Using Swift for:
X-ray Monitoring of Fermi Blazars, X-ray Counterparts to Fermi Unassociated Sources, and Periodicity Searches (e.g. J1644)

Abe Falcone

(Penn State University)

Collaborators: C. Griffith, M. Pryal, M. Stroh, D. Burrows, C.C. Cheung, D. Donato, E. Ferrara, N. Gehrels, E. Grove, J. Kennea, P. Saz Parkinson, Swift-XRT Team

Outine

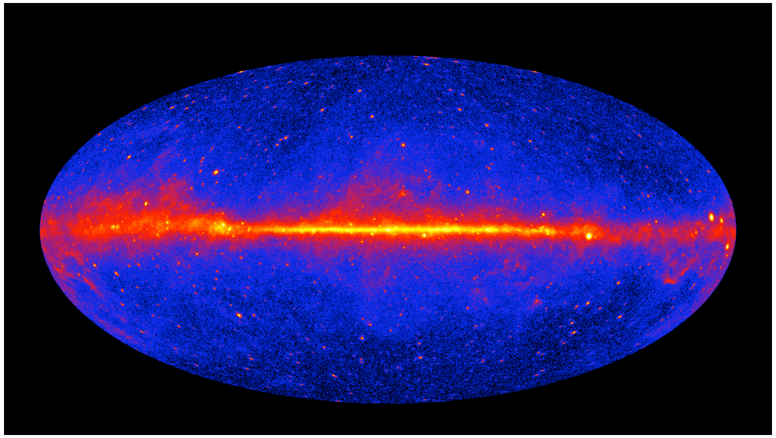
Three Public Monitoring Programs Using Swift X-ray Telescope

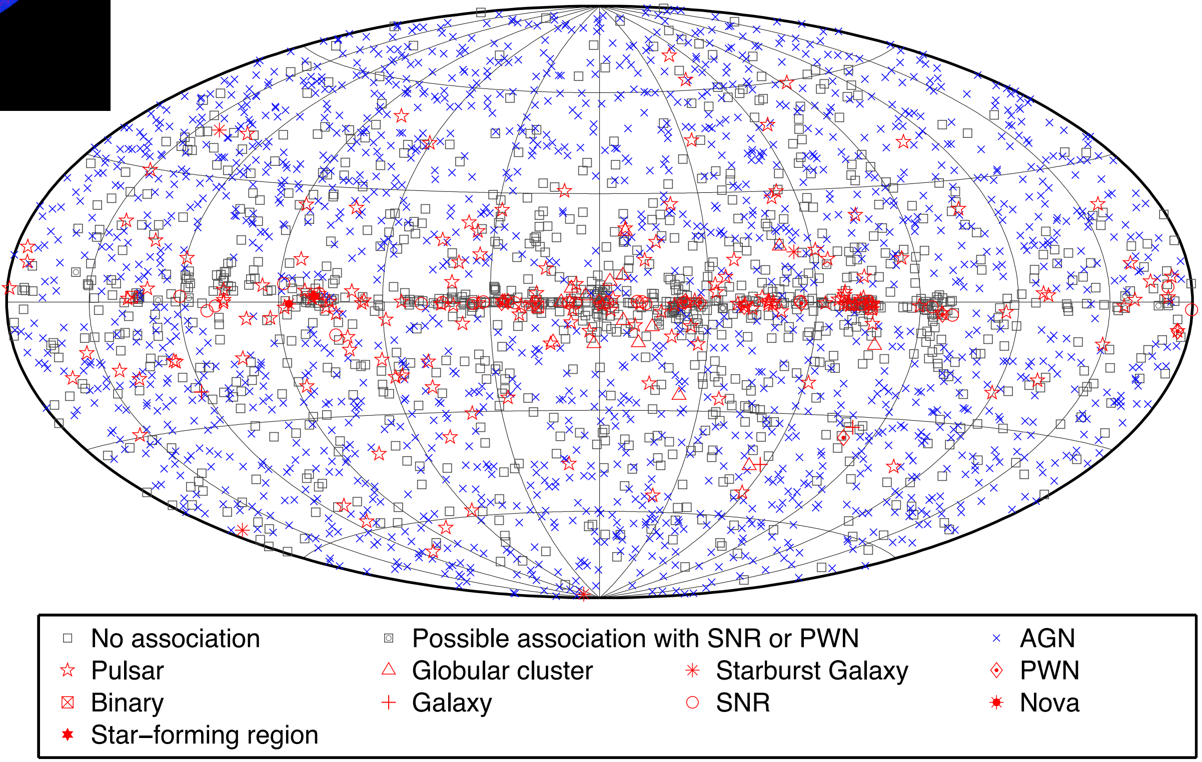
- **Unassociated Fermi-LAT Gamma Ray Source Follow-Up**

- **Blazar & Fermi “Source of Interest” Monitoring**

- **Swift J1644+57: Possible Periodicity from a TDE**

Skymap and Gamma-ray Sources (Fermi 3FGL)





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

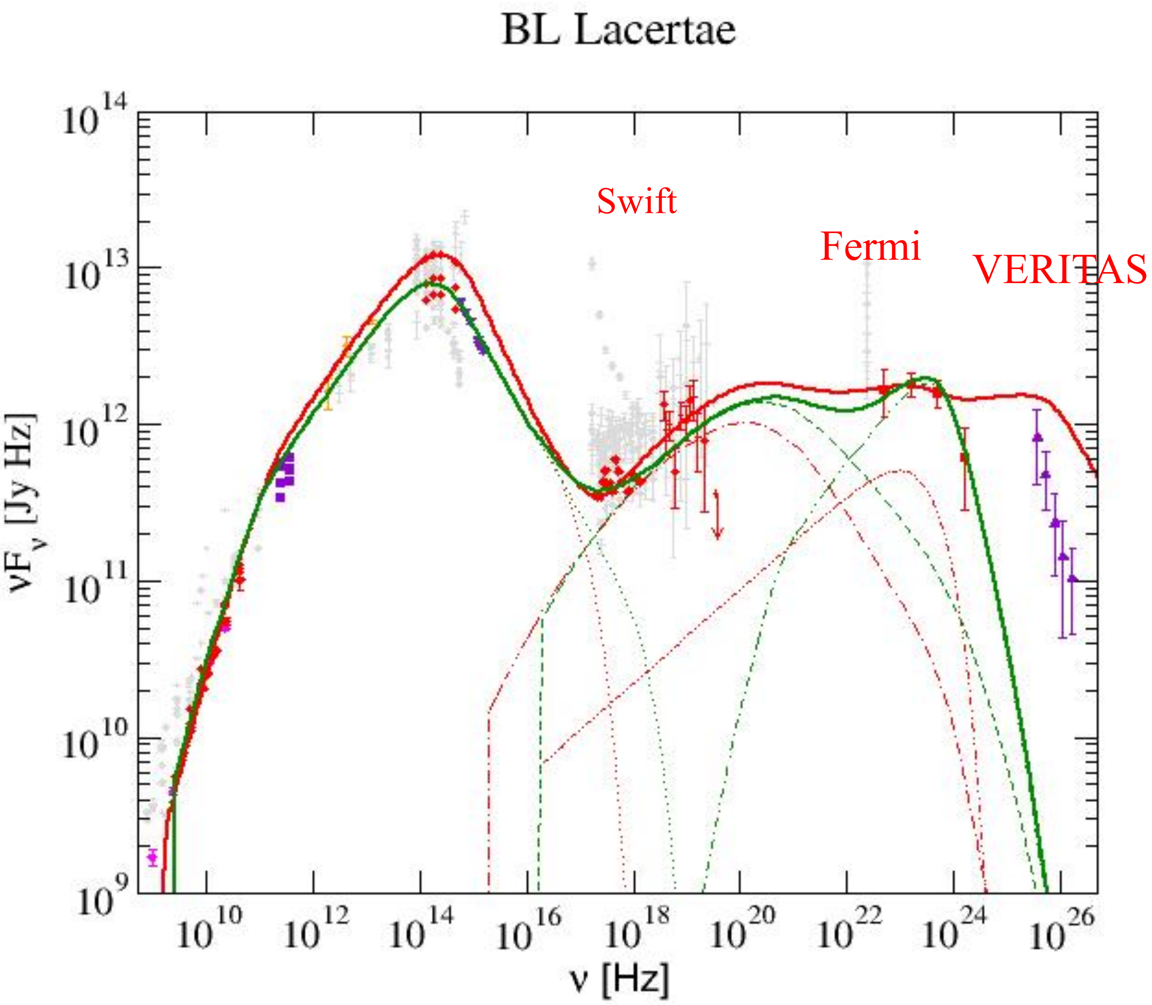
LAT Unassociated Source Catalogs

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

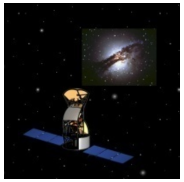
These remaining unassociated Fermi sources are ripe for X-ray emission searches

