Fermi Unassociated Sources: Using Swift to Search for X-ray Counterparts

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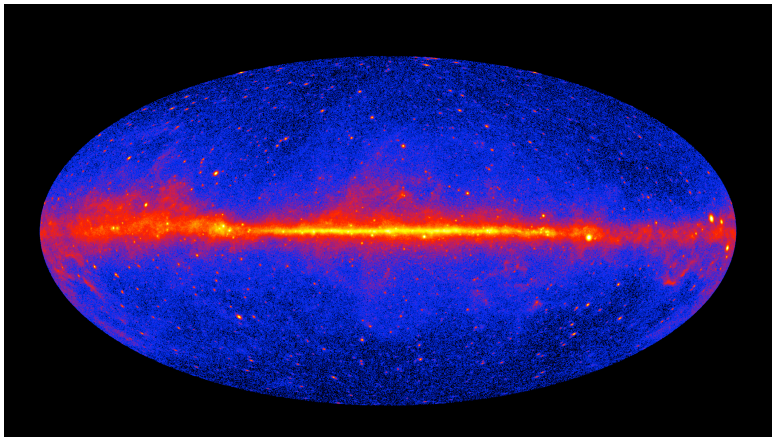
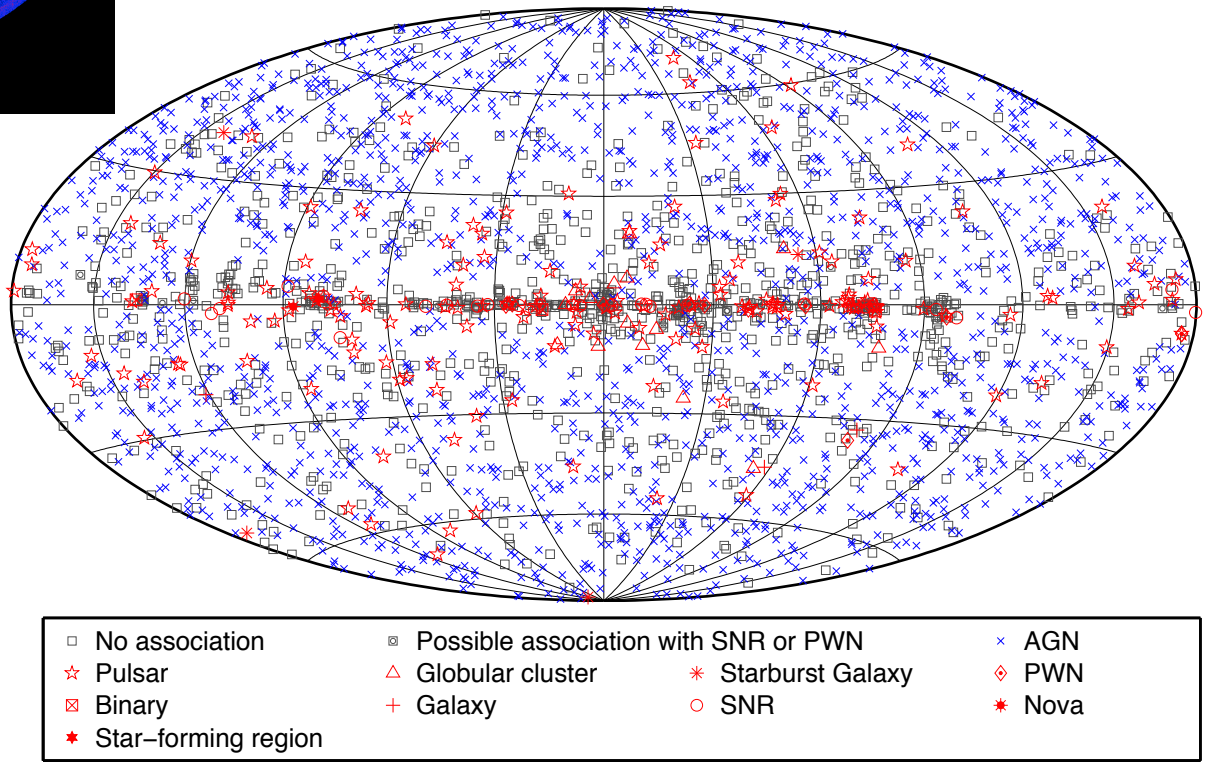
Skymap and Gamma-ray Sources (Fermi 3FGL)





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

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 with X-rays***, some counterparts have been found, but many unidentified γ-ray sources remain unidentified
- Fermi ….

