Why Your Favorite Gamma-ray Pet Needs X-rays: Observations and Strategies

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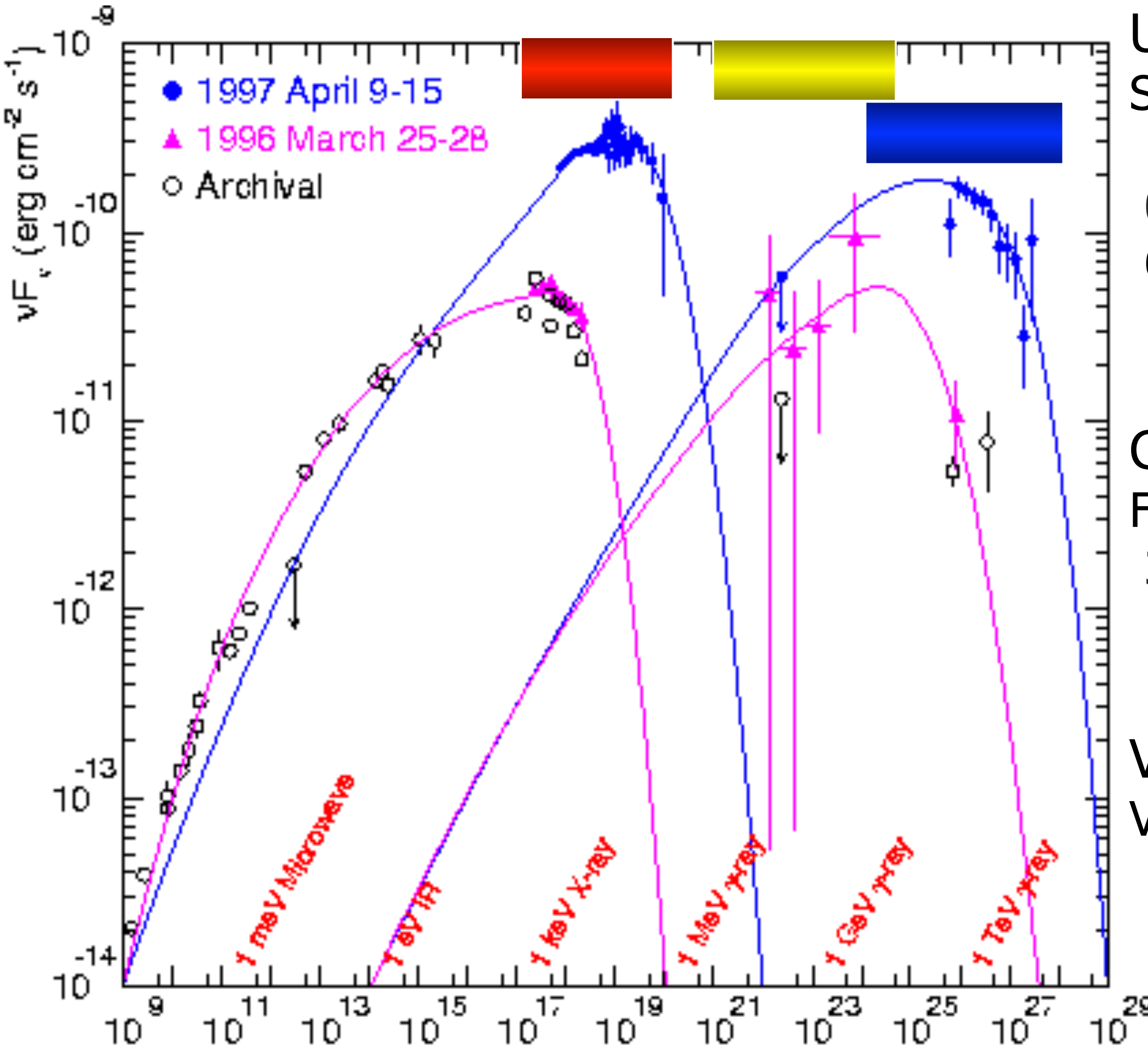
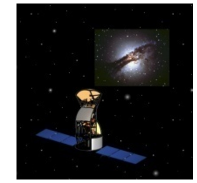
Importance of Broadband Simultaneous Coverage



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

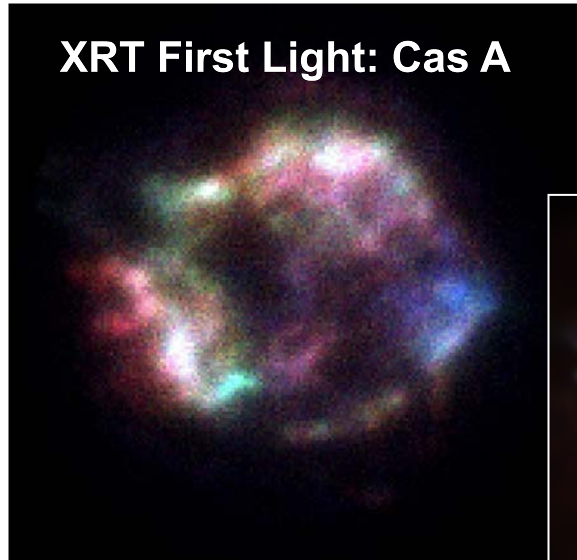


Gamma ray:
Fermi, AGILE,...
30 MeV – 300 GeV
all sky

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

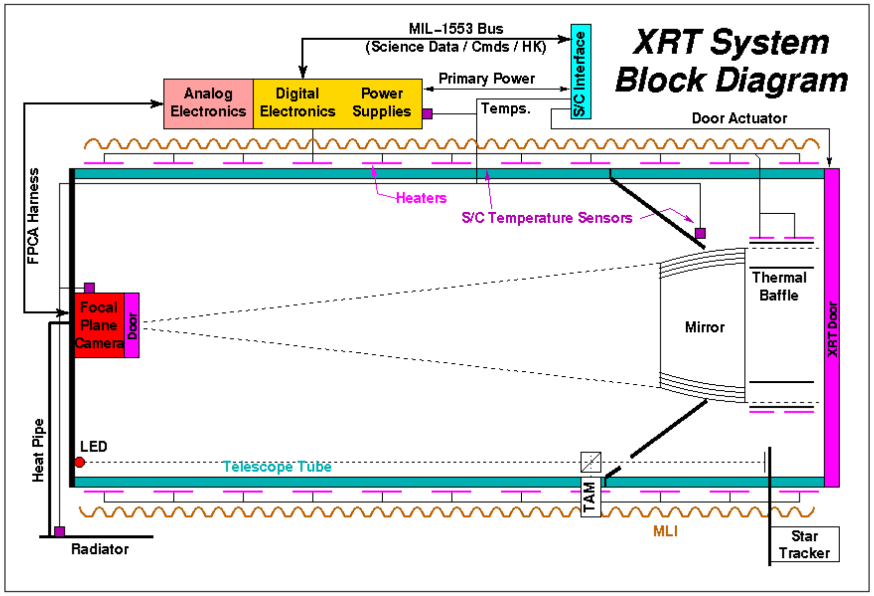
The Swift Observatory

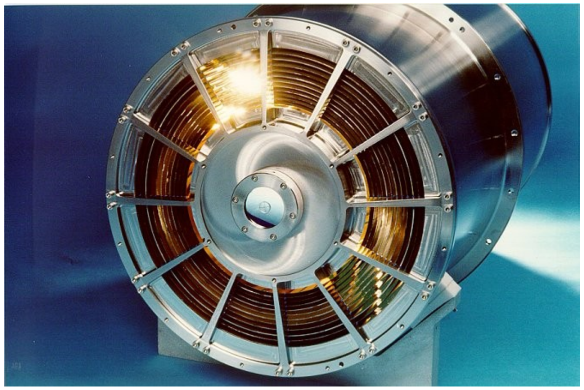
- •BAT First Light: 3 December 2004
- •XRT First Light: 11 December 2004

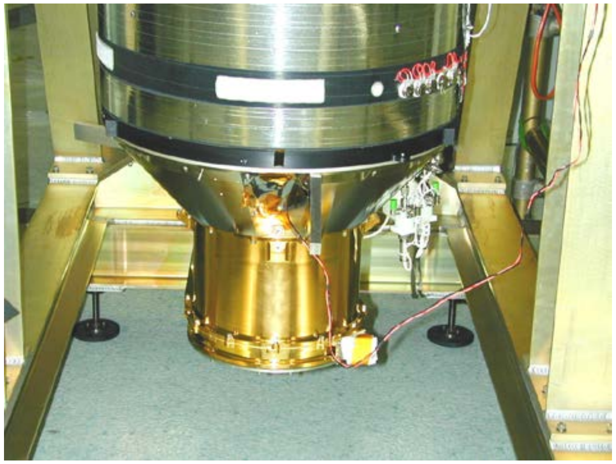


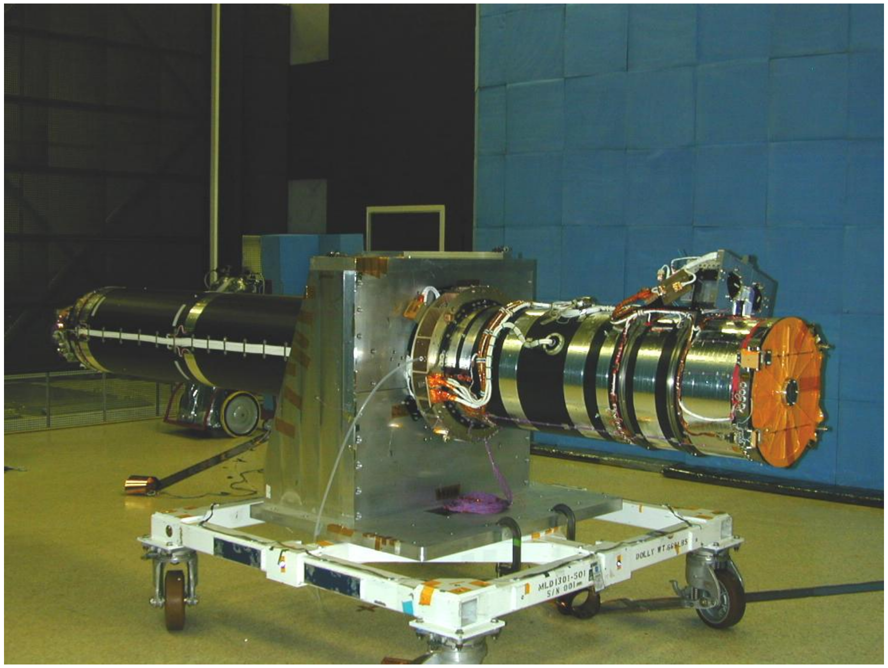
- •First BAT Burst: 17 December 2004
- •First XRT Afterglow: 23 December 2004
- •UVOT First Light: 12 January 2005
- •Data public since 5 April 2005

The X-Ray Telescope

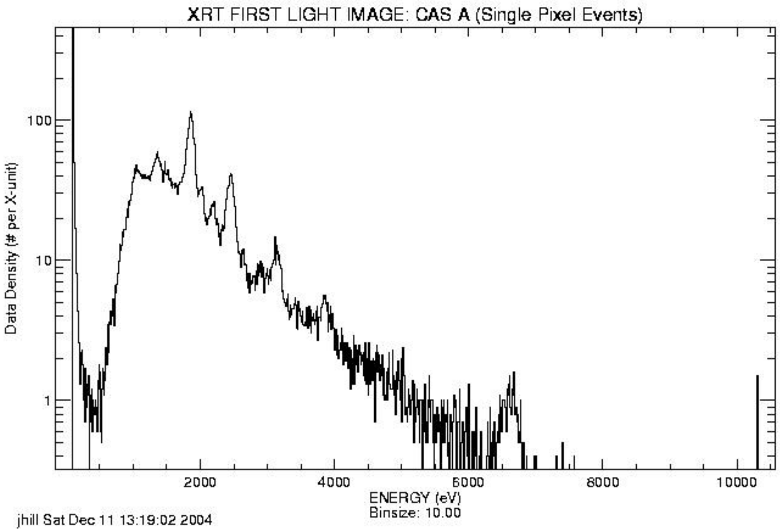




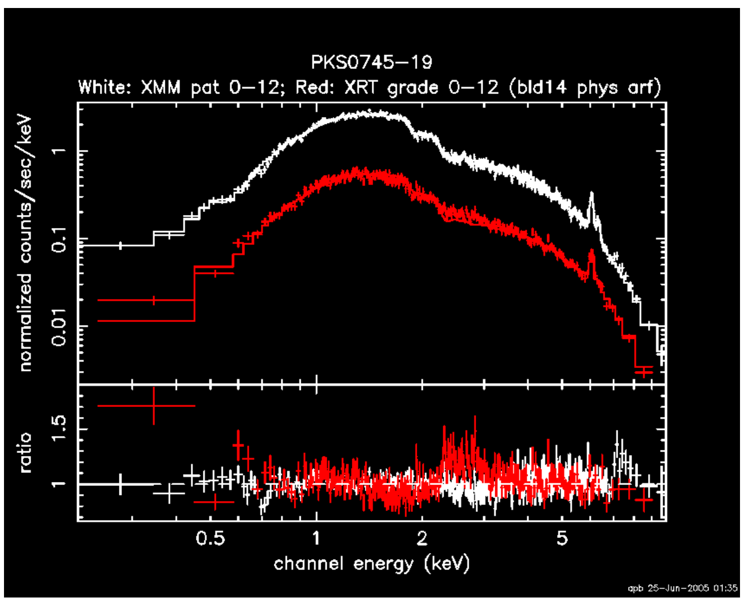




Swift X-Ray Telescope



Spectroscopy
(example from first light on Cas A)



