VERITAS and Swift

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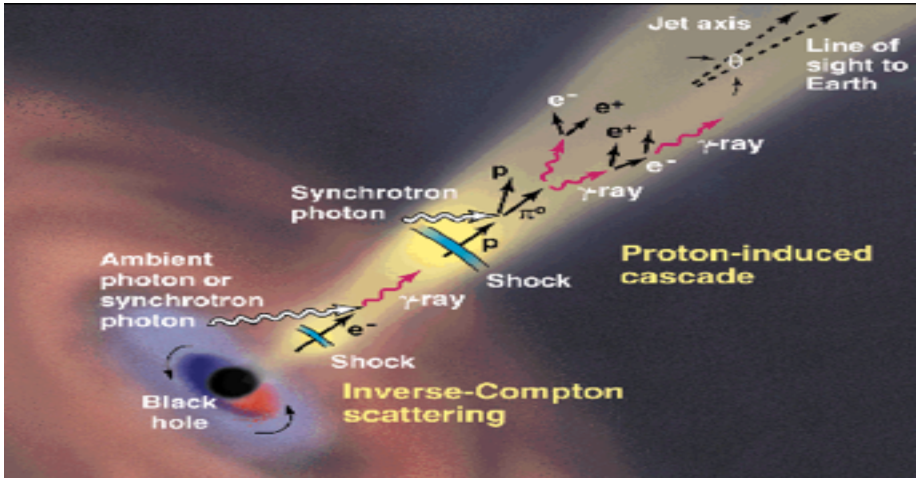
(Penn State University)

Outline

- **Why should VHE Gamma-ray & astroparticle scientists care about X-rays**
  ... and what does Swift do for us

- **Gamma-ray bursts**
- **Blazars (and EBL)**
- **Unassociated Sources**
- **Binaries**
- **Tidal Disruption Events**
- **Neutrinos, gravity waves, etc.**

Why study VHE sources with X-rays?