…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

Initial Survey Results

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

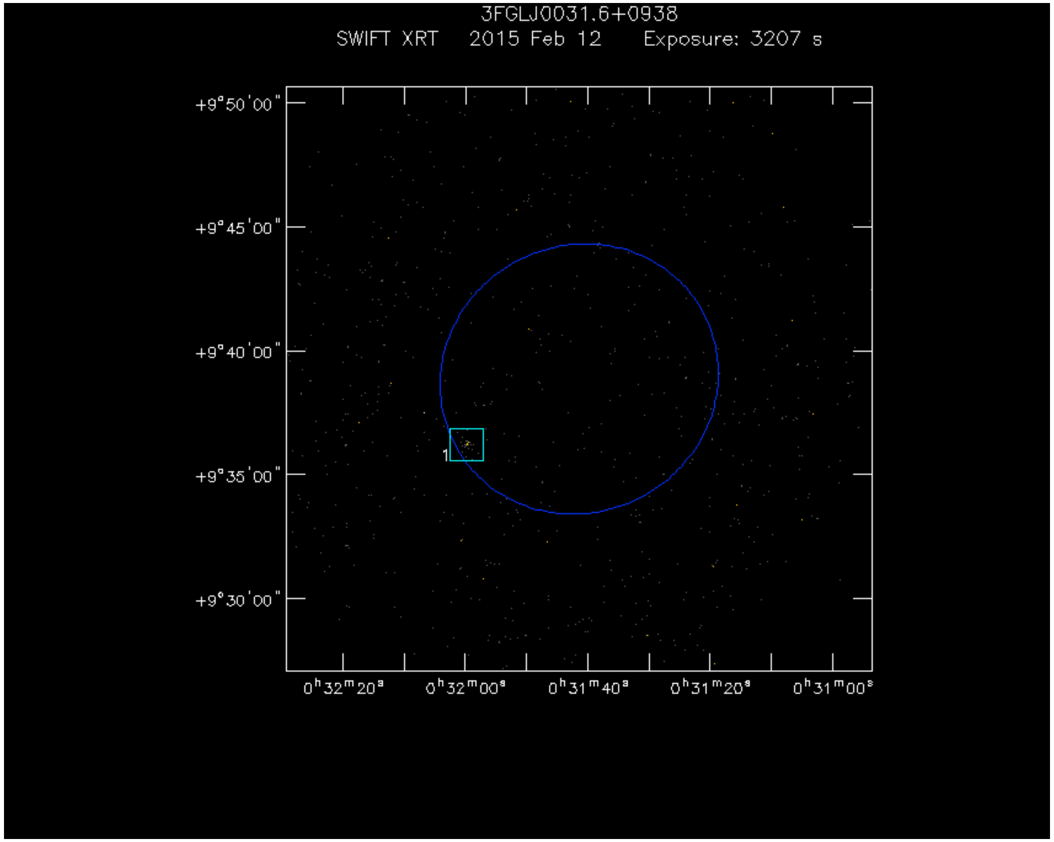
- ~30% have a >3σ detection of a new X-ray source within the 95% Fermi confidence region
  - ~45% of these candidates have no cataloged radio/optical source
- ~20% have a >4σ detection of a new X-ray source within the 95% Fermi confidence region
  - ~60% of these candidates have no cataloged radio/optical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

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

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

An example:

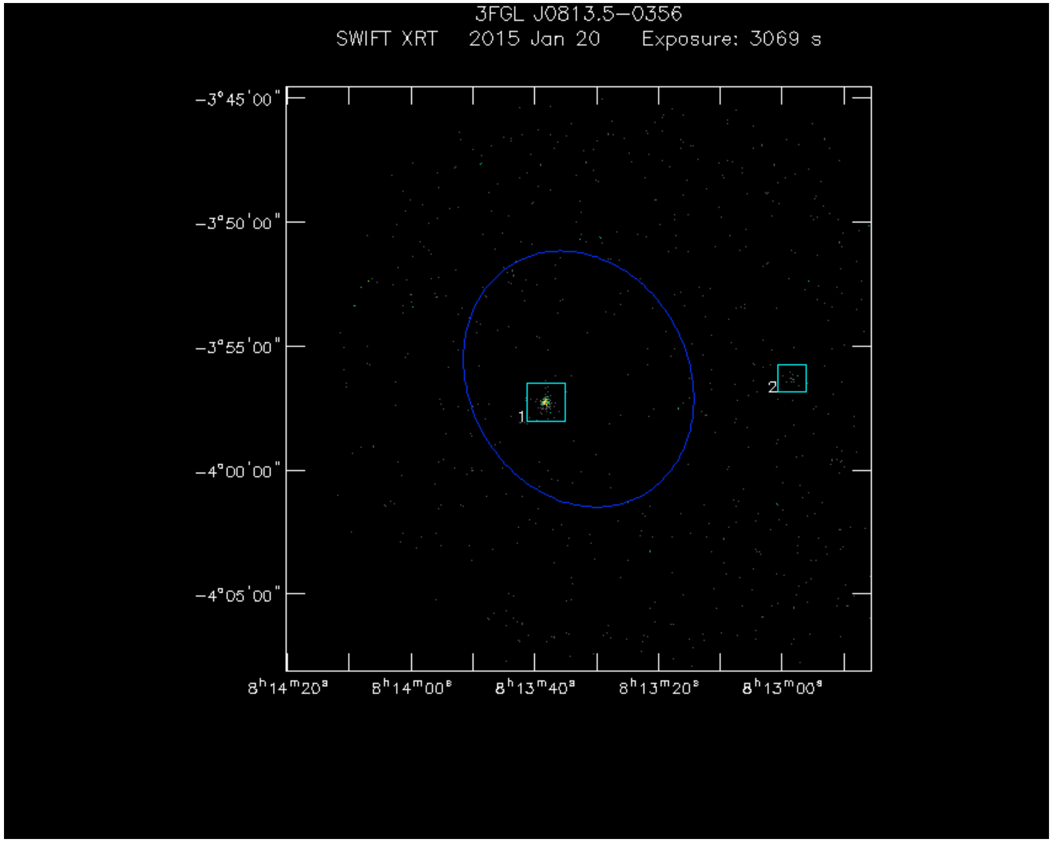
Grabbed first 3FGL observation with >3 ksec Swift observation:



A newly discovered X-ray source (5.2σ) is the only known x-ray source within the 95% conf. region at a rate of ~0.012 c/s (0.2-10 keV flux is roughly ~1×10^{-13} erg cm^{-2} s^{-1}).

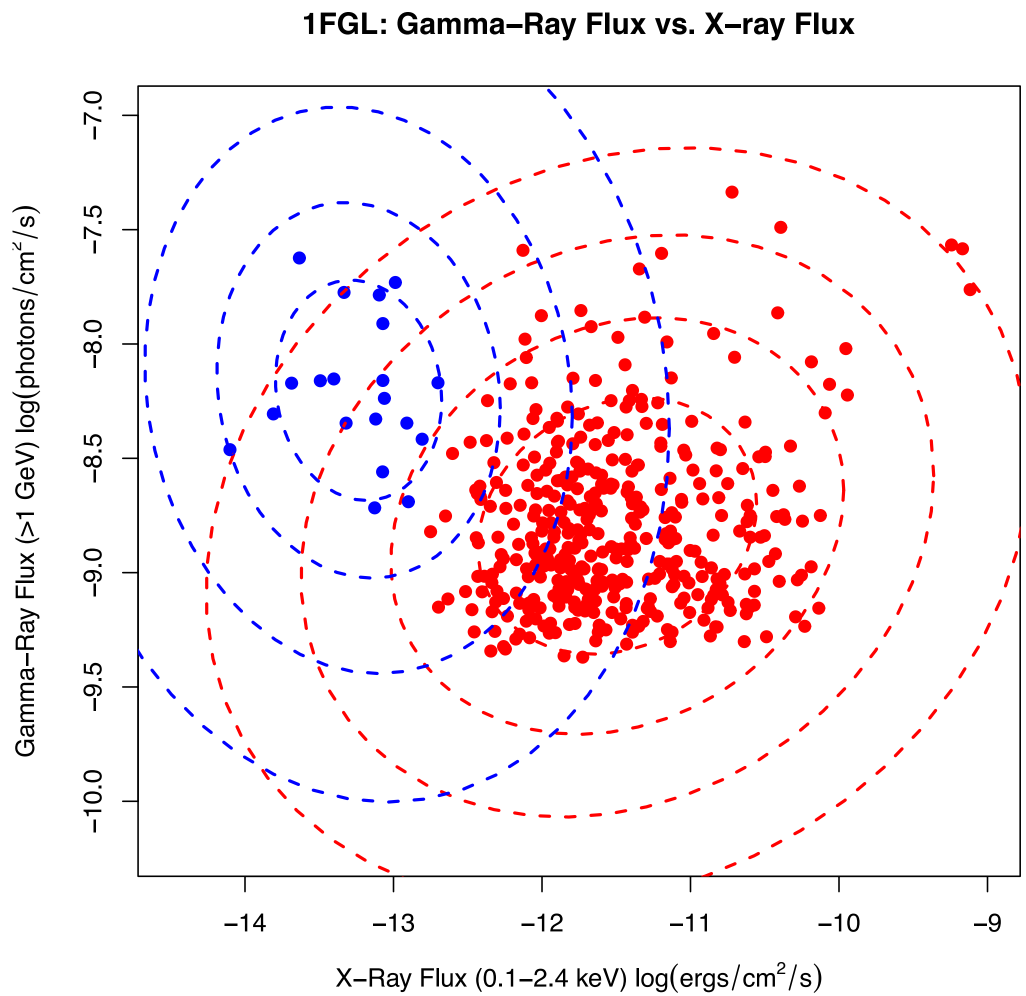
Another example:

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



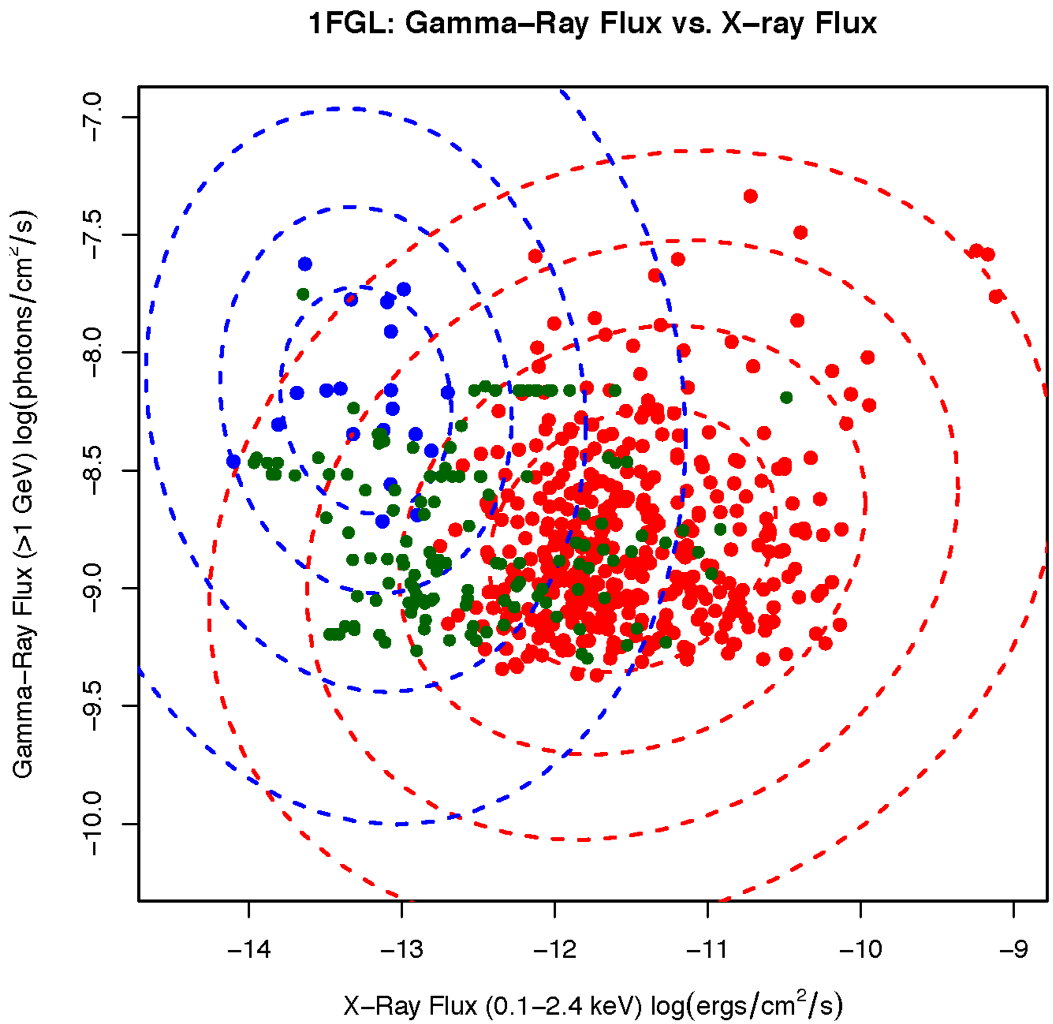
Within Fermi 95% confidence region, there is a single newly discovered X-ray source (>13.8σ) at ~0.076 c/s (0.2-10 keV flux is roughly ~7×10^{-13} erg cm^{-2} s^{-1}).

Discriminating with x-ray flux vs gamma-ray flux



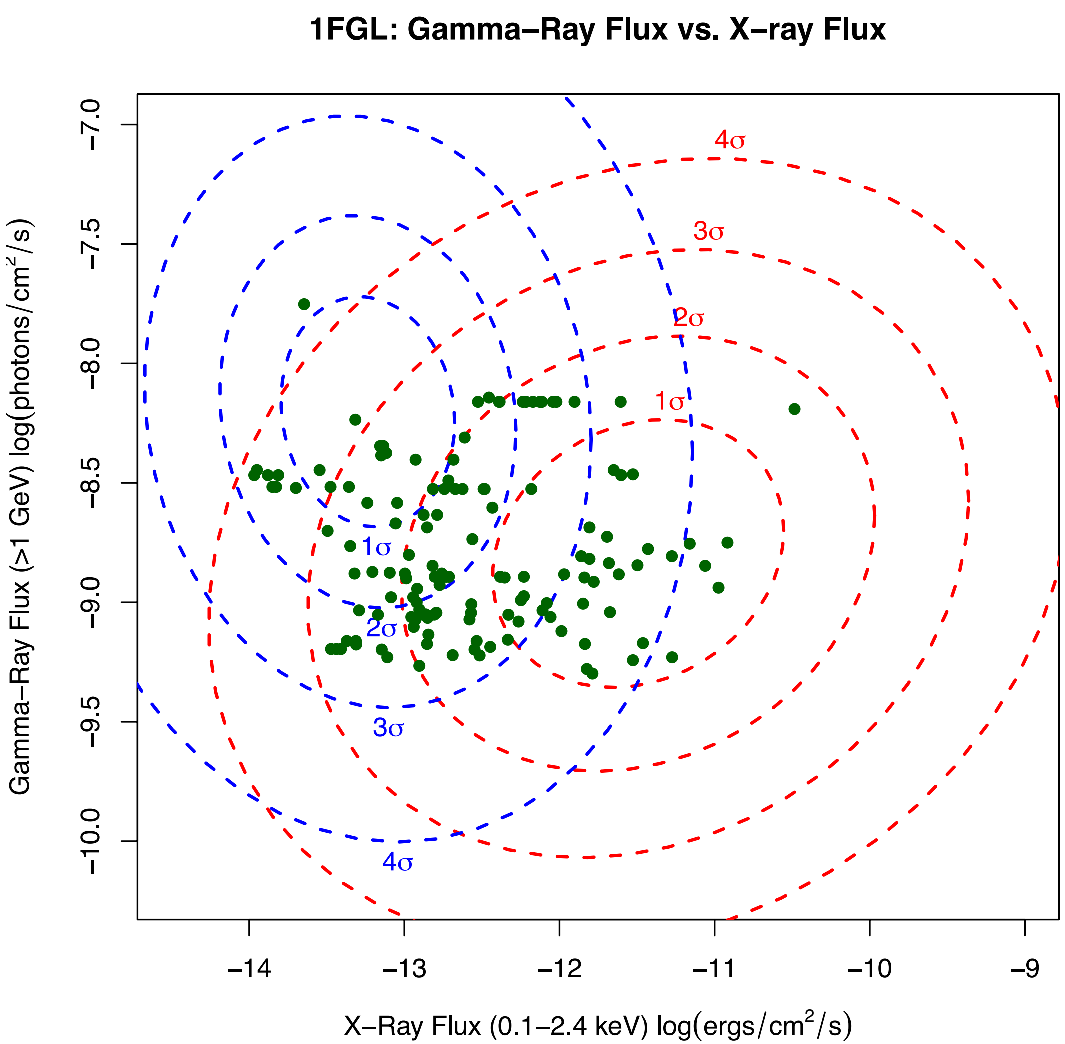
Red = known blazars, blue = known pulsars