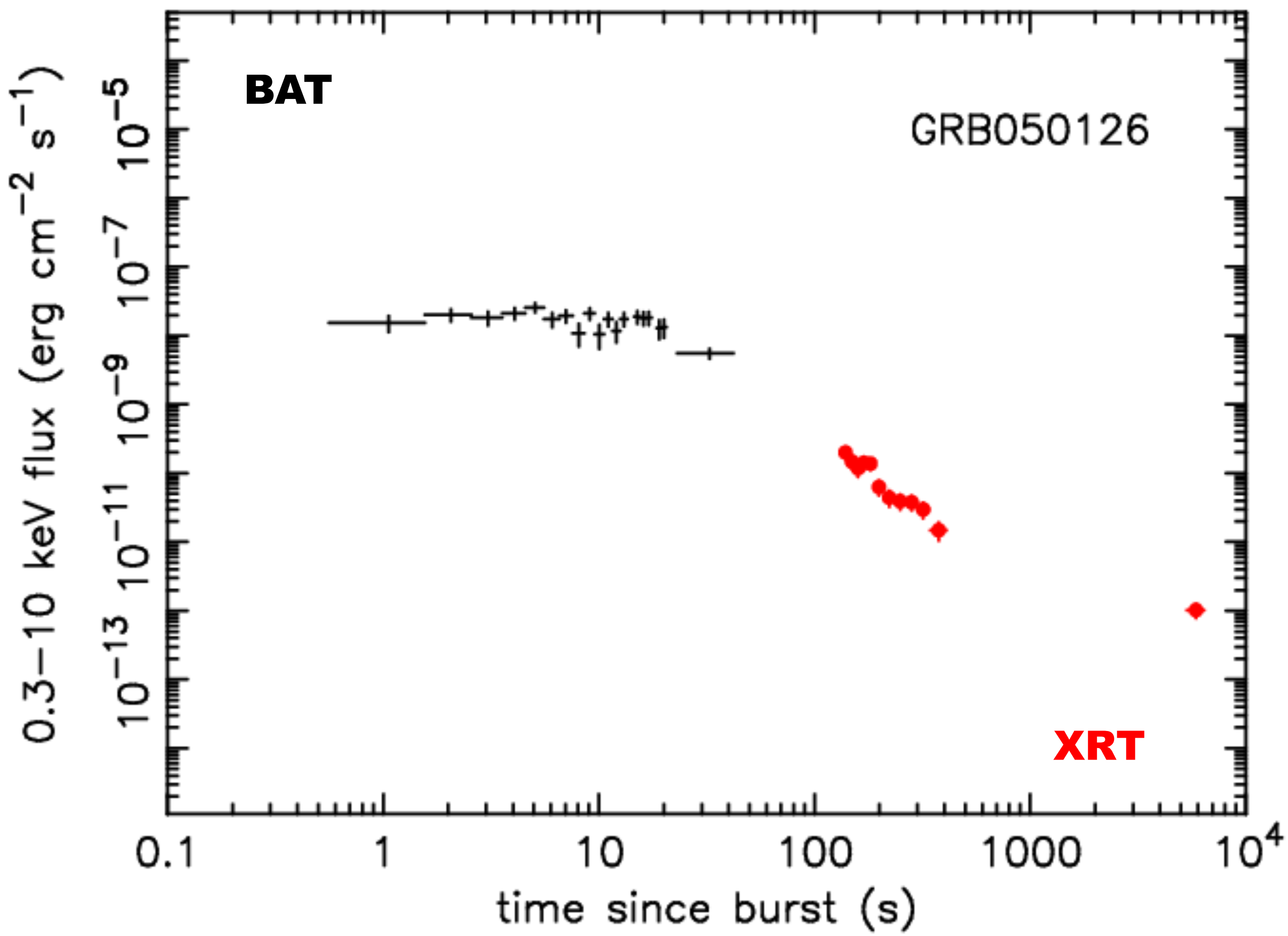
Flux limit ~10^{-15} erg/cm2/s

(Swift can see typical TeV sources in seconds to minutes and obtain time resolved spectra in most ~1 ksec blazar observations)

Example AGN spectrum

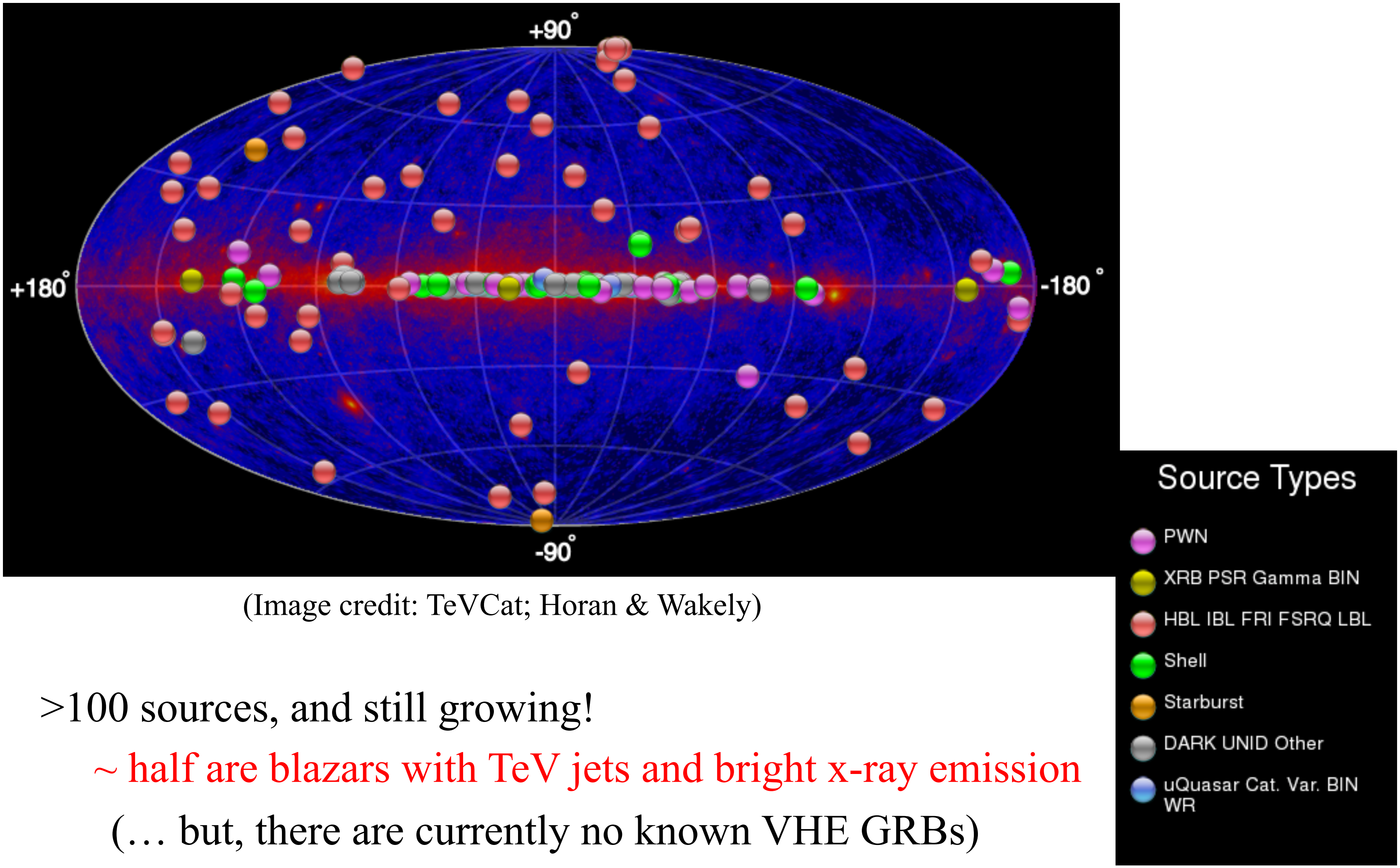
==> We can see Fe Lines
(when they are there) !!!

Swift Lightcurves – the Movie



Paul O' Brien / UL

The TeV Sky Now



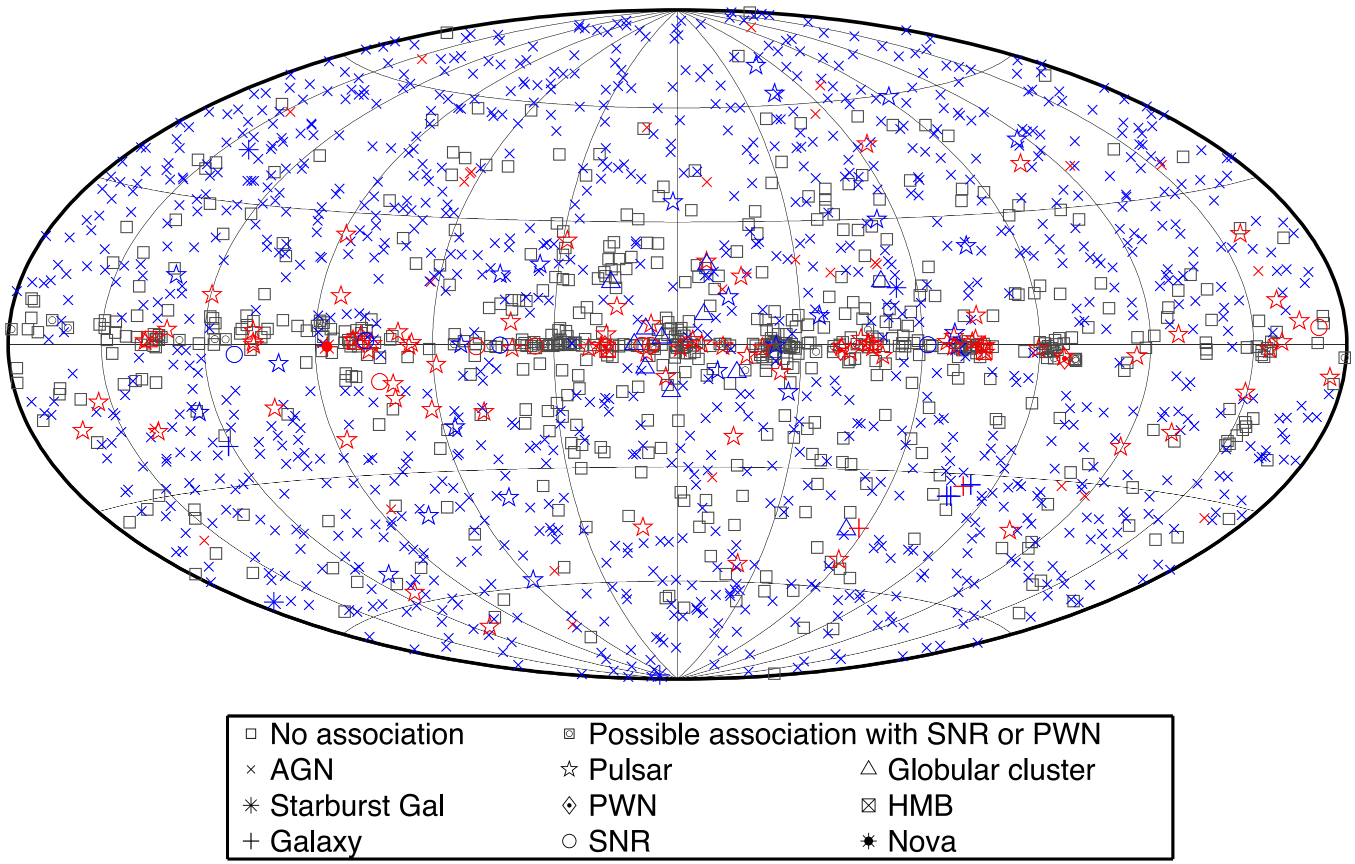
(Image credit: TeVCat; Horan & Wakely)

>100 sources, and still growing!

~ half are blazars with TeV jets and bright x-ray emission

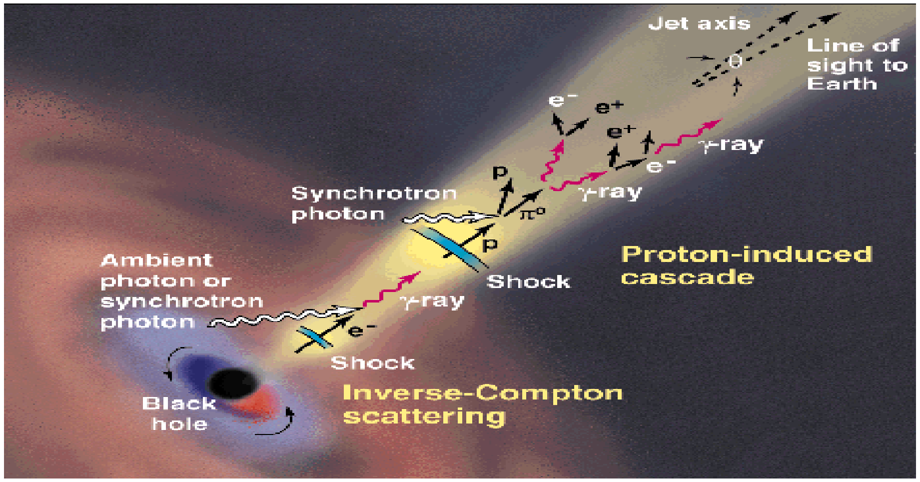
(… but, there are currently no known VHE GRBs)

GeV Gamma-ray Sources (Fermi 2FGL)



The Fermi point source catalog is also dominated by blazars.