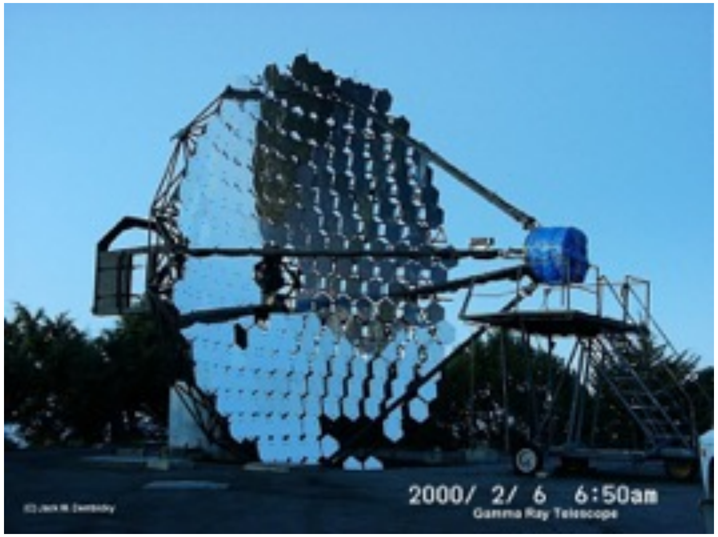


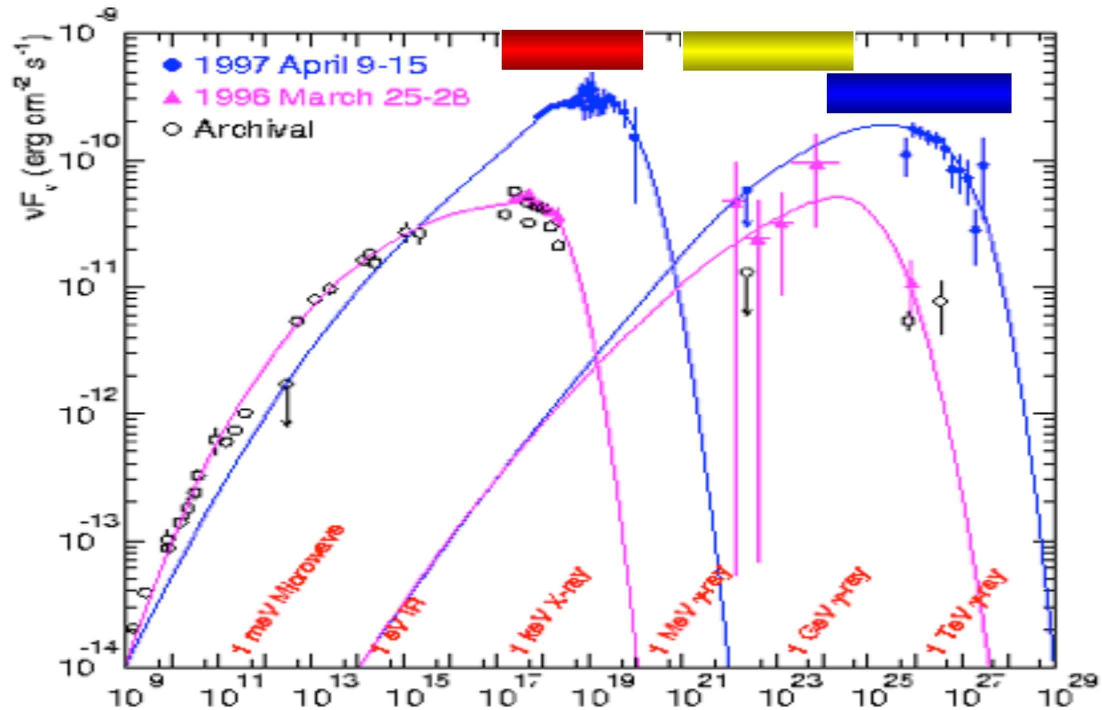
- ***Jets typically produce variable synchrotron emission in X-ray band. This is a required input for modeling the higher energy emission.***

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

Where were we before VERITAS & Swift?