LAT Unassociated Source Catalogs

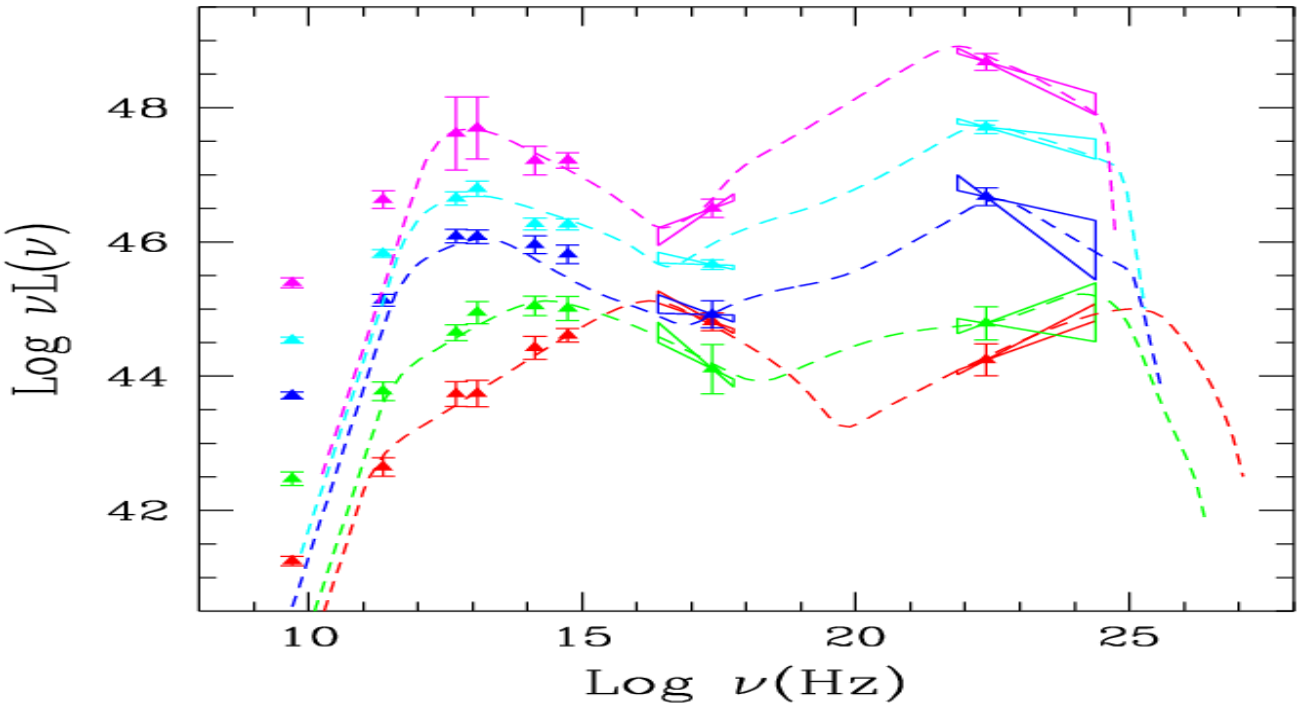
- Of the 1451 1FGL sources, 691 are cataloged as being associated with blazars, other AGN & QSOs, radio galaxies, and starburst galaxies, 56 are identified as pulsars, 41 are SNRs without a detected pulsar, 3 are HMXBs, and 1 is the Galactic Center (Abdo et al. 2010a).
- Several of the initial (0FGL) unassociated sources were associated with newly discover millisecond pulsars (see works of Ransom, Ray, Saz Parkinson, etc…)
- The 2FGL catalog has a total of 1873 sources, with 577 of these listed as unassociated (207 of these overlap with 1FGL unassociated sources)
- The 3FGL catalog has 3033 sources, with ~1100 associated with known blazars (another 538 candidate blazar associations) and 1010 cataloged as unassociated.
- Large fractions of the LAT catalogs are unassociated!
  - However, since the time of the catalogs, some of these sources have been found to be millisecond pulsars and some have found blazar associations through multiwavelength follow-up, particularly radio.

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

…and Swift is an ideal observatory for this search

Blazar Categories

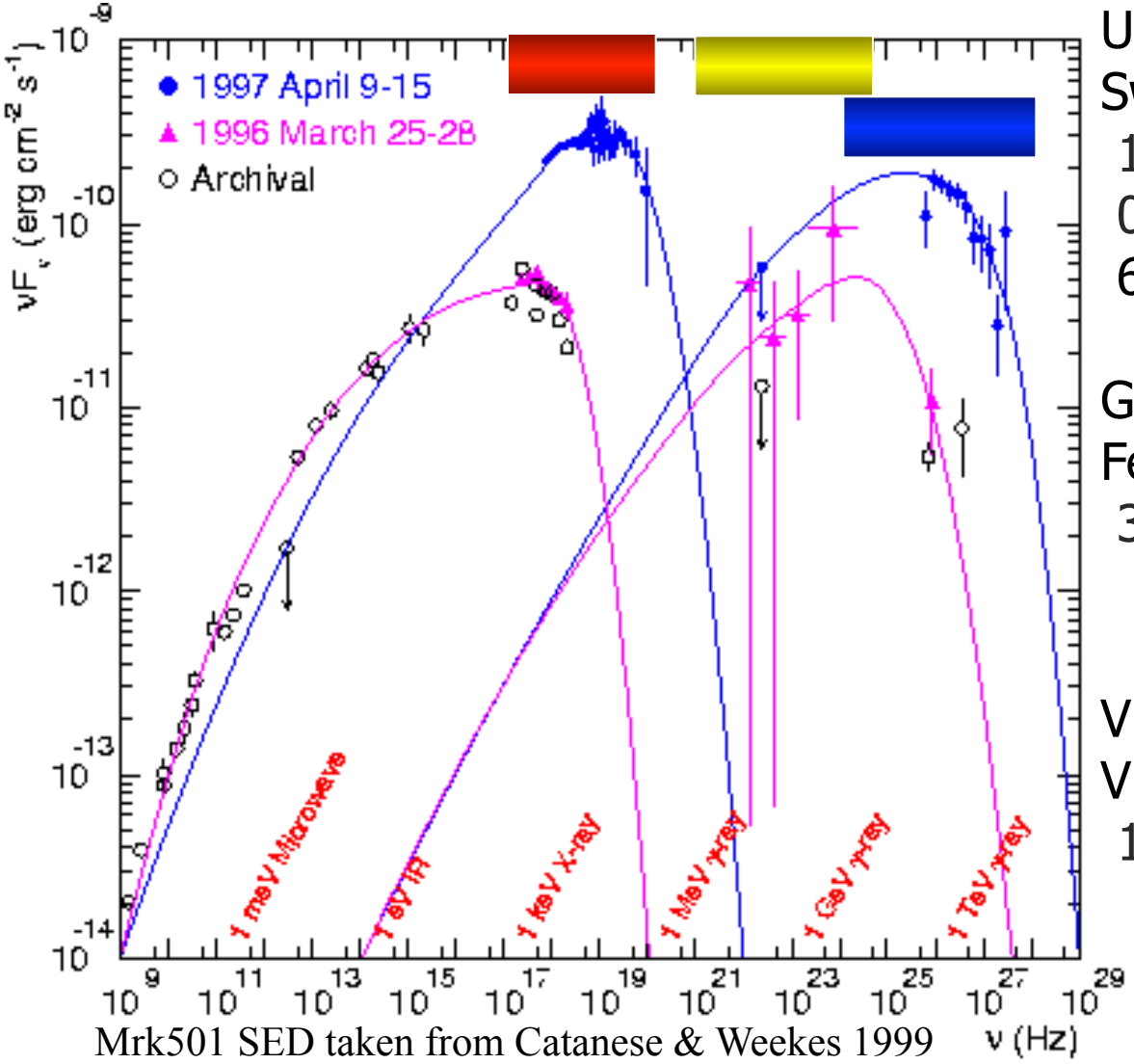
- FSRQ Vs. BL Lac
  - High power w/broad lines Vs. low power with no broad lines
- Low Peaked Vs. High Peaked
  - Variable peak energy for synchrotron emission, along with other parts of SED



