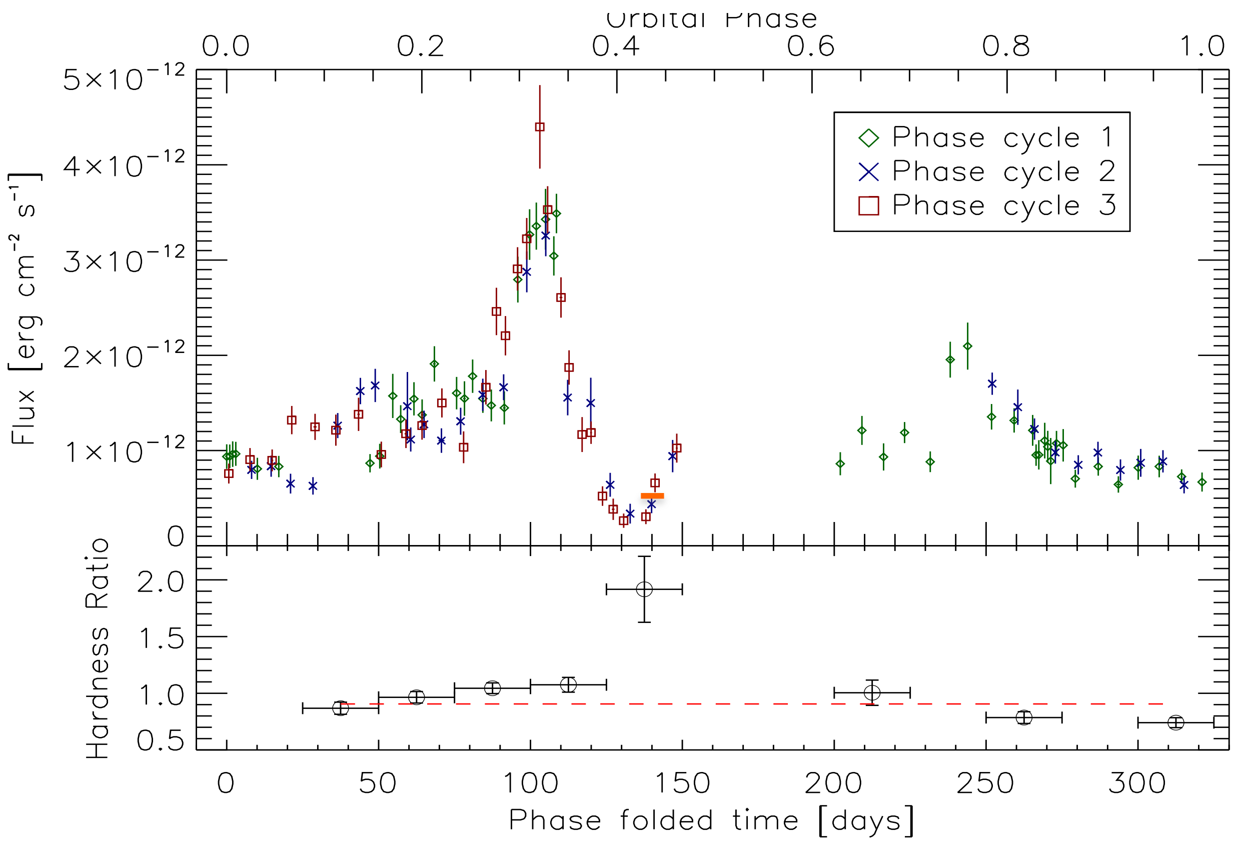
The SED of BL Lacertae made from quasi-simultaneous data from Swift-XRT, Swift-UVOT, Fermi-LAT, VERITAS, and others. The leptonic model (solid green curve) does not provide a good fit, while a hadronic model (solid red curve) provides some improvement, but overproduces the TeV emission (Boettcher et al. 2013).