Mrk501 SED taken from Catanese & Weekes 1999

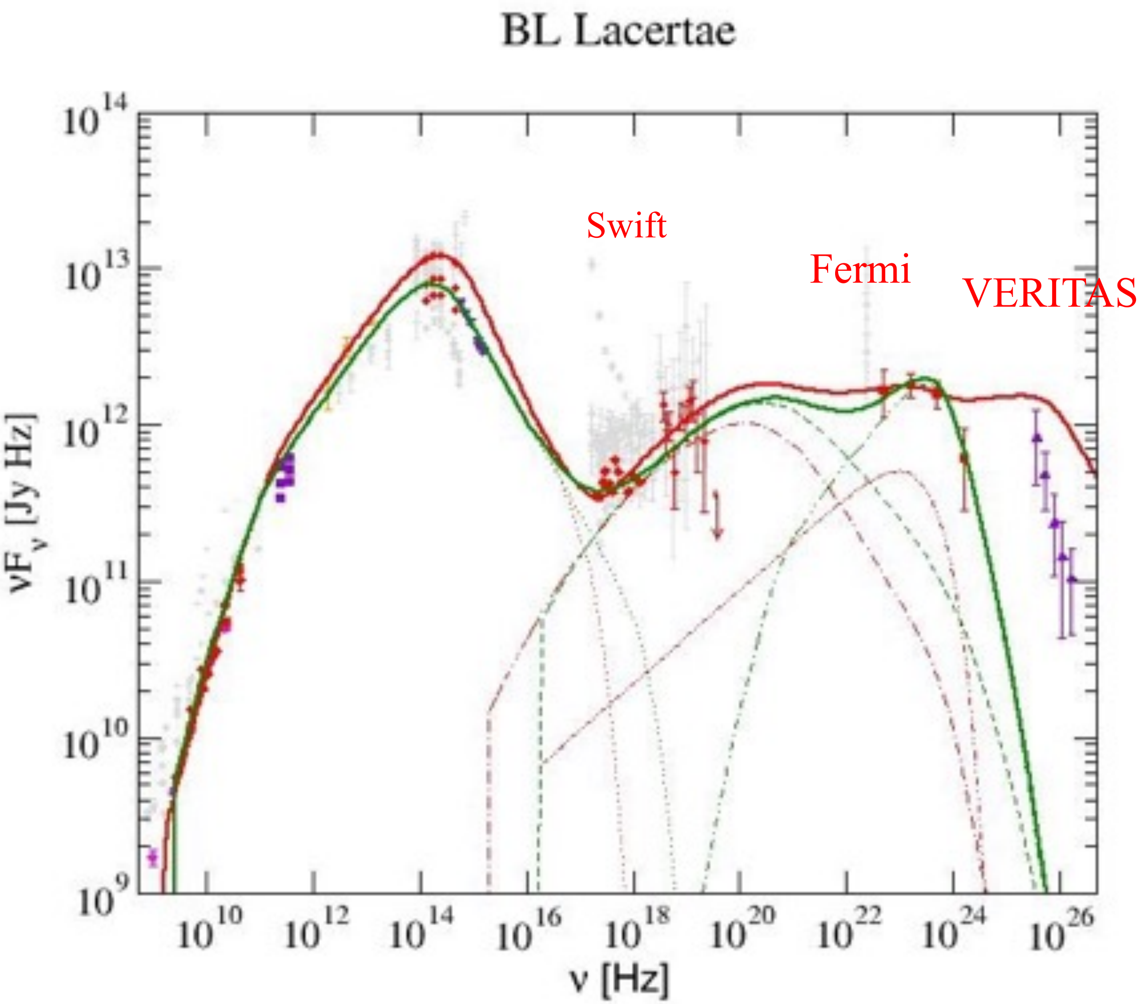
“Minimal” sensitivity at TeV energies meant that we were primarily detecting only the Crab and handful of bright sources/flares. Needed to execute very long integrations over multiple dark runs. (Crab was ~7 σ in 1 hour, in VHE band)