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

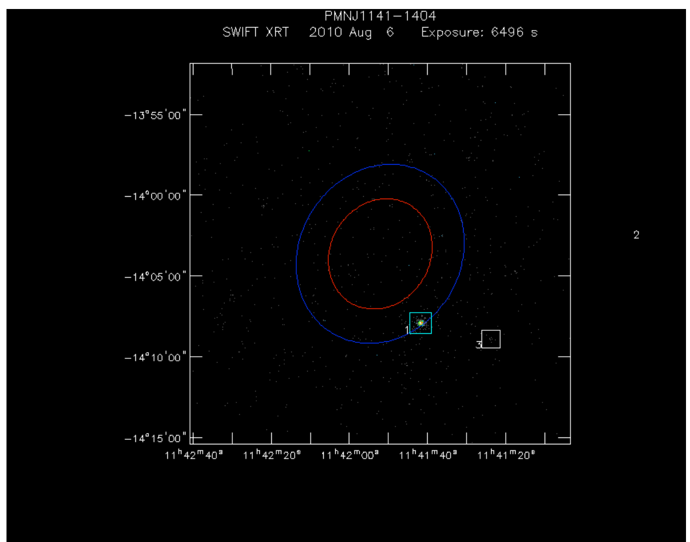


Red = known blazars, blue = known pulsars
green = Fermi Unassociated possible X-ray counterpart

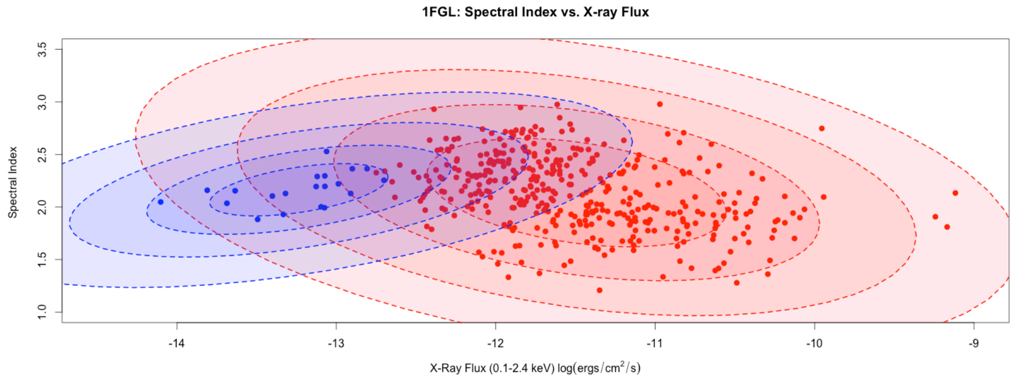
Categorizing possible counterparts

- 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)