Why Study the extreme TeV sources with X-rays?

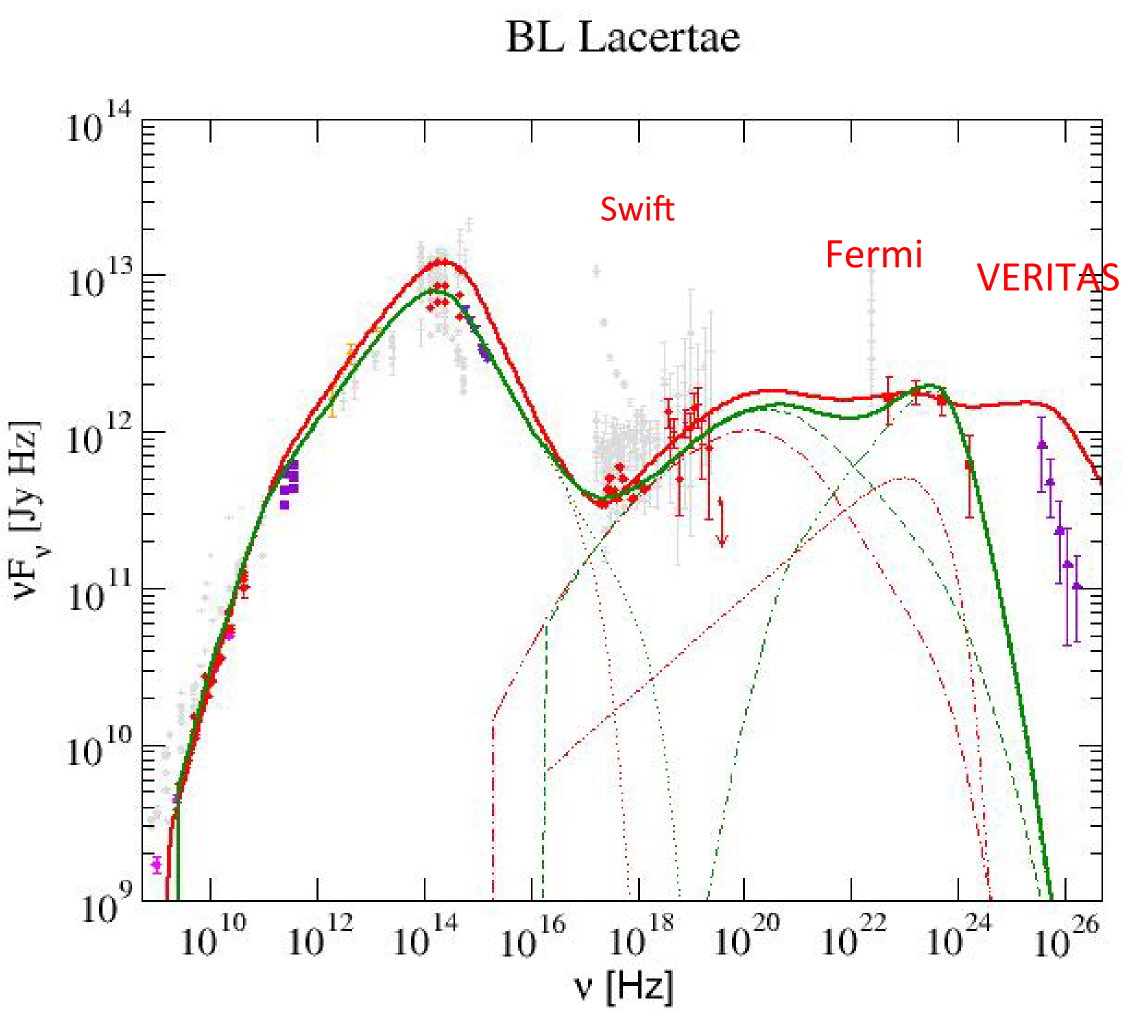


- ***Jets typically produce variable synchrotron emission in X-ray band. This is a required input for modeling the higher energy emission.***

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 Simultaneous Coverage



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

15 keV - 150 keV
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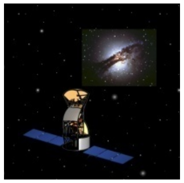


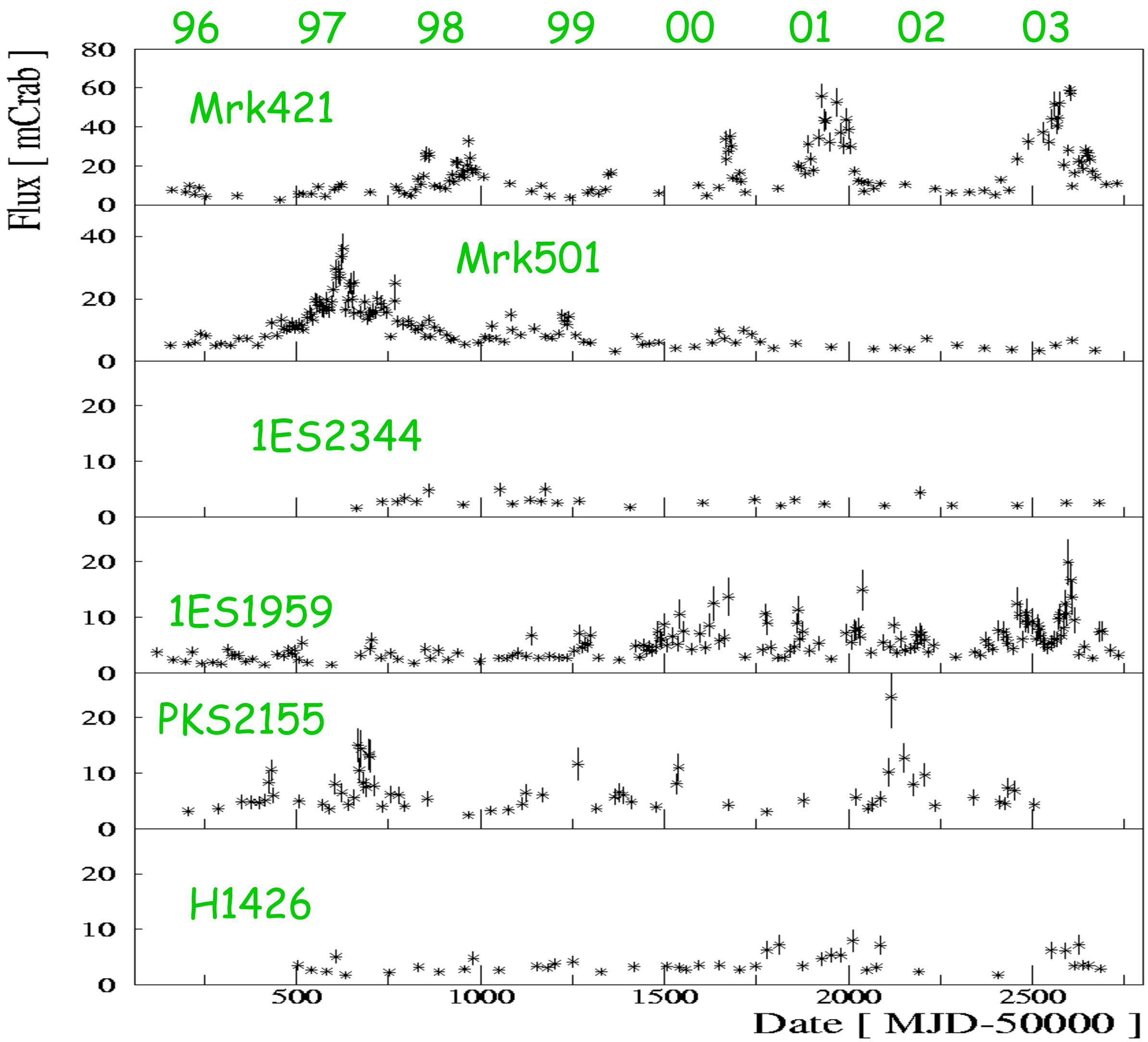
Gamma ray: Fermi, AGILE,...

30 MeV – 300 GeV
all sky

VHE: VERITAS, HESS, MAGIC, ...

100 GeV – 50 TeV

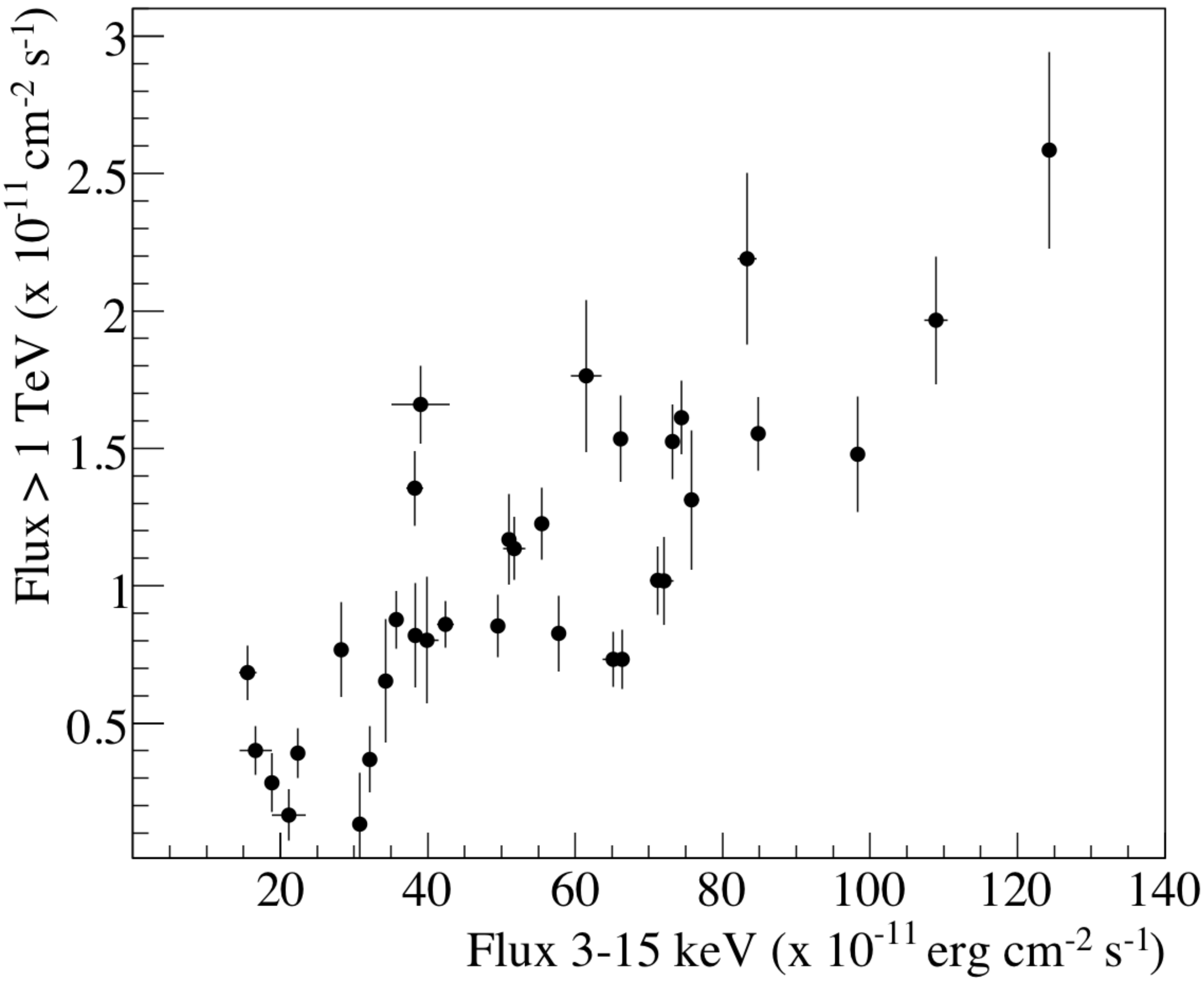
TeV Blazars - Myriad Variability Timescales



From RXTE-ASM x-ray monitoring (2-12 keV)