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

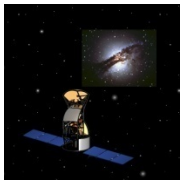
- Note: FR I & FR 2 are off-axis jet cousins of BL Lac & FSRQ blazars

Importance of Broadband Simultaneous 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

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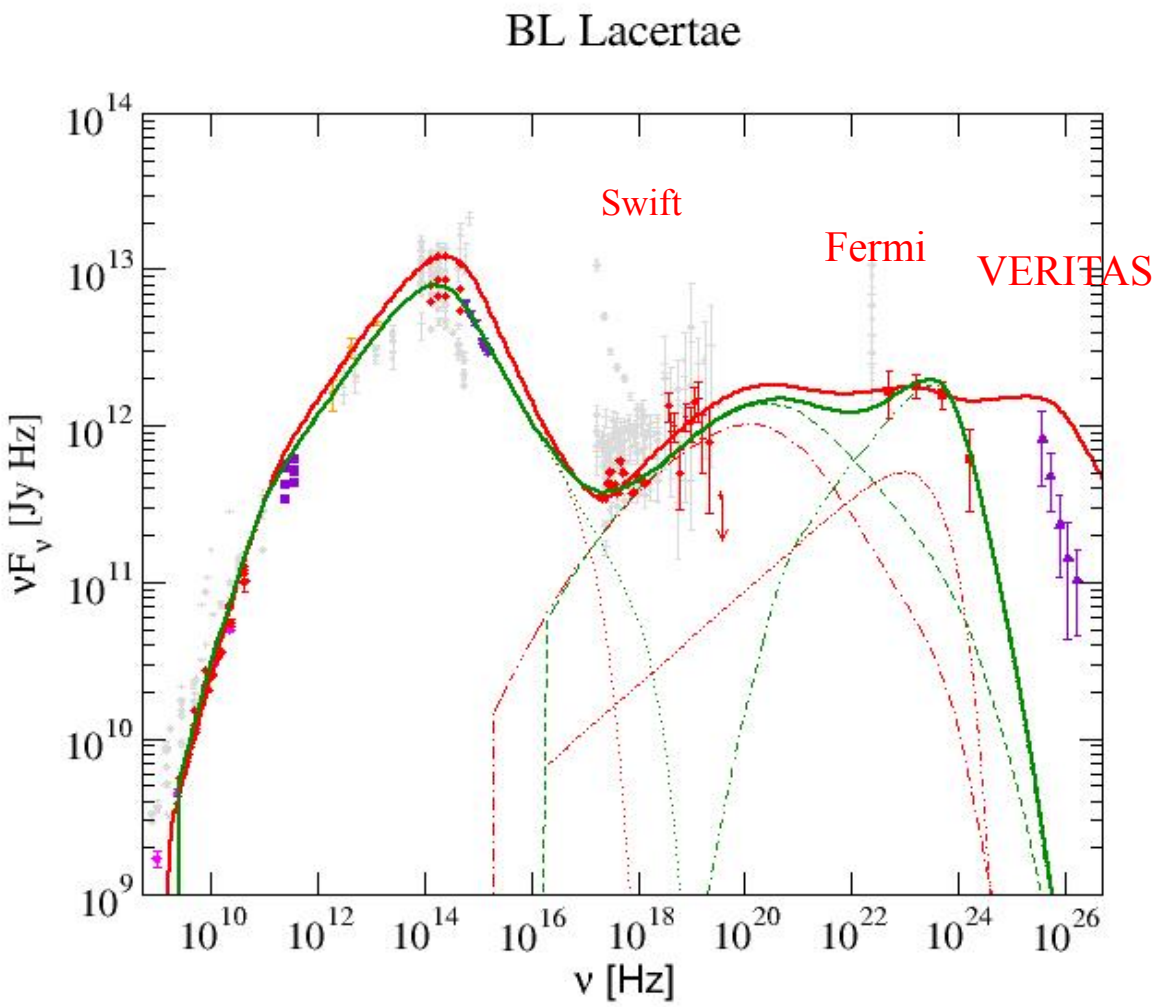

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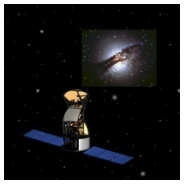