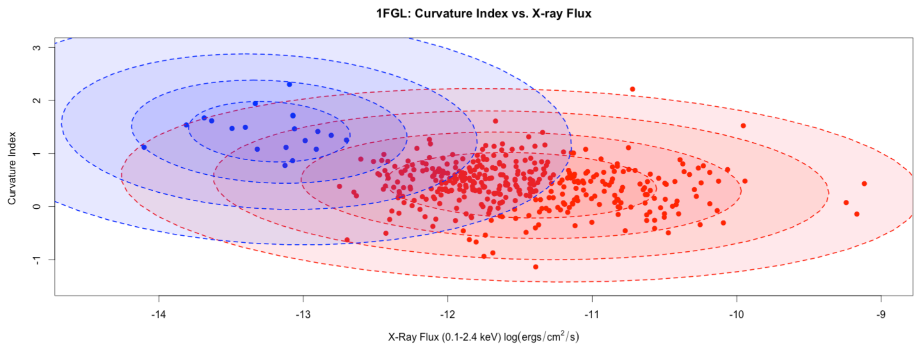


Discriminating with more variables

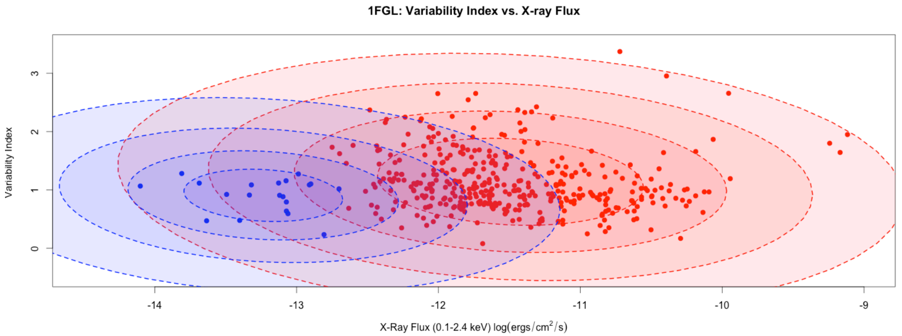


Spectral Index

Curvature

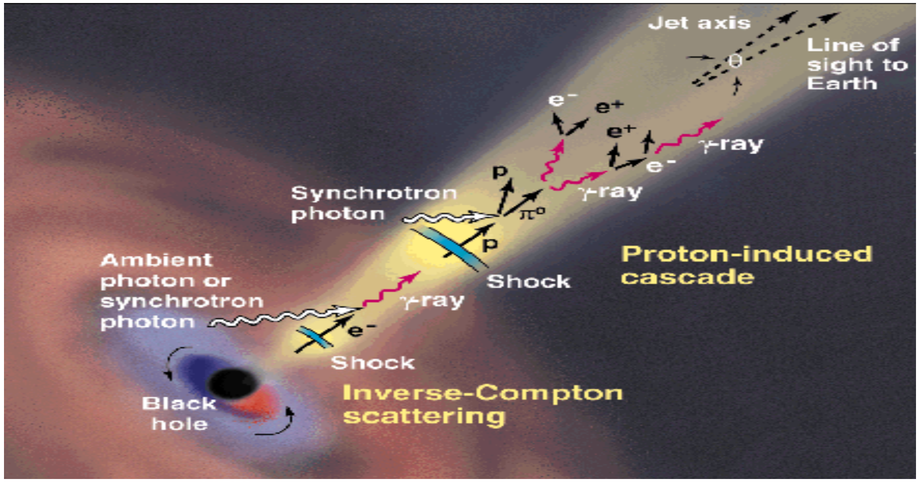


Variability Index



Red = known blazars, blue = known pulsars

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

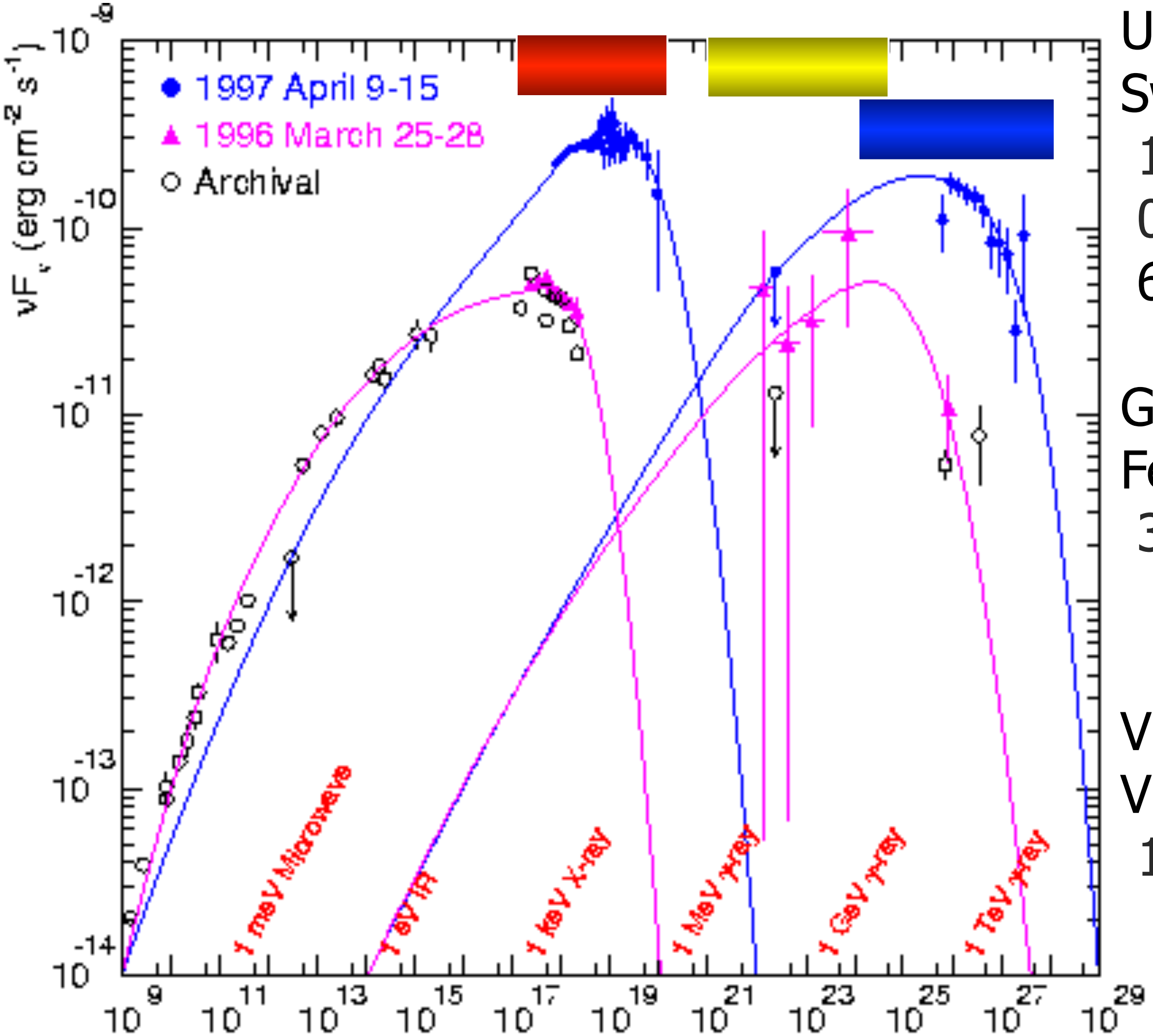


- ***Jets typically produce variable synchrotron emission in X-ray band. This is a required input for modeling the higher energy emission.***

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

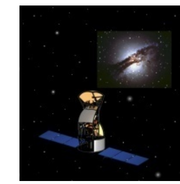
Importance of Broadband Coverage



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

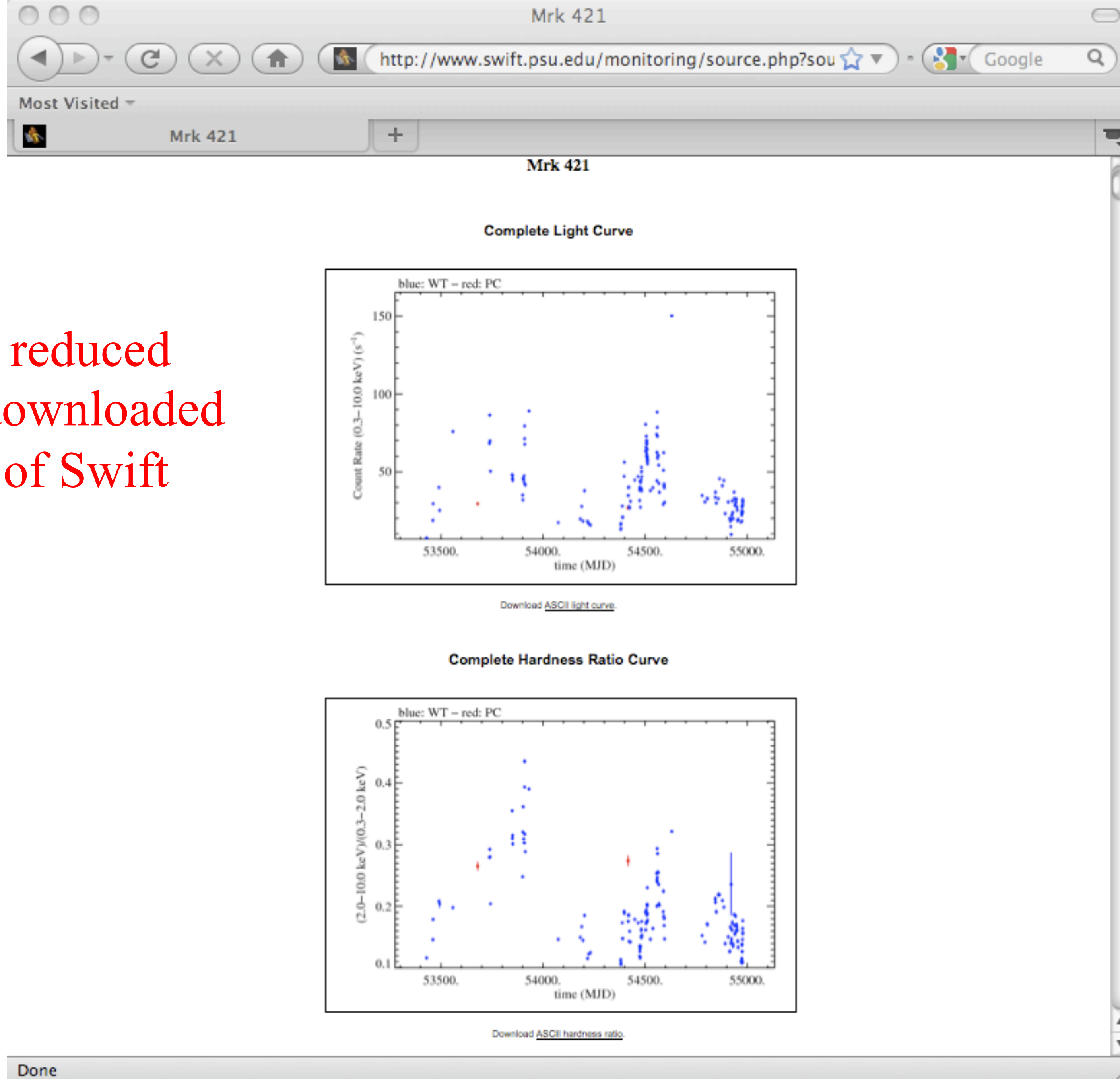
Swift Monitoring of Fermi "Sources of Interest" and other GeV-TeV sources

0208-512
0235+164
PKS 0528+134
PKS 0716+714
0827+243
OJ 287
Mrk 421
W Com
3C 273
3C 279
1406-076
H 1426+428
1510-089
PKS 1622-297
1633+383
Mrk 501
3EGJ1733-1313
1ES 1959+650
PKS 2155-304
BL_Lacertae
3C 454.3
1ES 2344+514
LS I +61 303

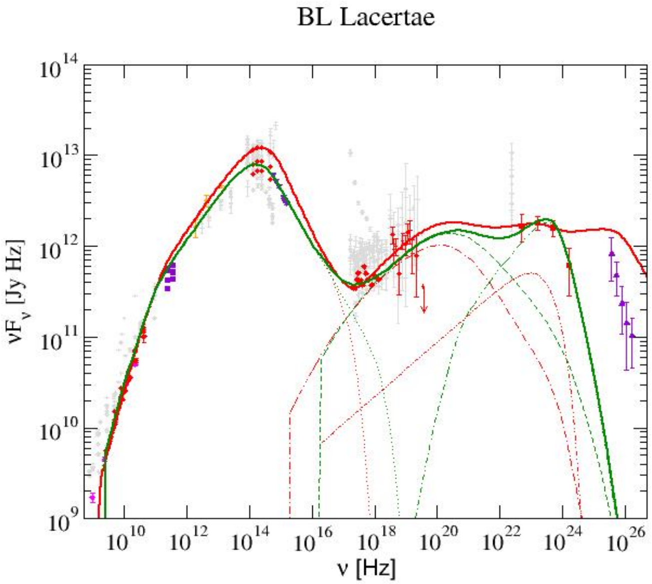
- Swift is monitoring several sources on weekly basis for 1-2 ksec per week for ~4 months per source
- Additionally, intensive Swift monitoring sometimes results as part of larger campaigns and ToOs
- This follow-up is frequently coordinated with TeV observatories, resulting in multiwavelength data from UVOT, XRT, BAT, Fermi, TeV telescopes, and others
- Near-real-time light curves are publicly available: http://www.swift.psu.edu/monitoring
- Contact afalcone@astro.psu.edu if you are interested in further coordination for your favorite source