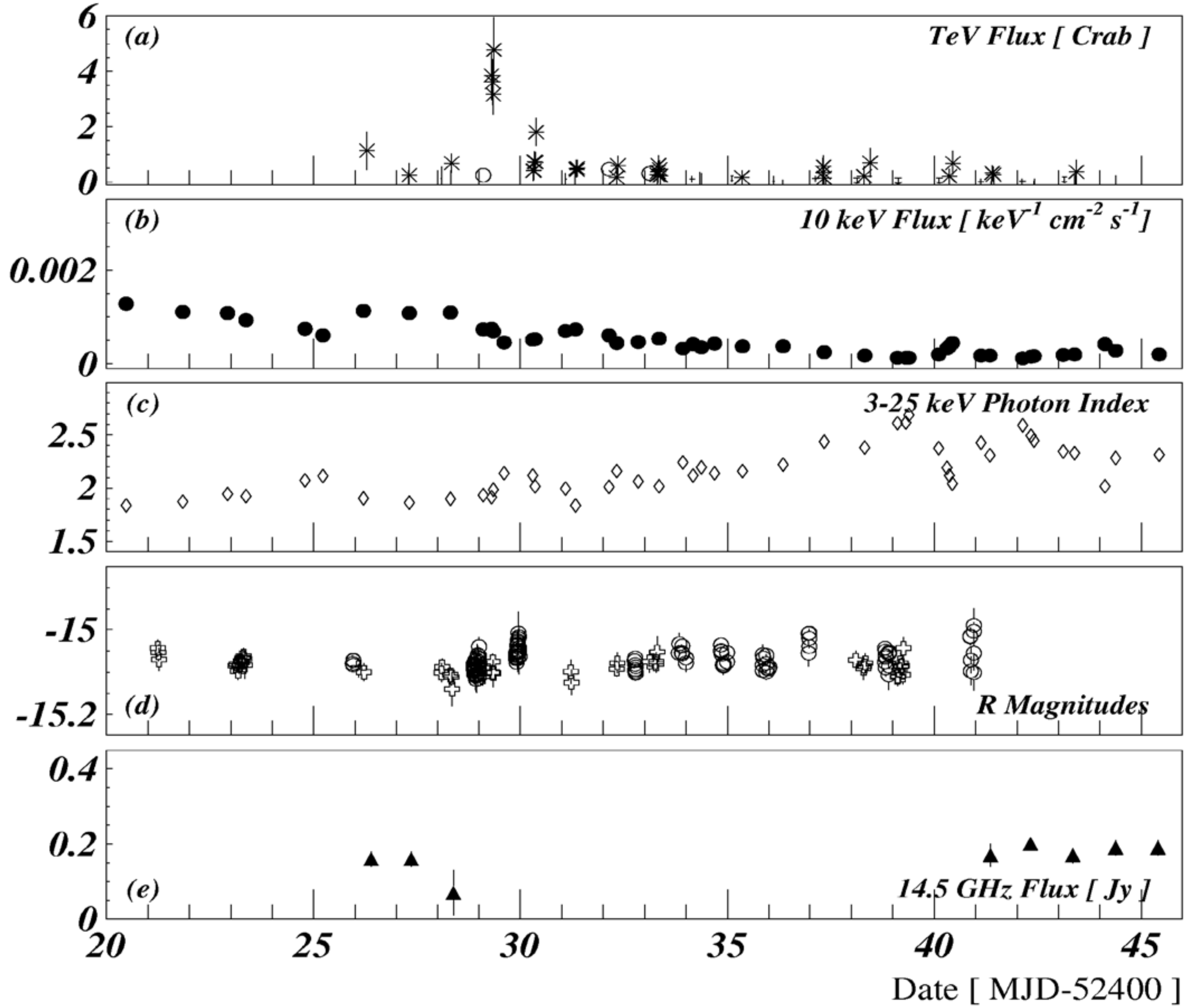
Krawczynski et al. 2003

Mrk 421: X-ray/TeV Correlation



Grube et al 2007

1ES1959: Overall Lightcurves & Orphan Flare



Campaigns

Simultaneous (or at least contemporaneous) data are critical. Otherwise, SEDs are of very limited use and correlations studies look like scatter plots.

→ Plan campaigns to allow coordination, for both monitoring and ToOs

This can be done with the following process:
- find the broad time regions for your observations with the GeV/TeV instrument
- Submit the X-ray observation request (e.g. Swift-XRT) with this time window specified
- Refine the observing plan to match the planned X-ray times

This last step won't be necessary for wider field instruments like HAWC and LAT, but the top two steps should be done.

(You'd be amazed how often these simple steps are not attempted.)

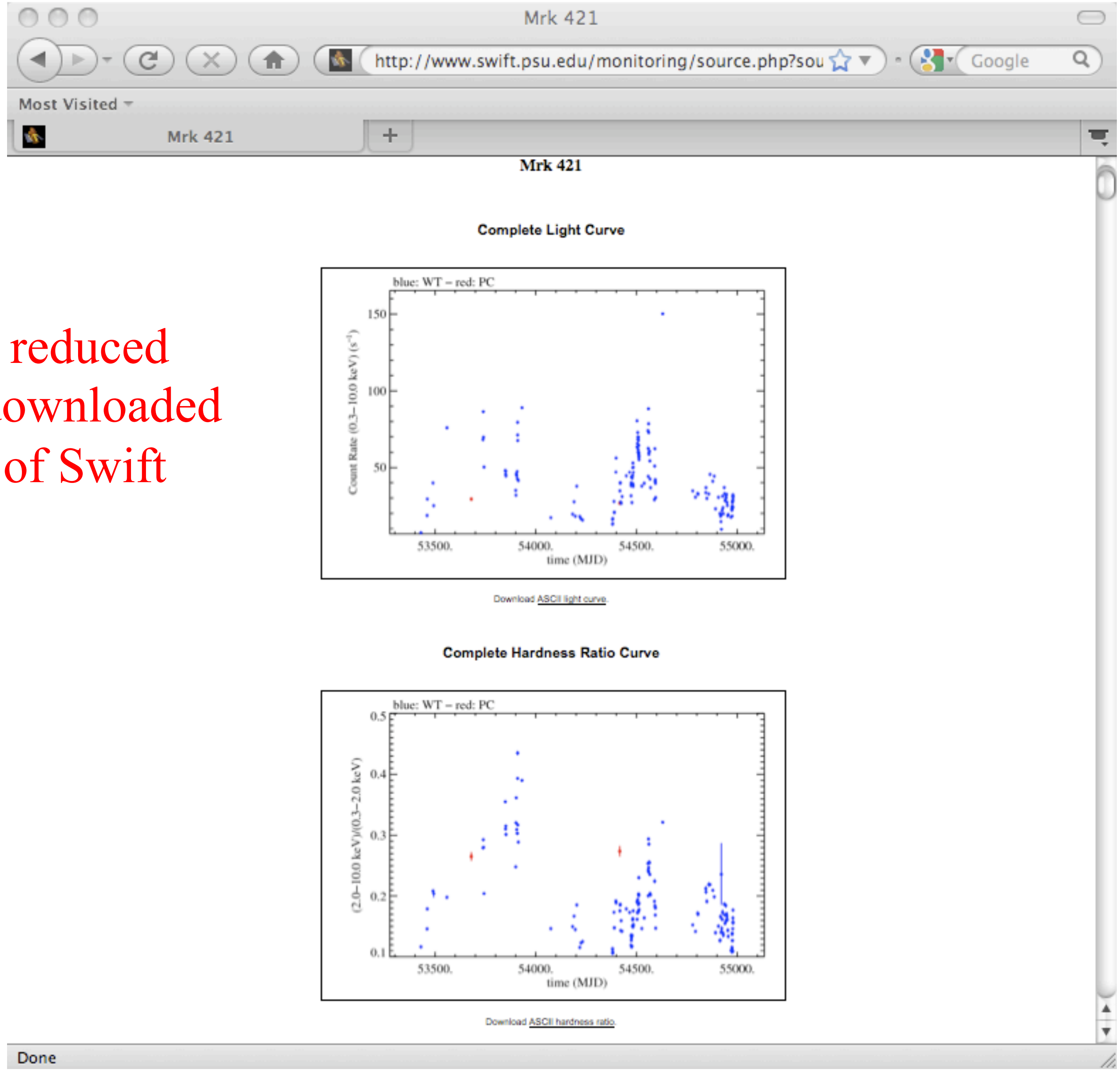
Swift Monitoring of Fermi "Sources of Interest" and other GeV-TeV sources

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

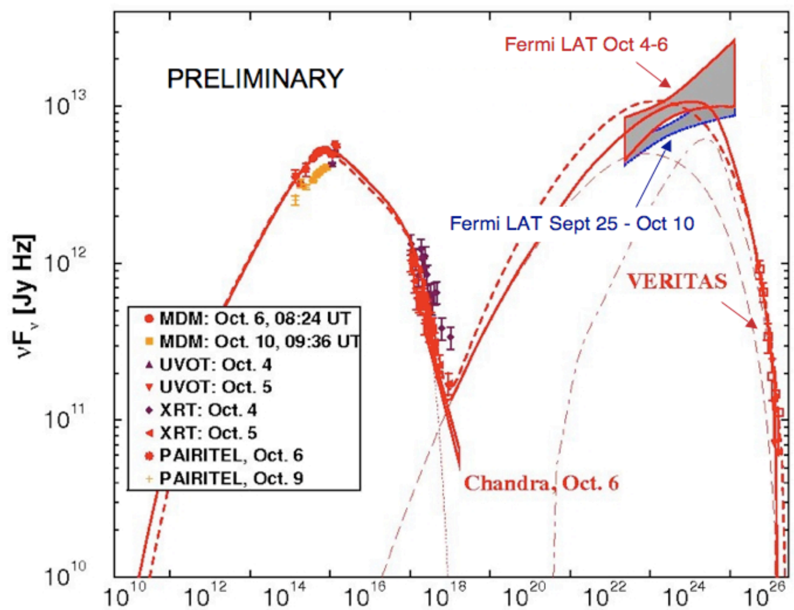
All plots and reduced data can be downloaded within hours of Swift observations



A Couple Examples

3C 66A (IBL/LBL)

- Swift, MDM, Fermi, & VERITAS (time averaged) spectral data during high state on Oct 4-6
- Due to broadband coverage, spectrum is tightly constrained
- ***Model including an external Compton component favored***



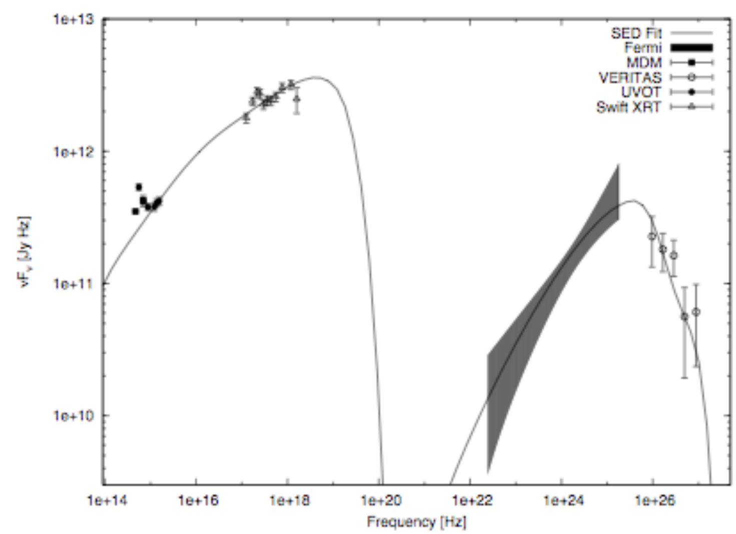
Dashed line: pure SSC, solid line: SSC+EC

See: Reyes et al. 2009, ICRC proc.

Benbow et al. 2010

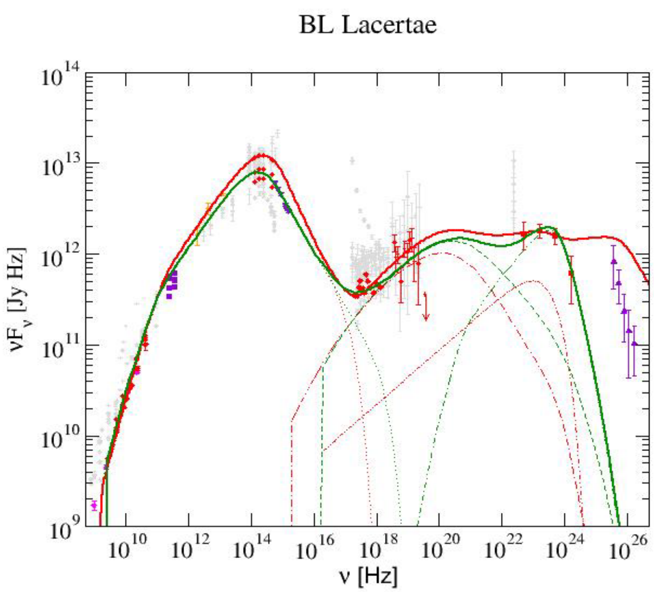
RGB J0710+591 (HBL)

- New VERITAS detection with contemporaneous Swift & Fermi data
- SSC model fits data nicely, and EC is allowed, but does not improve fit. Model of Chiang & Boettcher (2002) is used with TeV photon absorption model of Franceschini et al. (2008).
- Low, sub-equipartition magnetic field is implied by the fit (~10 mG), with remarkably hard electron injection spectrum (q ~ 1.5).