SED of PKS1424+240 with constraints on redshift and emission mechanisms from data using Swift, Fermi, VERITAS, and others (Acciari et al. 2010). Simultaneous data from high redshift blazars, during higher emission states, are needed to strengthen IR background estimates. Redshift now known to be >0.6 (Furniss et al. 2013).

Other motivations for X-ray follow-up of Unassociated Sources
An example: HESS J0632+057 & Periodicity

HESS gamma-ray unidentified source (Aharonian et al. 2007) for which Swift observations were used to discover a new and enigmatic gamma-ray binary (Falcone et al. 2010, Bongiorno et al. 2011)



The light curve folded over the 321 day periodicity (**Bongiorno et al. 2011**).

(Different color data points are offset by 321 days, i.e. from different cycles)

Note the hardening of the spectrum during "the dip."

Is this an occultation/absorption effect or is it a change in acceleration site parameters?

Initial Survey Sample Selection & Strategy

From the 1FGL unassociated sources, we chose to start a survey of the sources that satisfied:

- not listed as a confused source
- not on Galactic ridge where detections and positions were questionable
- no existing XMM, Chandra, Swift observations with sufficient depth
- error ellipse with semi-major axis < 10'

This resulted in a sample with 261 Fermi unassociated sources (including ~30 that were selected as good pulsar candidates) for follow-up with Swift

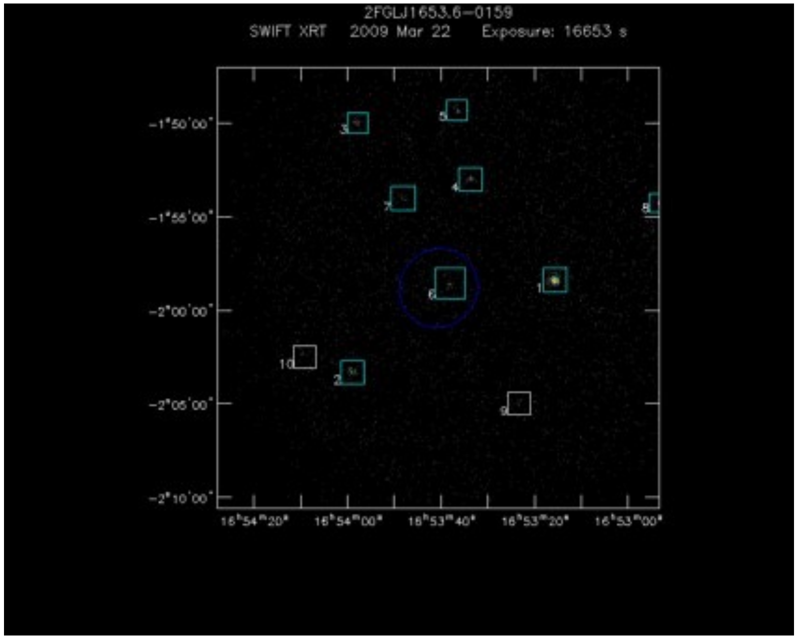
These were targeted with ~4 ksec observations (sensitive to ~1×10^{-13} erg cm^{-2} s^{-1})

For the 2FGL and 3FGL sources, we opened up our strategy and began searching for X-ray counterparts to all sources with Fermi error ellipses that fit within XRT field of view (i.e. we started looking on the plane)

Plausible Pulsar Counterparts

(a parameterization/discrimination study led by P. Saz Parkinson)

- Saz Parkinson et al 2016 find ~120 pulsar candidates from bright (> 10 sigma) LAT 3FGL sources
- *Swift* X-ray sources within LAT error circles of many of these pulsar candidates
- X-ray fluxes of pulsars are 10-10000 times lower than gamma-ray fluxes (Marelli et al. 2011)
- X-ray flux of counterparts varies by type of PSR (e.g. MSPs relatively brighter than young pulsars).



One example: 2FGL J1653.6- 0159, plausible MSP candidate (e.g. Romani et al. 2014)!
***Swift*-identified counterpart**