See: Stroh & Falcone 2013, ApJ Supplement, 207, 28

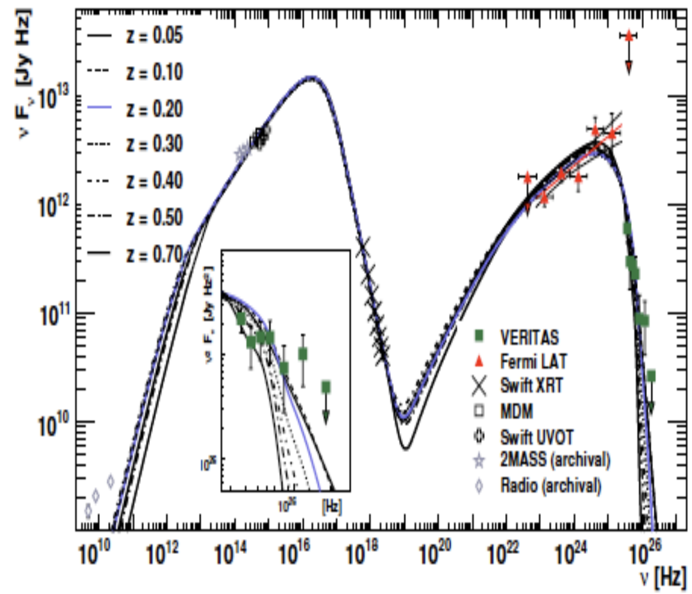
All plots and reduced data can be downloaded within hours of Swift observations



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 Variability Studies

The 23 "*Fermi* Sources of Interest" with photon indices and excess variances in the 0.3 – 10.0 keV band (Stroh & Falcone 2013).

Source	<α>	σ^2_{rms}
PKS 0208-512	1.83 ± 0.14	0.06
PKS 0235+164	1.93 ± 0.07	1.23
PKS 0528+134	1.75 ± 0.12	0.29
PKS 0716+714	2.31 ± 0.06	0.40
QSO B0827+243	1.80 ± 0.09	0.26
OJ 287	2.0 ± 0.3	0.11
Mrk 421	2.233 ± 0.014	0.34
W Com	2.83 ± 0.12	0.95
3C 273	1.62 ± 0.02	0.07
3C 279	1.70 ± 0.03	0.02
1Jy 1406-076	3 ± 1.4	0.00
H 1426+428	2.06 ± 0.06	0.08
PKS 1510-089	1.38 ± 0.08	0.03
PKS 1622-297	1.7 ± 0.4	0.10
1Jy 1633+383	1.5 ± 0.5	0.39
Mrk 501	2.18 ± 0.8	0.15
PKS 1733-130	1.6 ± 0.3	0.11
1ES 1959+650	2.32 ± 0.07	0.09
PKS 2155-304	2.66 ± 0.04	0.51
BL Lacertae	1.94 ± 0.05	0.06
3C 454.3	1.59 ± 0.04	0.30
1ES 2344+514	2.24 ± 0.05	0.32
LS I +61 303	1.71 ± 0.07	0.13

We also searched the entire Swift-XRT AGN catalog for significant flares with a flux doubling in less than ~10 minute timescale. While we found a handful of candidate flares, the post-trials significance was consistent with a null result

(see Pryal, Falcone, & Stroh 2015, ApJ, 802, 33)

Swift J1644+57

- Swift J1644+57 was a highly luminous tidal disruption event discovered by Swift on MJD 55648 when it triggered the onboard GRB response.
- It is thought to have been caused by the infall of material from a tidally disrupted star in the vicinity of a black hole, and it is thought to have formed a jet which explains its super-Eddington luminosity (see Burrows et al. 2011, Bloom et al. 2011, Levan et al. 2011, Berger et al. 2012, etc…)
  - {Note: Kara et al. 2016 have performed a reverberation study and offer a different view of the source of the x-ray emission}
- The black hole mass has been estimated to be between 10^5 - 10^7 $M_{\odot}$, and the luminosity reached $\sim 10^{48}$ erg/s during the outburst (> 100 L_{edd})
- *Swift* has monitored the source regularly since its detection, and it has exhibited major fluctuations on multiple timescales in addition to a general power law decay with decay index between 3/3 and 5/3, depending on where/how you fit the decay.

Swift J1644+57

- Saxton et al. 2012 used a Lomb-Scargle analysis and found what they referred to as “plausible periodicities” at > 99% confidence during different phases of the lightcurve, citing periods at:
  - 2.6 and 16.2 days in the ‘early decline’ stage from 4.5 < t < 55 days
  - 10.4 days in the ‘late decline’ stage from 55 < t < 104 days
  - 12.7 days in the ‘plateau’ stage from 104 < t < 145 days
  - 16.2 days in the ‘post plateau’ stage at t > 145 days

- We used a Z-transformed discrete correlation function (ZDCF) analysis, which is appropriate for sparsely sampled and erraticly variable data, to search for periodicities.

0 < t < 4.5 days

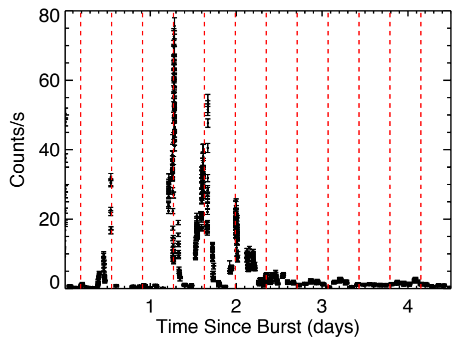


Figure 2. Light curve of *Swift* J1644+57 from 0 to 4.5 days after the onset of the TDE. The red dashed vertical lines are drawn at a period of 0.36 days with an arbitrary offset that was determined by eye.

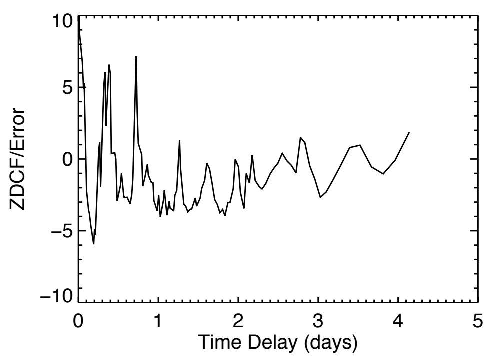


Figure 1. ZDCF divided by the error of the 0 to 4.5 day light curve of *Swift* J1644+57. Two periods are detected at 0.36 ± 0.05 and 0.72 ± 0.05 days.

4.5 < t < 55 days

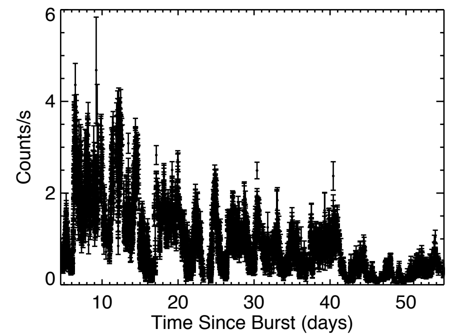


Figure 4. Light curve of *Swift* J1644+57 from 4.5 to 55 days after the onset of the TDE. The detected periods cannot be seen due to the number of periods found and the overall variability of the light curve.

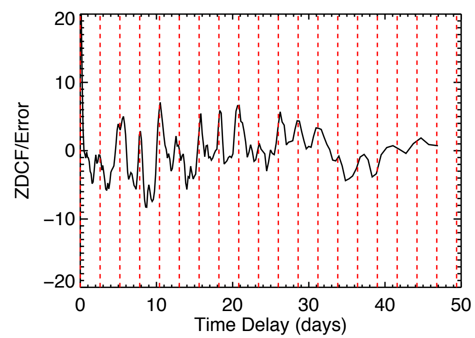


Figure 3. ZDCF divided by the error of 4.5 to 55 days after burst of *Swift* J1644+57. The vertical line is drawn every 2.6 days. The most significant periods can be seen at 5.2 ± 0.9, and 10.4 ± 0.6 days. There is likely a 2.6 day period underlying some of the periodic peaks.

55 < t < 104 days

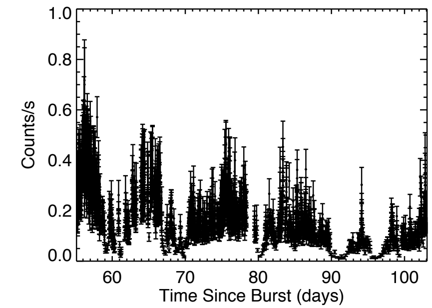


Figure 6. Light curve of *Swift* J1644+57 from 55 to 104 days after the onset of the TDE.