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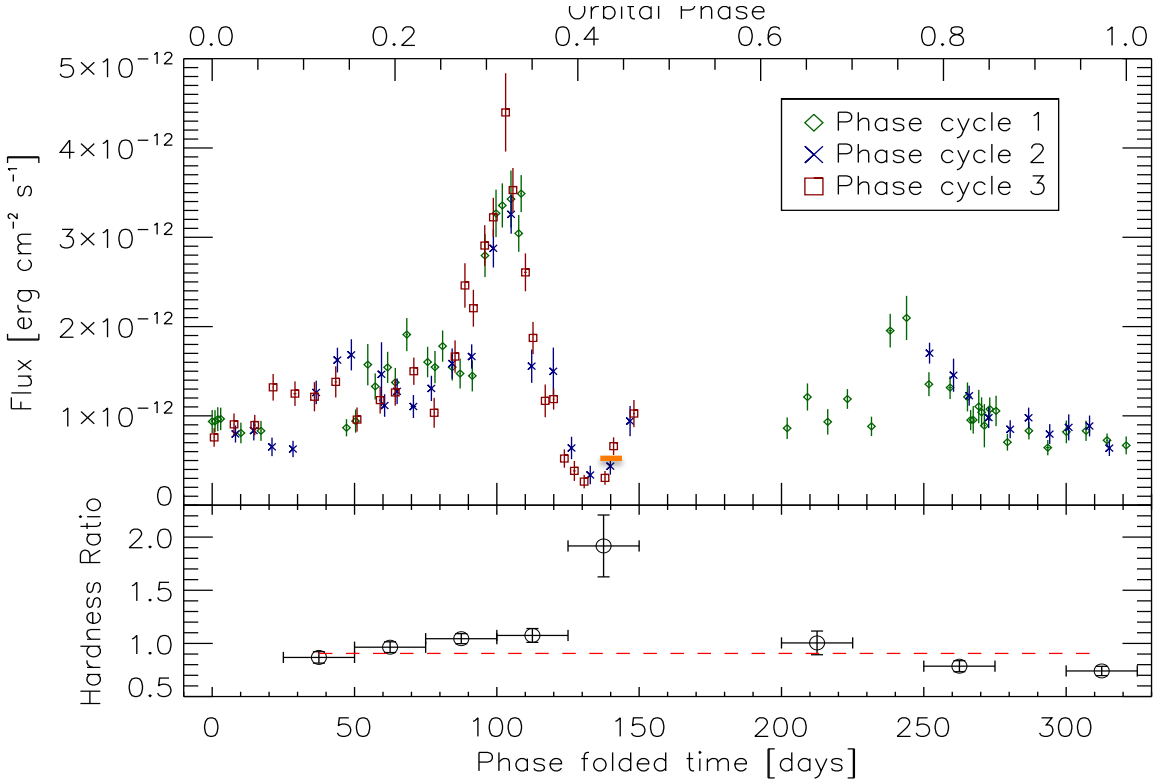
Other motivations for X-ray follow-up of Unassociated Sources
An example: HESS J0632+057 & Periodicity

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

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)

Initial Survey Results

- >430 1FGL & 2FGL sources with ~4 ksec exposures
  - >30 of them have >10 ksec exposures

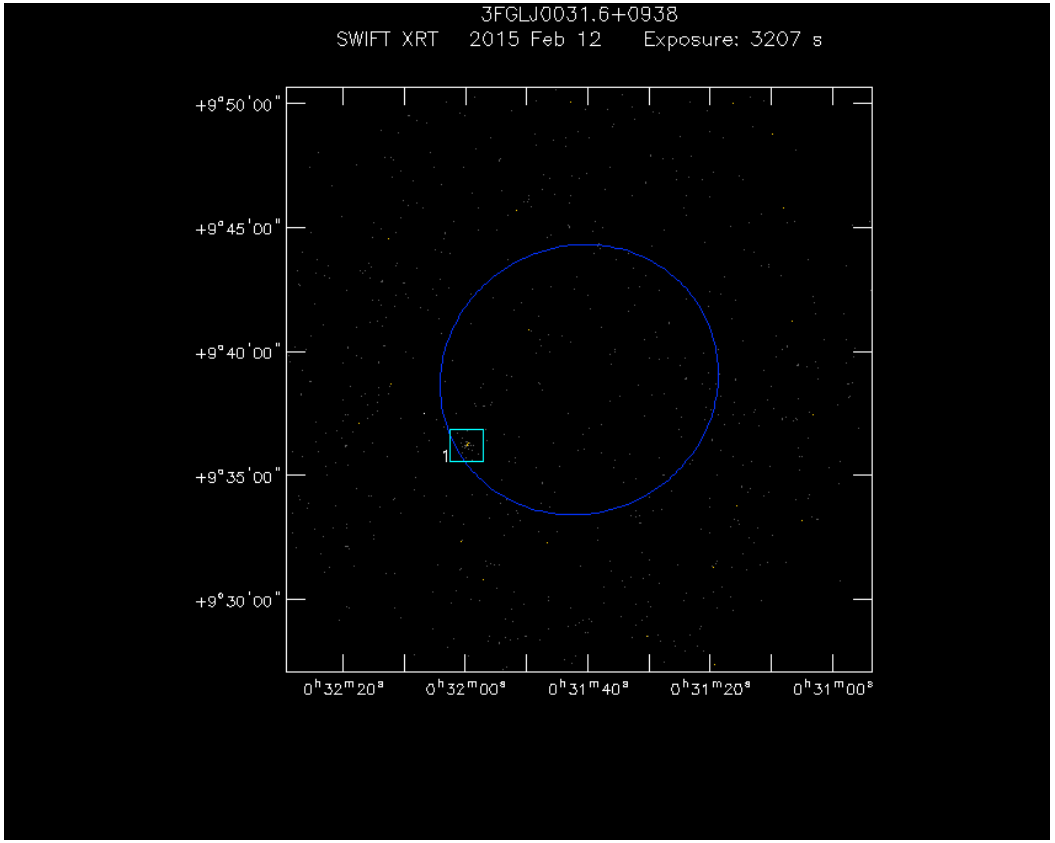
- ~30% have a >3σ detection of a new X-ray source within the 95% Fermi confidence region
  - ~45% of these candidates have no cataloged radio/optical source
- ~20% have a >4σ detection of a new X-ray source within the 95% Fermi confidence region
  - ~60% of these candidates have no cataloged radio/optical source