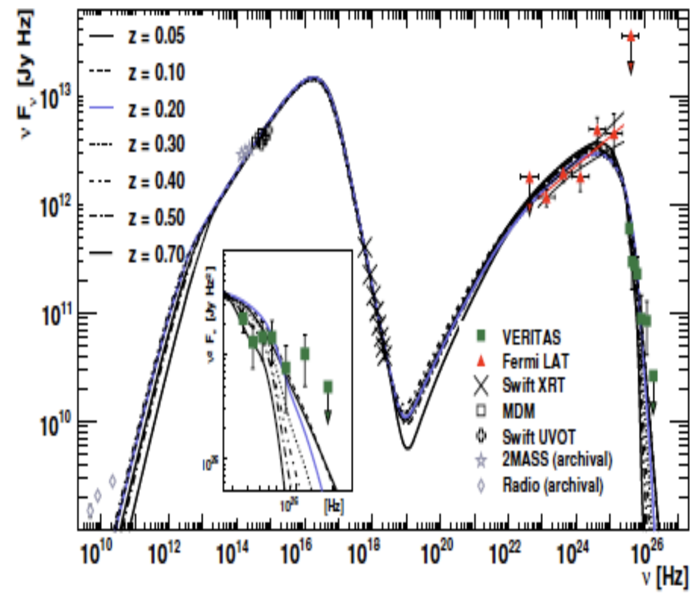


Fortin, Perkins, et al. 2010 , Acciari et al. 2010

Two Blazar Campaigns with critical x-ray and multiwavelength data

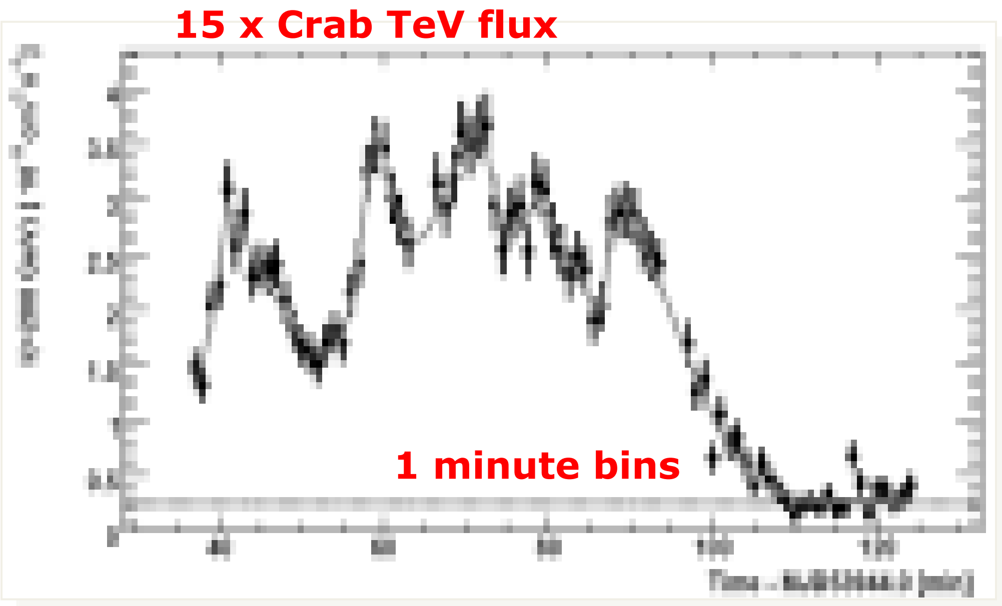


The SED of BL Lacertae made from quasi-simultaneous data from Swift-XRT, Swift-UVOT, Fermi-LAT, VERITAS, and others. The leptonic model (solid green curve) does not provide a good fit, while a hadronic model (solid red curve) provides some improvement, but overproduces the TeV emission (Boettcher et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

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}!!!

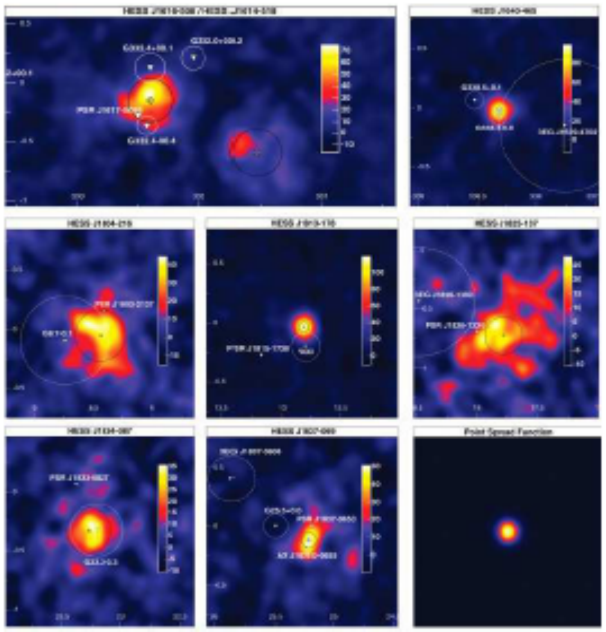
Do these timescales eliminate reconnection in subjet models? (see e.g. Narayan & Piran 2012, Lyutikov et al.…)

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

What Has Been Learned about blazars?

- Very short TeV emission timescales (~3 minute doubling times)
  ➔ small regions for TeV gamma-ray acceleration
- One flare is not the same as another flare. Some TeV flares have correlated X-ray emission, while others do not (and vice versa).
  - ➔ Simple one-component SSC does not explain all emission, while it seems to work for some cases
  - ➔ Cooling electrons in the jet are certainly related to the TeV emission at some times, but the coupling may be either directly or indirectly
  - ➔ ***Some SEDs can not be fit by expected models***
- The TeV blazar zoo contains more than just HBLs (LBLs and FSRQs), and some of these may have environments more favorable to hadron acceleration
- Photon fields external to the jet are required for some blazar models
- Extragalactic IR photon field is less dense than originally expected
- *Much work to be done by applying more robust and diverse models and much work to be done to obtain full contemporaneous multiwavelength coverage for blazar flares!*

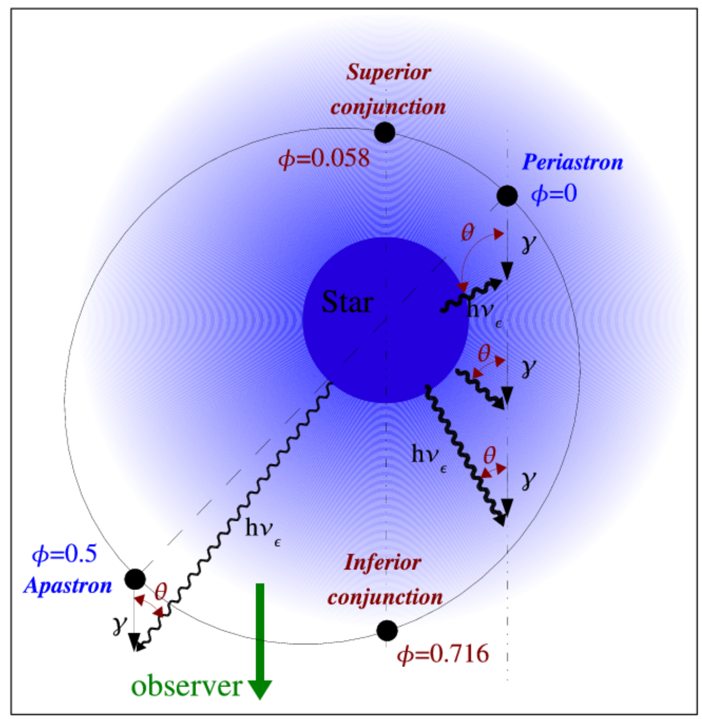
Some other Swift/GeV/TeV Programs on Astroparticle accelerators



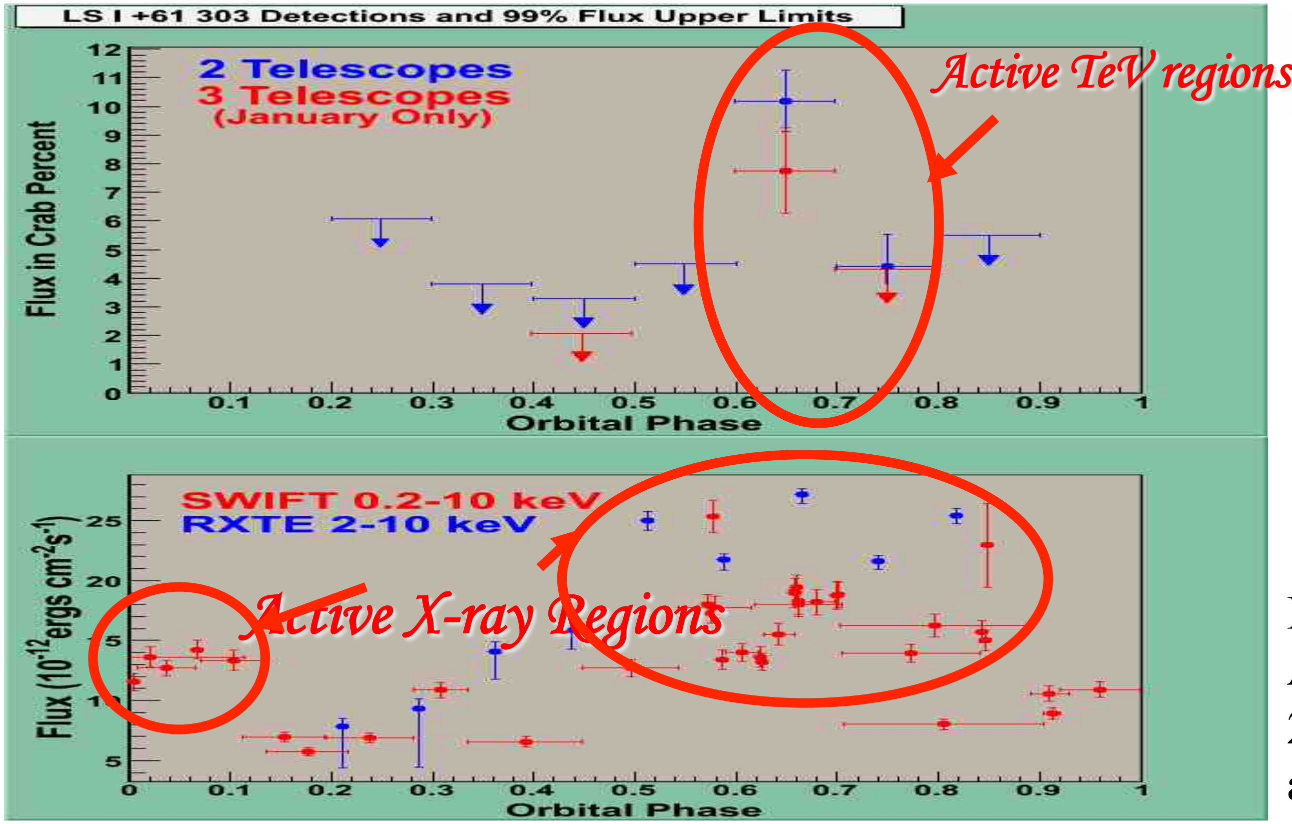
Selected TeV UnID sources,
Aharonian et al. 2008

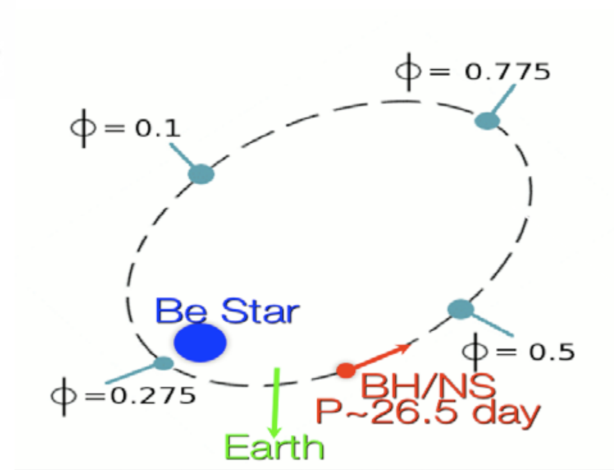
Swift is searching for counterparts **to *MeV/GeV and TeV Unassociated sources***. We have executed a program to spend nearly 1 Msec searching all Fermi unassociated sources in the first catalog, and we are now moving on to the 2nd Fermi catalog.

Swift is obtaining multi-wavelength data on ***TeV/X-ray binaries*** which may have strong particle accelerating jets and/or wind interaction shocks, e.g. LS I +61303



LSI+61303: X-ray binary (Microquasar??)