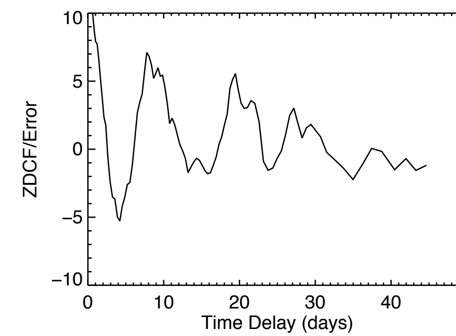


Figure 5. ZDCF divided by the error of 55 to 104 days after burst of *Swift* J1644+57. A period is detected at 9 ± 2 days, and multiples of this period also show up as bumps in the periodogram.

Griffith & Falcone 2016, submitted

Swift J1644+57

- Saxton et al. 2012 used a Lomb-Scargle analysis and found what they referred to as “plausible periodicities” at > 99% confidence during different phases of the lightcurve, citing periods at:
  - 2.6 and 16.2 days in the ‘early decline’ stage from 4.5 < t < 55 days
  - 10.4 days in the ‘late decline’ stage from 55 < t < 104 days
  - 12.7 days in the ‘plateau’ stage from 104 < t < 145 days
  - 16.2 days in the ‘post plateau’ stage at t > 145 days
- We used a Z-transformed discrete correlation function (ZDCF) analysis, which is appropriate for sparsely sampled and erratically variable data, to search for periodicities.
- We find evidence for periodicity confirming some of the periods indicated by Saxton et al. 2012, and we find some additional periods. At S/N ratio > 5, we see:
  - 0.36 and 0.72 days in the ‘early decline’ stage from 0 < t < 4.5 days
  - 5.2 and 10.4 days in the ‘early decline’ stage from 4.5 < t < 55 days (with indications of an underlying, yet undetectable, 2.6 day period)
  - 9 ± 2 days in the ‘late decline’ stage from 55 < t < 104 days
  - No significant periodicity in the ‘plateau’ stage from 104 < t < 145 days
  - No significant periodicity in the ‘post plateau’ stage at t > 145 days

Griffith & Falcone 2016, submitted

Conclusions

- Swift provides an ideal multiwavelength observatory for follow-up of enigmatic unassociated gamma-ray sources, and may have detected many new x-ray counterparts:
  - ~30% of the fields have a firm detection of a possible X-ray counterpart (~half of these are new sources)
  - Most of these are likely to be blazars
- Swift results (including images and new source positions) are being posted to: **http://www.swift.psu.edu/unassociated/**
- Swift is obtaining regular monitoring data and target of opportunity campaign data to support Fermi "sources of interest" and many (>100) additional flaring blazar and binary sources

  These data are released as light curves and hardness curves in near-real-time

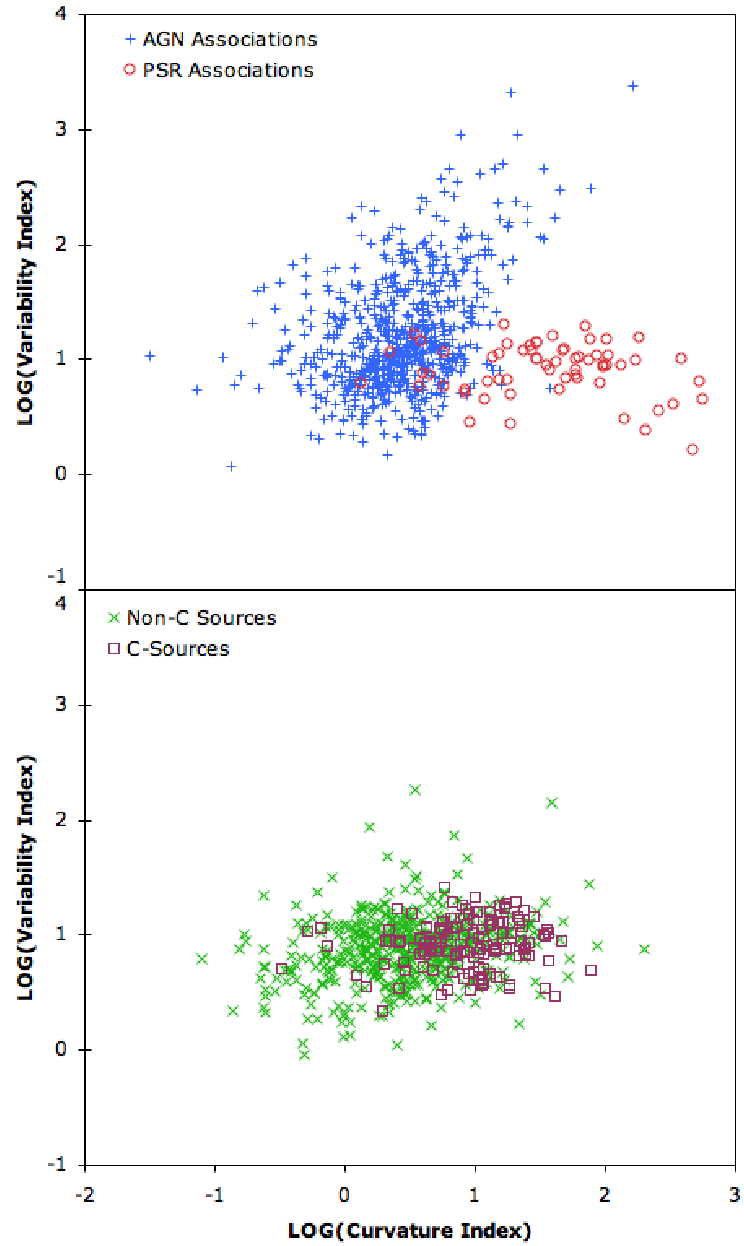
  see: **http://www.swift.psu.edu/monitoring**
- HESS J0632+057 monitoring has led to the discovery of a new TeV binary and begun to characterize its nature
- Swift J1644+57 monitoring has provided evidence for periodicity from this exciting TDE with a likely jet (see Griffith & Falcone 2016, submitted). Causes: clumping in accretion disk? jet precession? Cyclical magnetic dynamo reversal in disk? …?

Extra Slides

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.

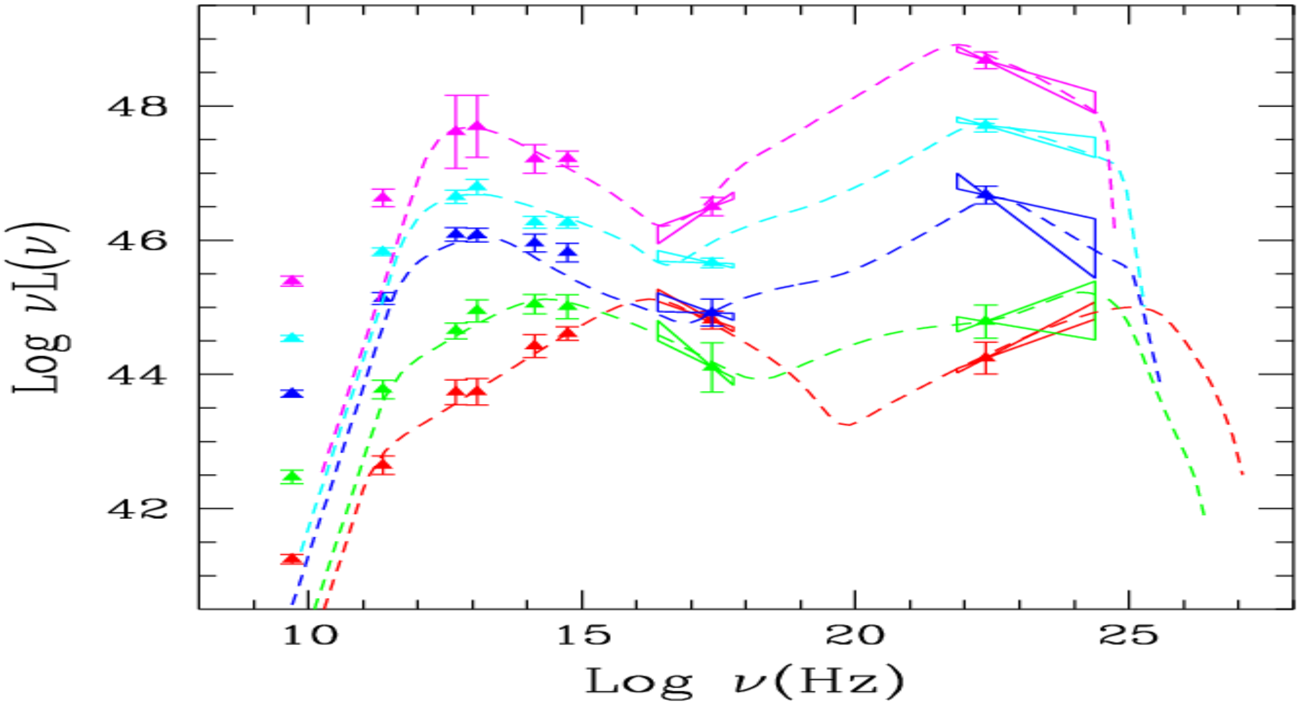
This makes initial screening difficult and necessitates large counterpart search programs