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

You can see the reduced results at:
http://www.swift.psu.edu/unassociated/
(automatically updated in nearly real-time)

An example:

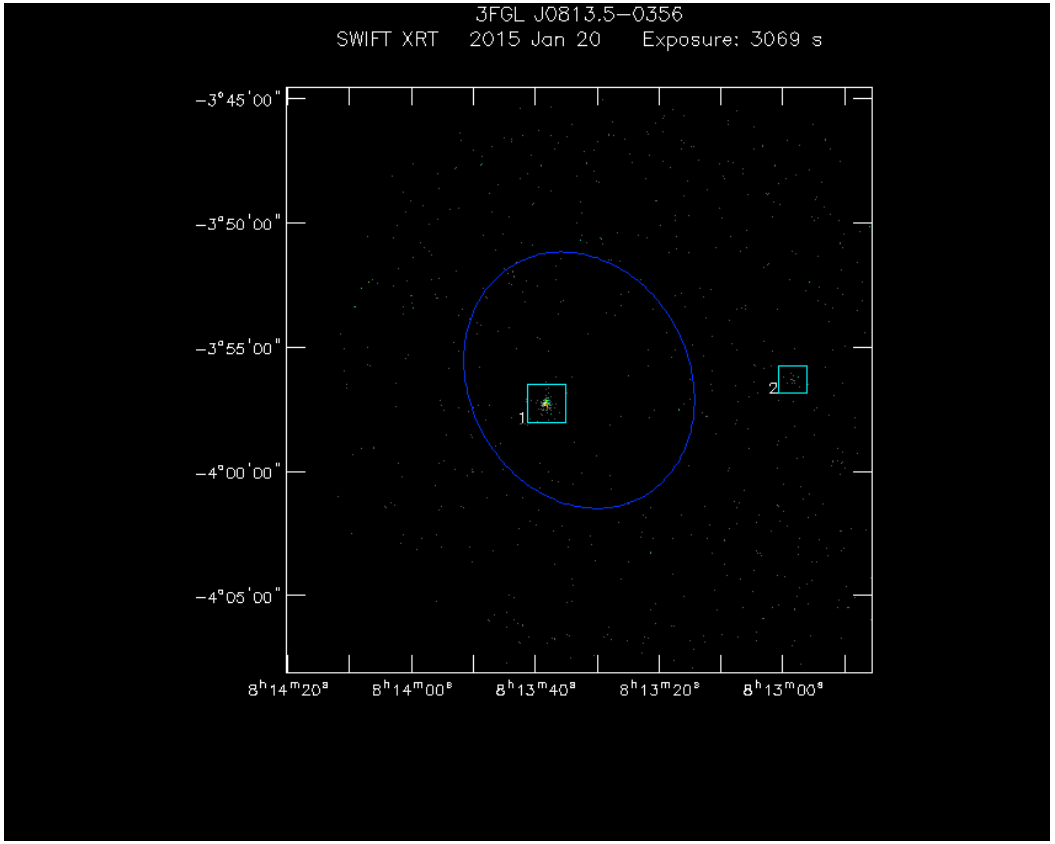
Grabbed first 3FGL observation with >3 ksec Swift observation:



A newly discovered X-ray source (5.2σ) is the only known x-ray source within the 95% conf. region (rate ~0.012 c/s).

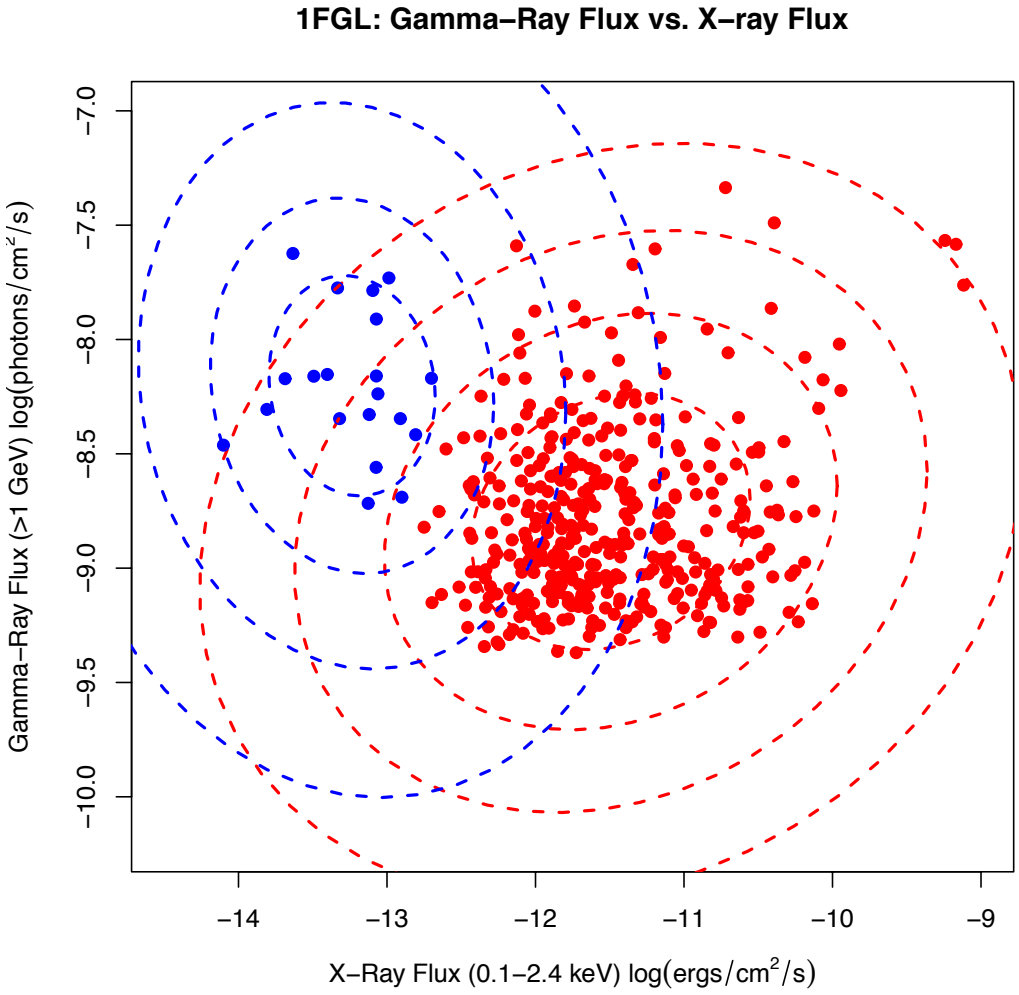
Another example:

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



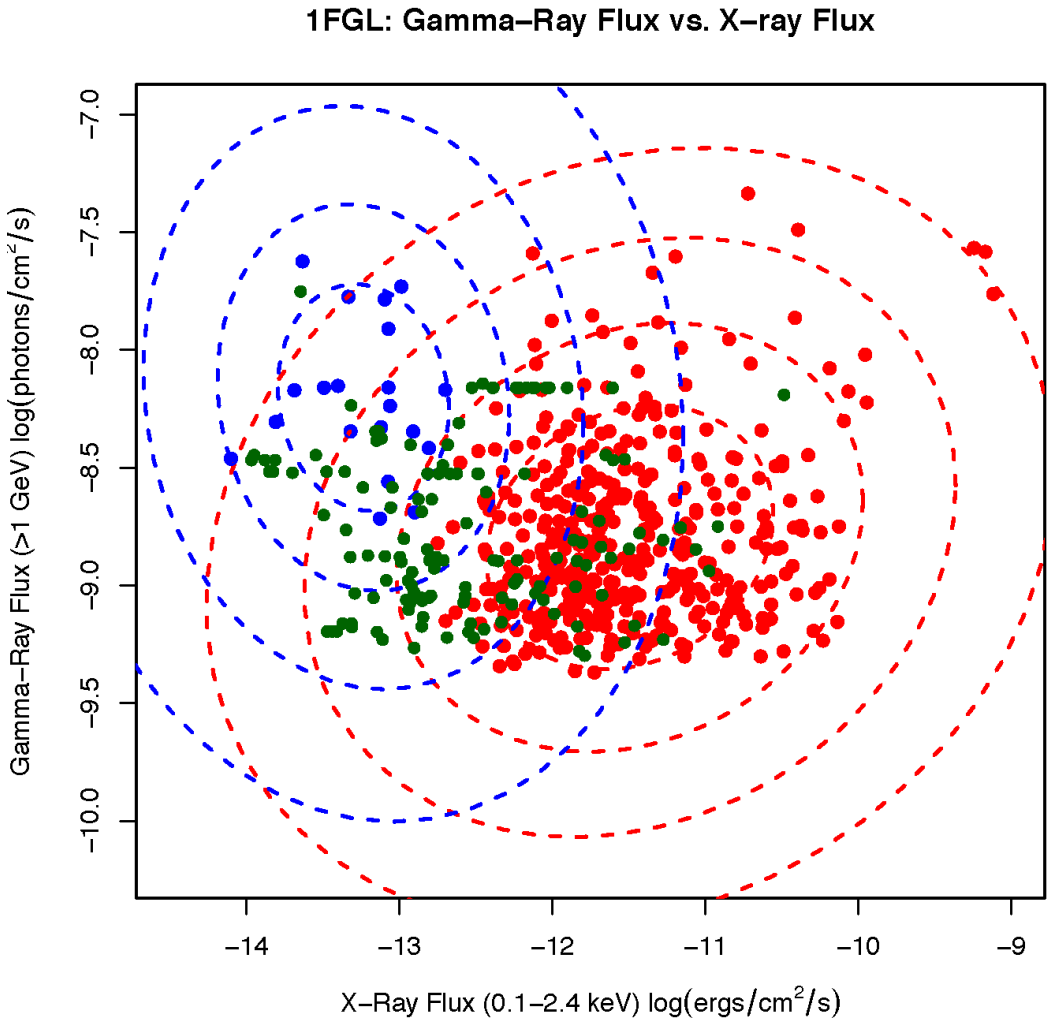
Within Fermi 95% confidence region, there is a single newly discovered X-ray source (>13.8σ) at ~0.076 c/s.