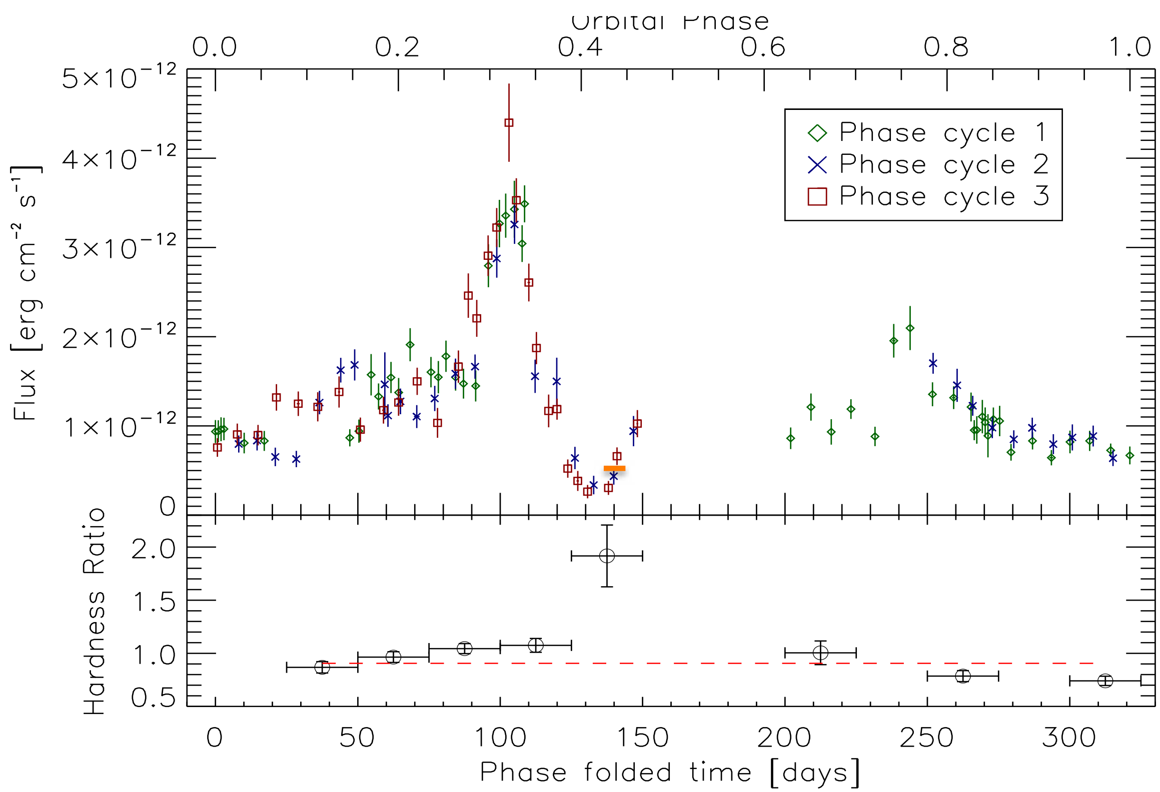


Holder, Falcone, Morris 2007; Acciari et al. 2009; Smith et al. 2007; Esposito et al. 2007; see also Aliu et al. 2013

- Variable TeV emission, particularly when measured in 2006/2007 (peaks at ~15% Crab)
- All data from 2006 to 2009:
  ~apastron (Phases 0.5-0.9), roughly 3%-4% Crab
  ~periastron (Phases 0.9-0.5) roughly 1%-2% Crab
- X-ray observations show incredibly fast flaring events (Smith et al. 2008)

HESS J0632+057 Periodicity

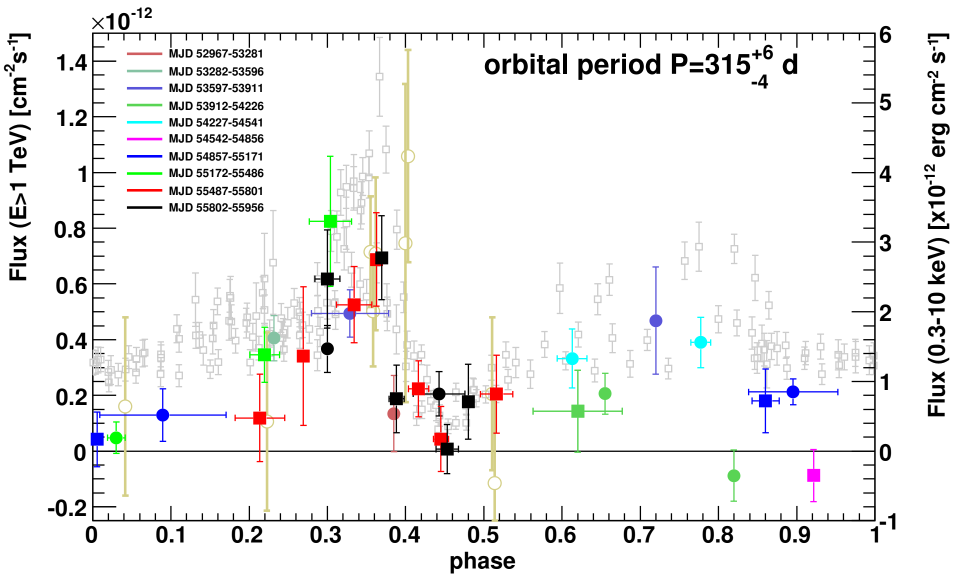
The light curve folded over the 321 day periodicity (**Bongiorno et al. 2011**).
(Different color data points are offset by 321 days, e.g. from different cycles)
Three incomplete cycles with nicely overlapping features (plus a 4th from XMM)

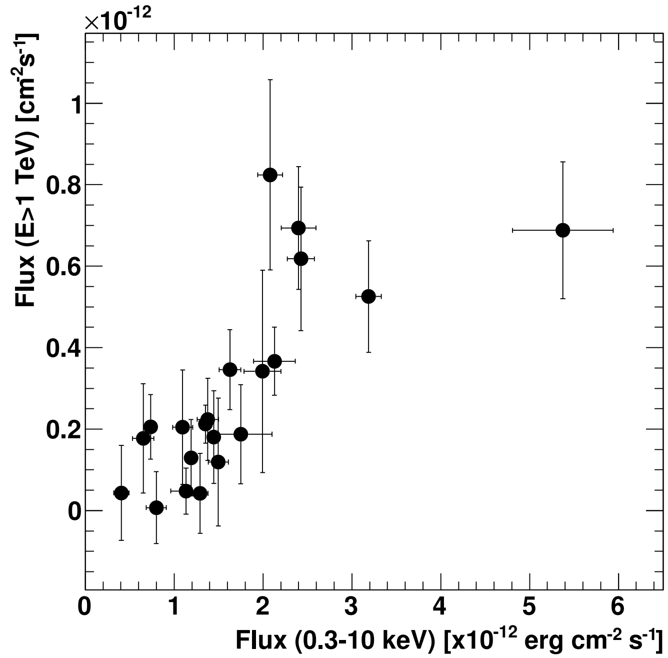


The small orange line is from an earlier observation by XMM

Note the hardening of the spectrum during "the dip."
Is this an occultation/absorption effect or is it a change in acceleration site parameters? *(probably not absorption)*

HESS J0632 X-ray / TeV correlation ?



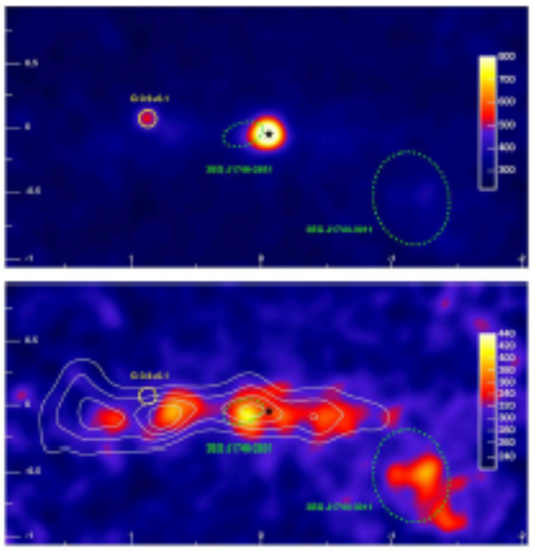


TeV data points from different epochs with VERITAS (filled square green, red, black, & blue points), HESS (filled round), and MAGIC (open round) compared to Swift XRT data from multiple epochs folded over a 315 day period (light gray open data points).

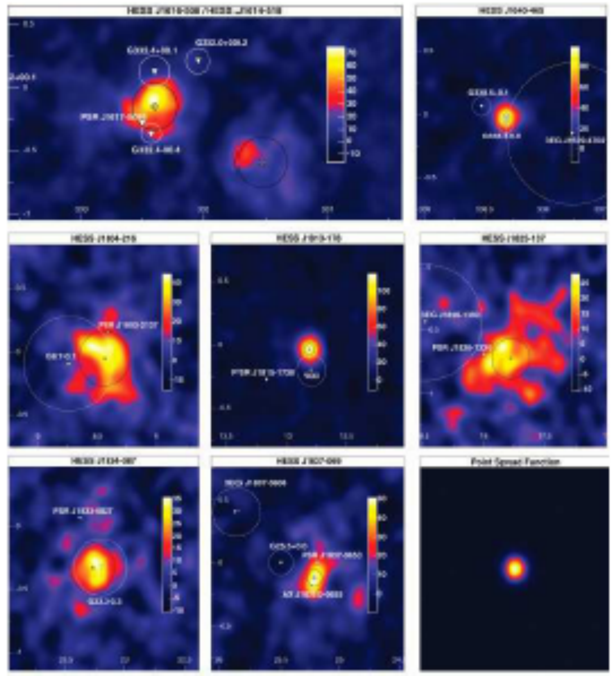
5.6 sigma evidence for correlation, but sub-orbital variability clearly present

(Aliu et al. 2014, ApJ, 780, 168)

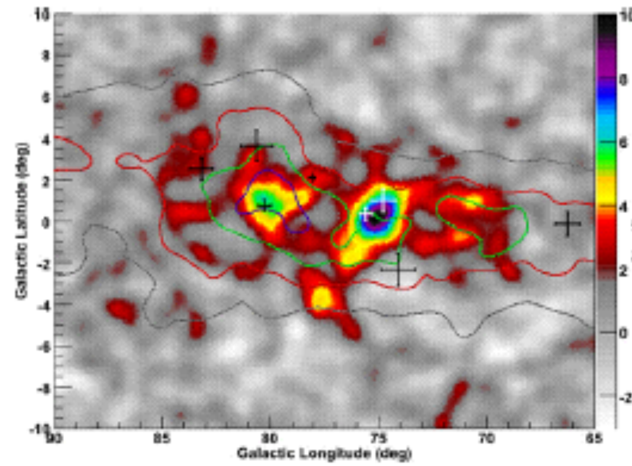
UnIdentified TeV Objects Followup



Gal Center, Aharonian et al. 2006



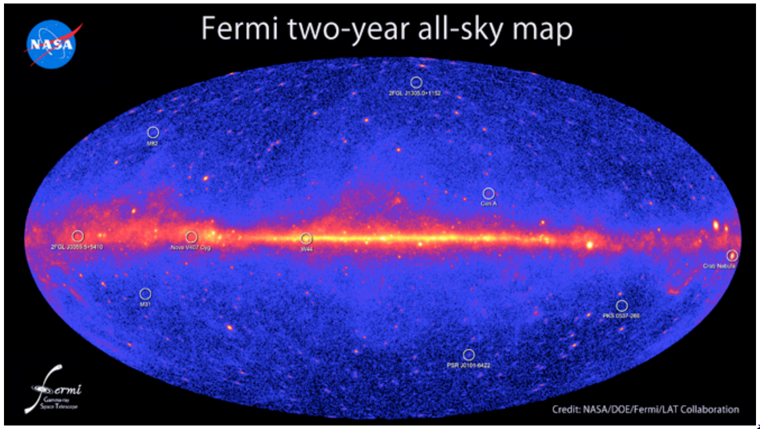
Selected TeV UnID sources, Aharonian et al. 2008



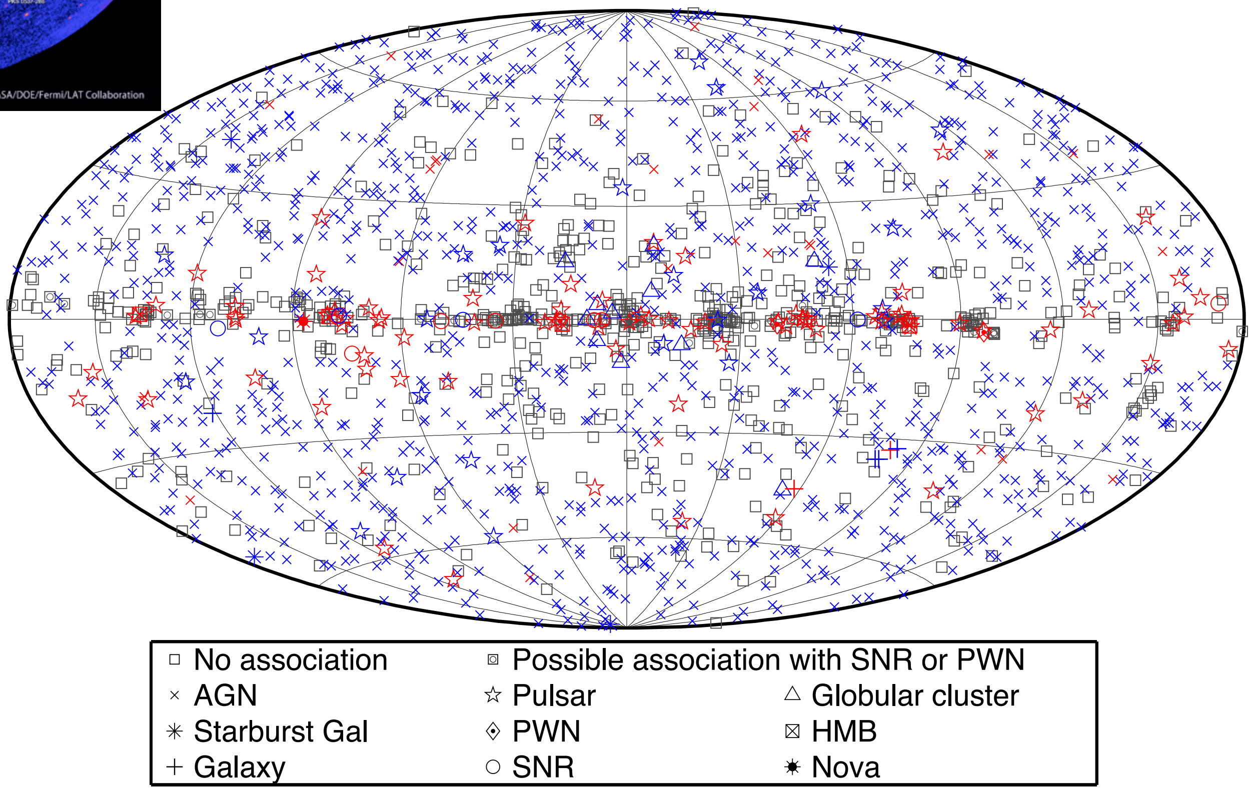
Milagro Diffuse near TeV 2032, Abdo et al 2007

- > 20 TeV objects waiting for identification
- SWIFT, Fermi, radio, and optical followup is ongoing!
- Wide open discovery space!!!