See: Ackermann et al. 2011; arXiV 1108.1202

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

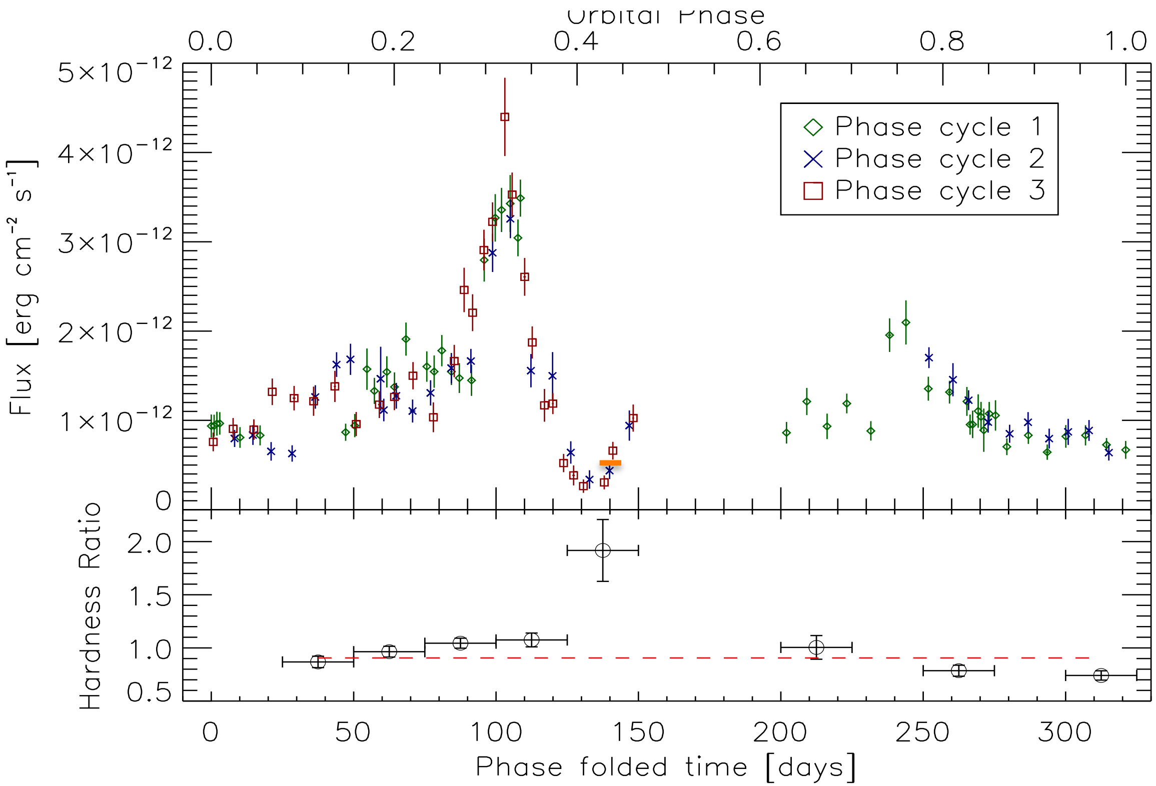


Fossati et al. 1998, Ghisselini et al. 1998, Abdo et al. 2010

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

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

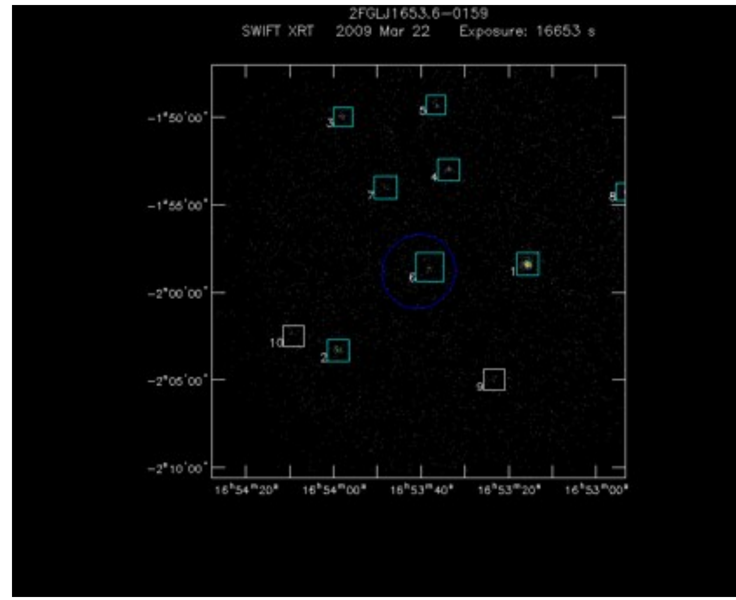
These were targeted with ~4 ksec observations (sensitive to $\sim 1 \times 10^{-13}$ erg cm^{-2} s^{-1})

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

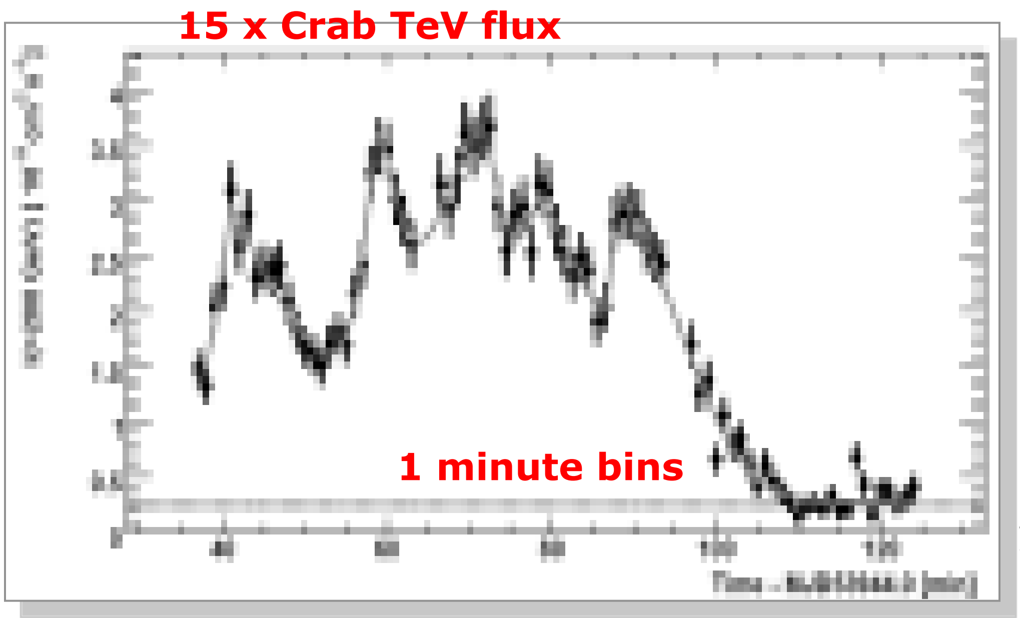
(a parameterization/discrimination study led by P. Saz Parkinson)

- 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**

PKS 2155-304: Huge Flares & Fast Variability



Costamante et al. 2007, Aharonian et al. 2007

(see also Foschini et al. 2007)

- A previously low flux (~0.05 Crab) source
- On 2006 Jul 27, HESS observes:
    - >10 Crab flux!!!
    - < 5minute doubling time!!!
- During huge TeV flares, the X-ray flux was also variable, but to a significantly lower degree
    - ~2x flux variability
    - Swift XRT data shows:

      little/no shifting of 1st E_{peak}!!!

Do these timescales eliminate reconnection in subjet models? (see e.g. Narayan & Piran 2012, Lyutikov et al….)

Are standard blob/shock in jet models capable of producing minimal synchrotron variability while producing massive fast TeV variability?

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): 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 ….