Discriminating with x-ray flux vs gamma-ray flux



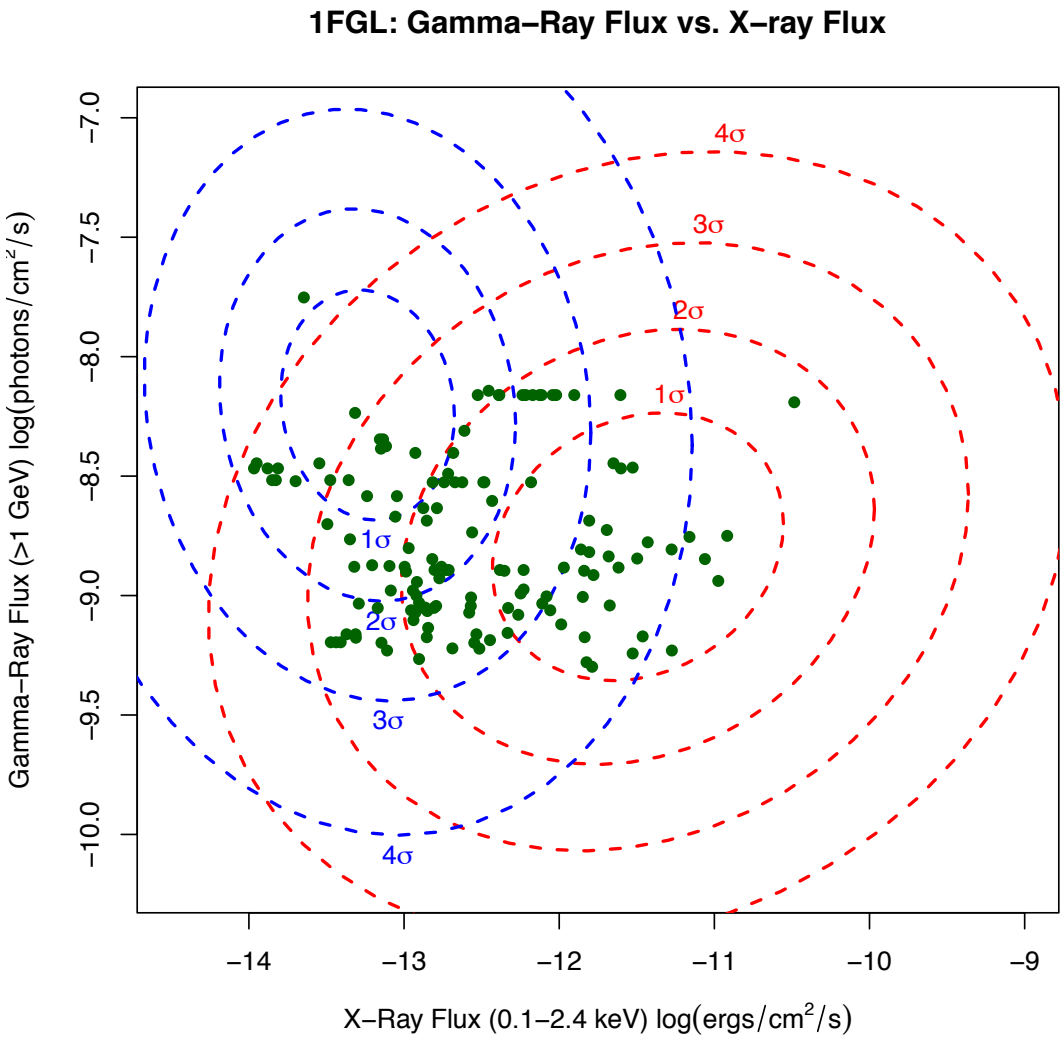
Red = known blazars, blue = known pulsars

Discriminating with x-ray flux vs gamma-ray flux



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

Discriminating with x-ray flux vs gamma-ray flux



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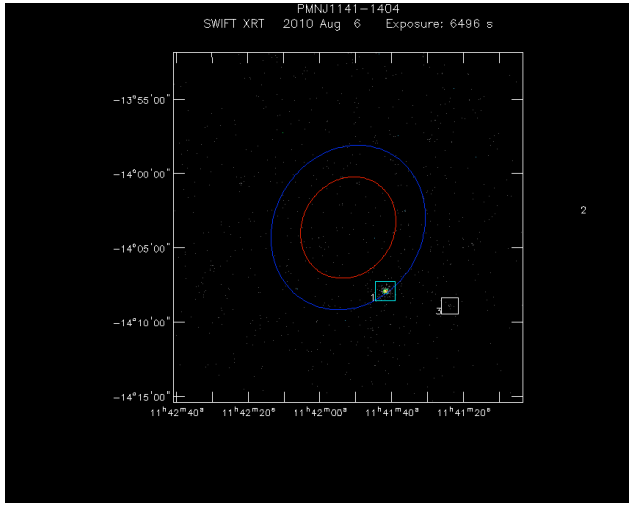
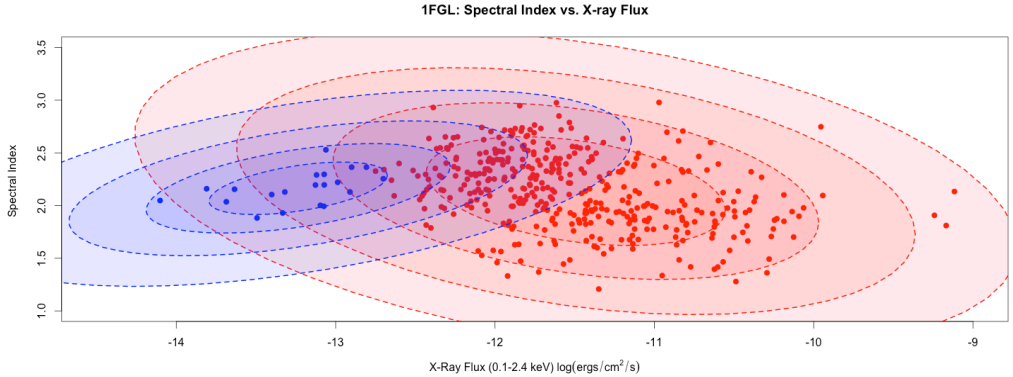
Categorizing possible counterparts

- For example, from X-ray Vs gamma-ray flux alone:

1FGL 1141.8-1403 has a possible x-ray counterpart that is likely to be a blazar (1.06e-5 chance of being associated with a pulsar)