Fermi Unassociated Source Follow-up



Skymap and Gamma-ray Sources (Fermi 2FGL)



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

Fermi-LAT Unassociated Source Catalogs

Of the 1451 sources released in the first *Fermi*-LAT catalog (Abdo et al. 2010a), approximately 50% are considered unassociated with any previously known gamma-ray emitting source class, and for the 2FGL catalog (Abdo et al. 2012a), there are 1873 sources, with 577 sources considered unassociated (207 of these 2FGL unassociated sources have a 1FGL possible counterpart).

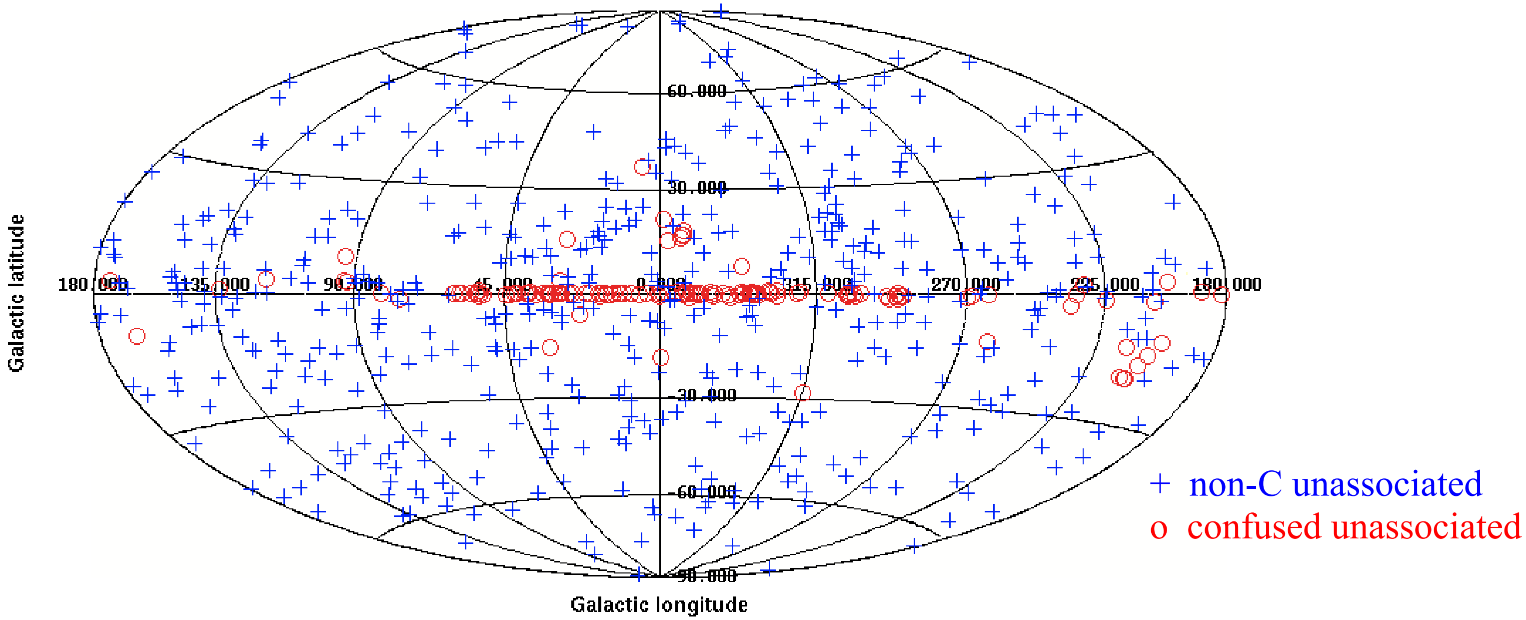
Initial Survey Sample Selection & Strategy

From the LAT 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 460 Fermi unassociated sources (including ~30 that were selected as good pulsar candidates) for follow-up with Swift

These are each being targeted with ~4 ksec observations. (For the good pulsar candidates, we look for ~10 ksec since they are likely to be fainter.)



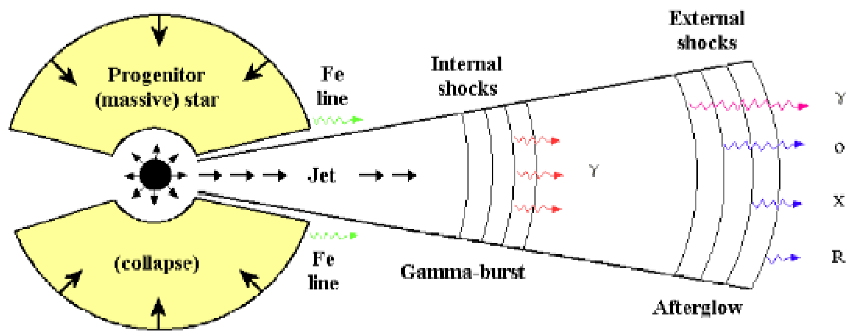
Initial Survey Results

- >430 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 within the 95% confidence region
- ~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 within the 95% confidence region

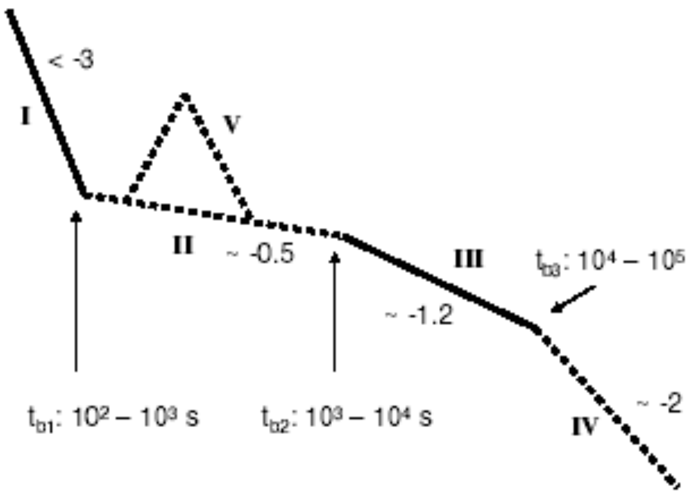
You can see the reduced results at:
http://www.swift.psu.edu/unassociated/
(automatically updated in nearly real-time)

Why Study GRBs at X-ray and Very High Energy?

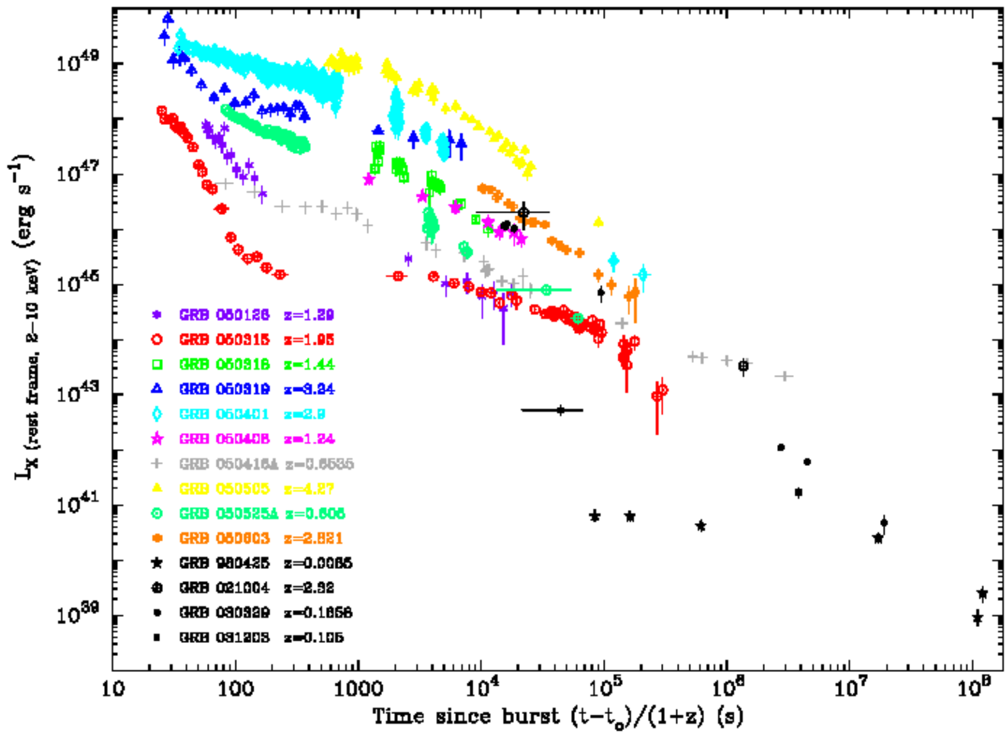


- Need to **understand acceleration mechanisms in jets**, energetics, and therefore **constrain the progenitors** and jet feeding mechanism
- Understanding progenitor then leads to an understanding of cosmology & stellar evolution required to support progenitor population
- Constrain local environment characteristics: Doppler factor, seed populations, photon density, B field, acceleration and cooling timescales, …
- Potential sources of **cosmic ray** acceleration
- Neutrinos and VHE gammas offer the possibility to distinguish between hadronic vs leptonic acceleration in GRBs; VHE gammas easier to observe