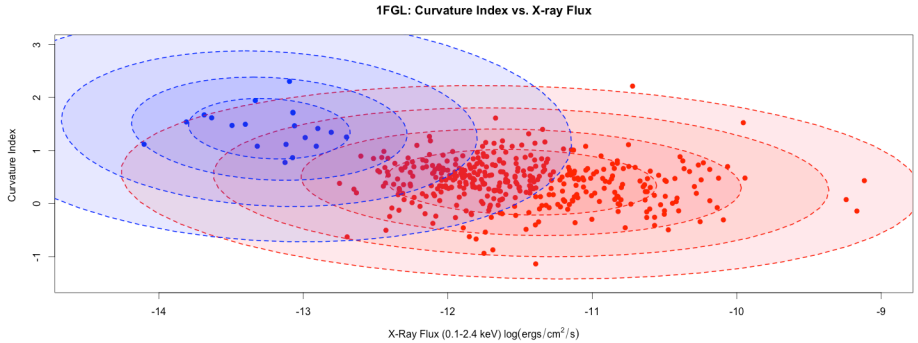


Discriminating with more variables

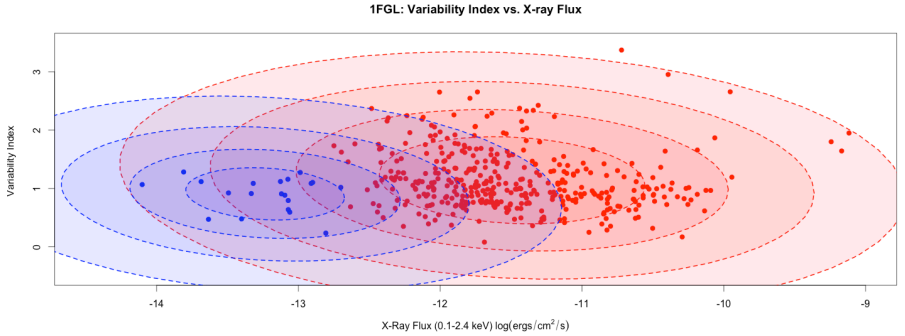


Spectral Index

Curvature



Variability Index



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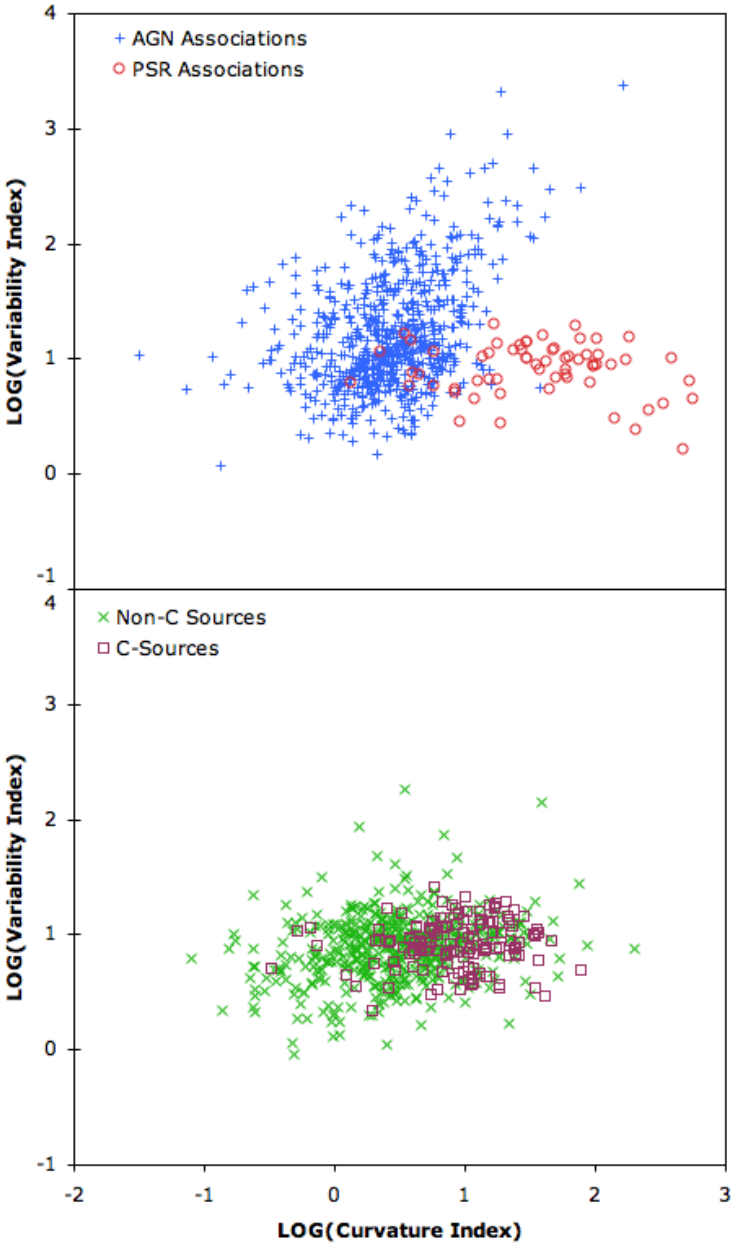
Conclusions

- Swift provides an ideal multiwavelength observatory for follow-up of enigmatic unassociated gamma-ray sources. X-rays are generally expected.
- Swift has observed *hundreds* of the Fermi unassociated sources down to a limiting magnitude of $\approx 1 \times 10^{-13}$ erg cm^{-2} s^{-1}
  - ~30% of the fields have a firm detection of a possible X-ray counterpart (~half of these are new sources)
- Swift results (including images and new source positions) are being posted to: http://www.swift.psu.edu/unassociated/
- Continued follow-up is planned. A catalog paper (and more results) will be released soon so stay tuned…

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