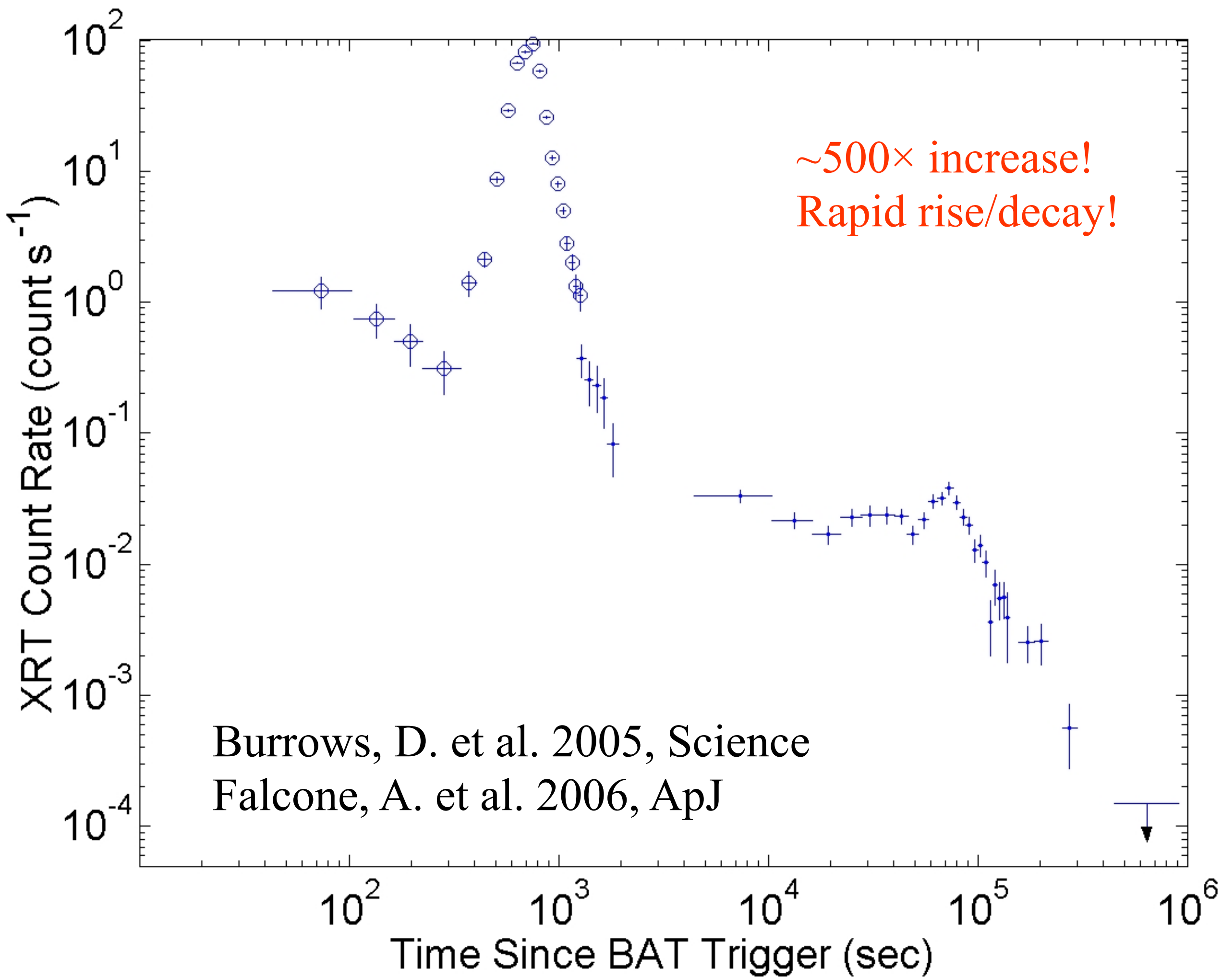
The Overall X-ray Lightcurve



Zhang et al. 2006
Nousek et al. 2006
O'Brien et al. 2006

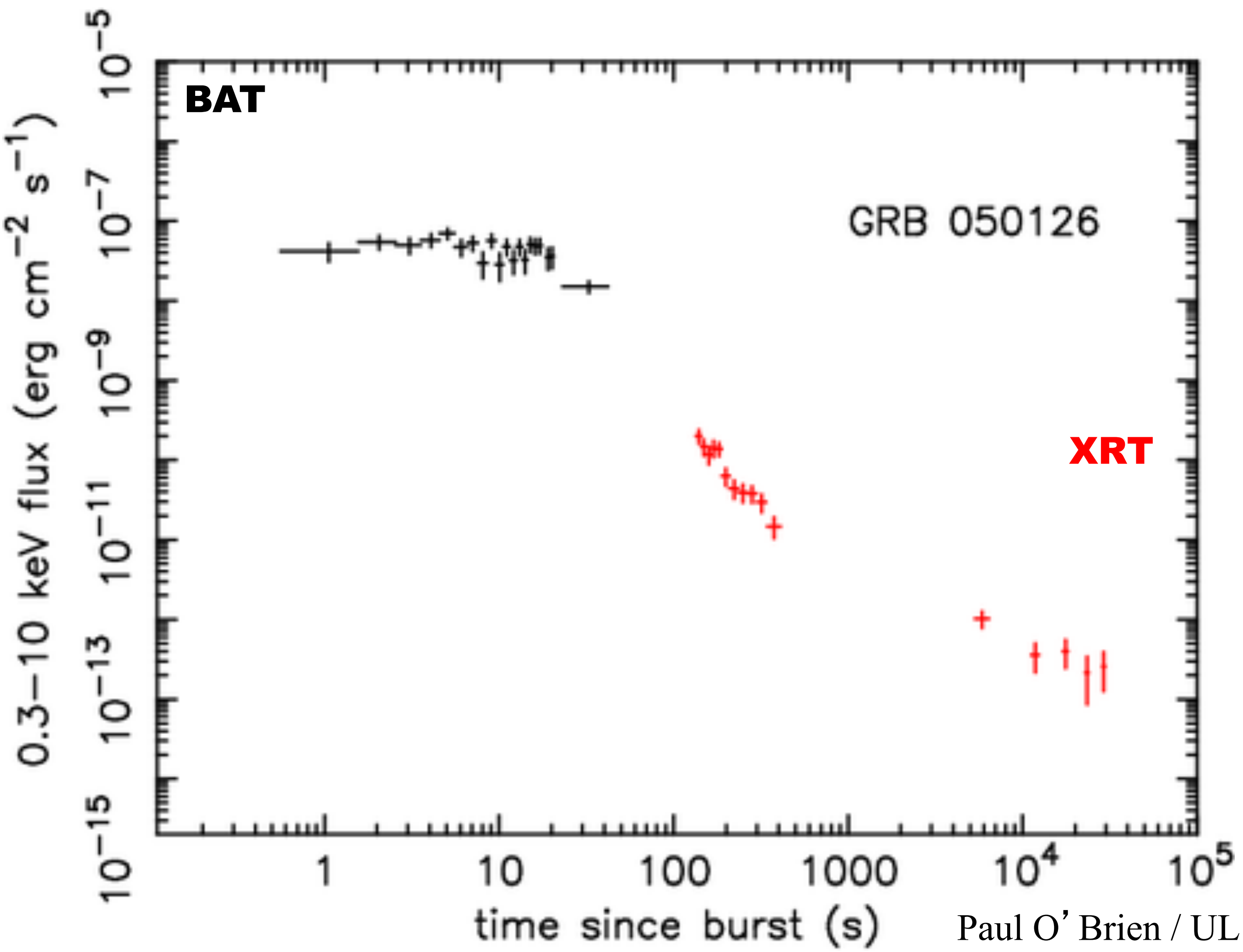


GRB 050502b: The Giant flare



- Flare fluence: $(1.1 \pm 0.05)\times10^{-6}$ erg cm^{-2}
- This is comparable to, or greater than, BAT prompt emission fluence
- Fast rise/decay ($\sim t^9$)
- Continuous power law fits underlying afterglow, with no energy injection shift evident

Swift Lightcurves – the Movie



Paul O' Brien / UL

How often do Swift GRBs have X-ray Flares?

~ 90% Swift XRT detections were prompt observations (< 300 s)

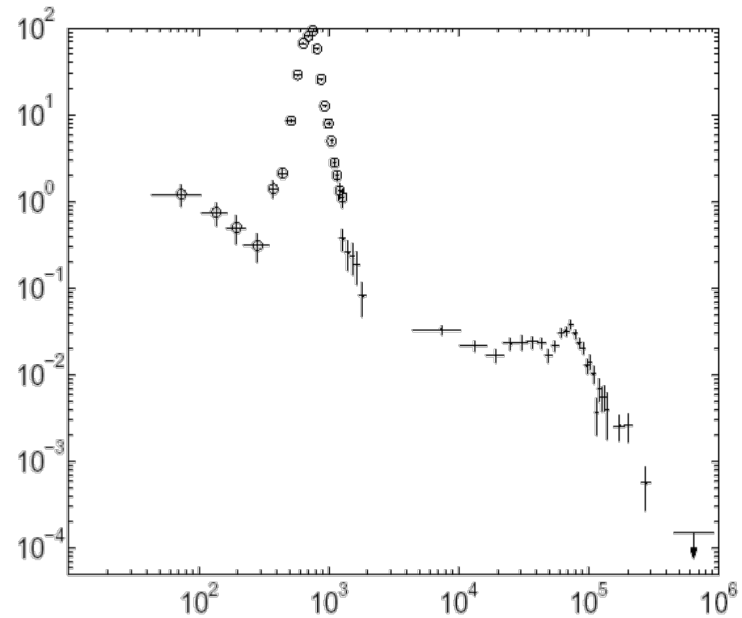
~1/3 - 1/2 of the prompt observations show flaring

-In a sample of 109 GRBs

--> 33 GRBs with at least one >3σ flare

--> 77 flares

--> 47 with >360 photons

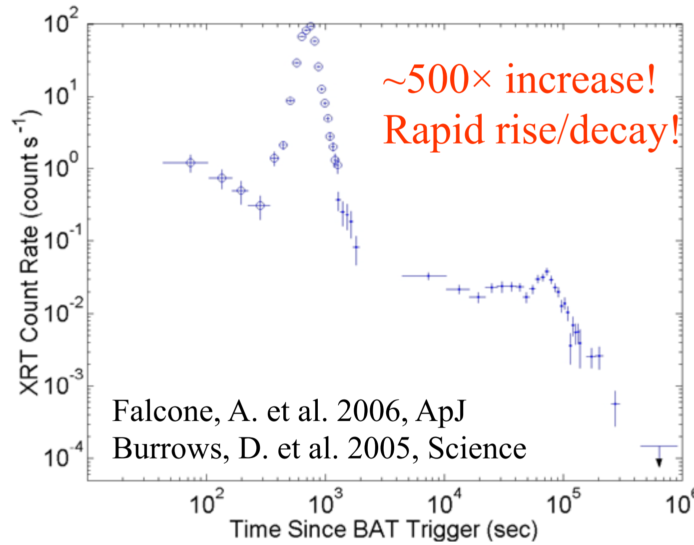


- Fit these flares and the underlying afterglow; spectral & temporal (Falcone et al. 2007, Chincarini et al. 2007)

(For similar studies, see Kocevski et al. 2007, and Butler et al. 2007)

VHE GRB Observations

- **At this time, there are no firm detections of >100 GeV photons from GRBs** (There are a few low significance potential detections at the ~3σ level; e.g. Atkins et al. 2000, 2003, and Amenomori et al. 1996)
- There are several reported upper limits (e.g. Saz-Parkinson et al. 2006, Atkins et al. 2005, Albert et al. 2007, Aharonian et al. 2009, Jarvis et al. 2010, Acciari et al. 2011)
- This is not surprising since the **predictions for emission are just barely obtainable by the most sensitive current instruments** such as VERITAS (Zhang & Meszaros 2001, Falcone et al. 2008)
- VHE photons from GRBs could be very constraining to jet parameters. In particular, it could help to determine the hadronic component of the jet and the bulk Lorentz factor of jet plasma. (Could solve mystery of UHECRs!)
- **X-ray flares may provide another mechanism** for detecting inverse Compton scattering from GRBs (Falcone et al. 2008; Wang, Lee, & Meszaros 2006)

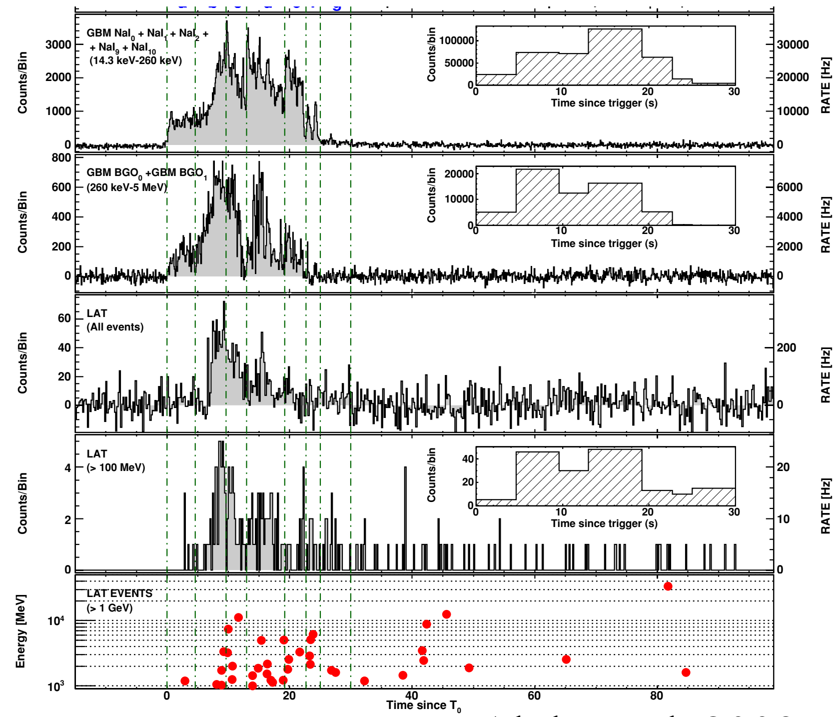


Fermi has recently achieved exciting GRB detections at GeV energies (up to ~33 GeV). VHE gamma ray telescopes, HAWC & IACTs, may open TeV discovery space for GRBs

We already know that >90 GeV photons are there:

e.g. from Fermi LAT:

	Highest γ Energy	z	Source γ Energy
GRB 090902b	~33 GeV	1.82	92 GeV
GRB 090510	~31 GeV	0.90	59 GeV
GRB 080916c	~13 GeV	4.35	70 GeV



Abdo et al. 2009

…But, we don't know:

- Flux above ~100 GeV
- Spectral shape
  - How far does synchrotron spectrum extend
  - Is there an additional VHE inverse Compton or hadronic component
- timing properties
  - Are all >10 GeV photons delayed and are >100 GeV photons delayed?
  - Is there short timescale variability?
  - Is there a major invers Compton component with a delay
  - Are these multi-GeV delayed photons actually delayed prompt emission or afterglow-related

➔ The large eff. Area (>10^4 m^2) of ground-based telescopes is needed !!!

Soft X-ray Future is uncertain

RXTE is no longer active, therefore we have lost a major wide-field/all-sky x-ray monitoring tool. The only x-ray monitoring instrument is MAXI, and it has difficulties due to (a) minimal sensitivity, and (b) systematic effects associated with ISS platform that cause flare detections to be less reliable.

Pointed instruments (Swift, Chandra, XMM, Suzaku) are aging. As long as funding holds out, Swift has potential to keep taking narrow field monitoring and ToO data for several years. Some possible future missions and mission concepts (such as ASTROSAT, eROSITA, LOFT, WFXT, ATHENA+, AXSIO, Smart-X, XCAT,…), but lots of uncertainty…

(1) Need a large, high-resolution spectral mission
(e.g. Smart-X) *Vikhlinin et al 2011 (PCOS X-ray RFI document)*

(2) Need a wide field X-ray monitor
(e.g. JANUS-XCAT, or similar) *Falcone et al. 2010*

Conclusions

- Swift, Fermi, and TeV telescopes are being coordinated, leading to unprecedented data and detailed studies of the dynamics of particle acceleration at blazar jets, X-ray/TeV binaries, GRB jets, etc.
  - New types of VHE gamma-ray blazars have been detected and modeled with m-wave spectral energy distributions.
  - Multiple emission zones with multiple seed photons and/or hadronic emission are implied, as well as small emission zones.
  - ***We now have enough data to be confused by sources that don't fit expectations!***

- HAWC has the potential to extend the energy reach of these studies and to discover new VHE jet sources. Detailed modeling and source associations will require contemporaneous x-ray data.

- Opportunities exist to work on a plethora of topics using these multiwavelength data to study known objects, and to study the exciting and enigmatic GeV/TeV unidentified sources. Some VERITAS, Fermi, HESS, and MILAGRO GeV-TeV objects are being associated with x-ray point sources using the spatial resolution of Swift, Chandra, and XMM.