Very few simultaneous multiwavelength campaigns, coupled with difficult observing constraints with large slewing overhead for typical space telescopes, led to sporadic coverage of the critical spectral regions below the peak of the 2nd bump. Most transient studies involved the use of archival data.

Swift launched in November 2004
→ rapid pointing with excellent sensitivity to MANY sources in a day
→ intrinsic multi-wavelength platform

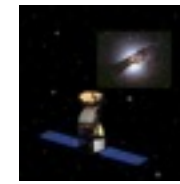
All 4 VERITAS telescopes operating since Spring 2007 (with further upgrades in 2009 and 2012)
→ huge increase in VHE sensitivity

Now we have:



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

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



Gamma ray:
Fermi, AGILE,...

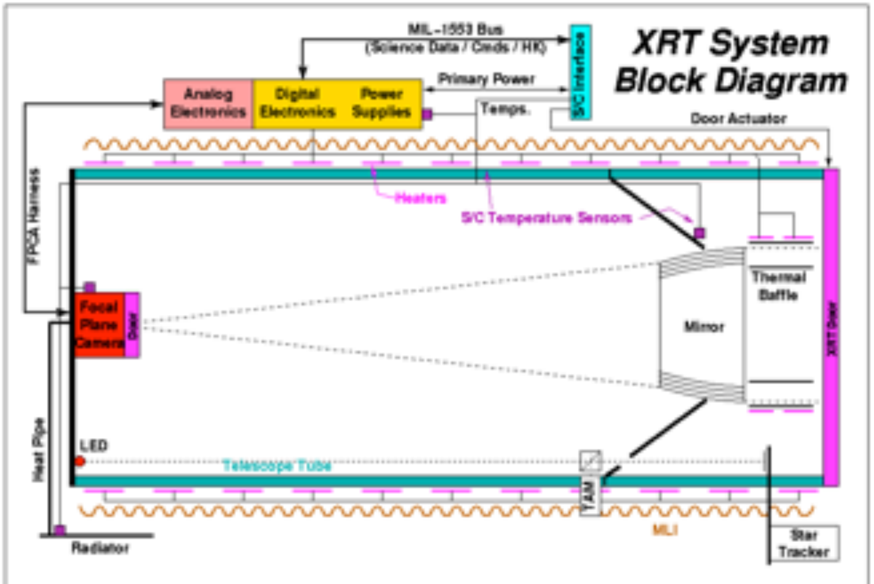
30 MeV – 300 GeV
all sky

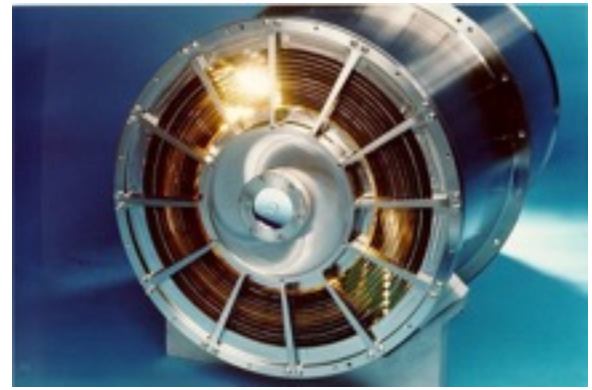
VHE:
VERITAS, HESS, MAGIC, ...

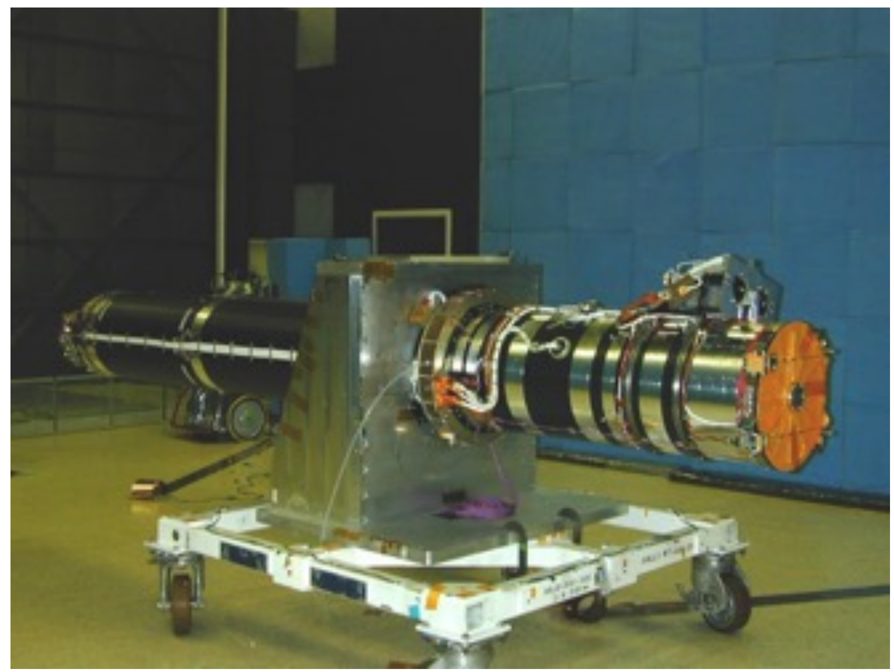
100 GeV – 50 TeV

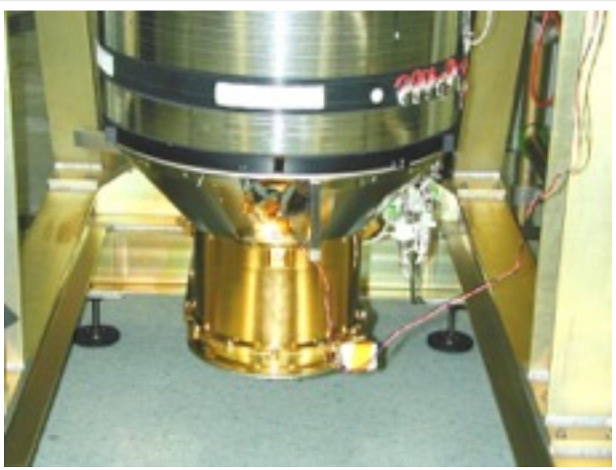
Frequent simultaneous broadband coverage, capturing many components & details of SEDs with complementary sensitivities

The X-Ray Telescope

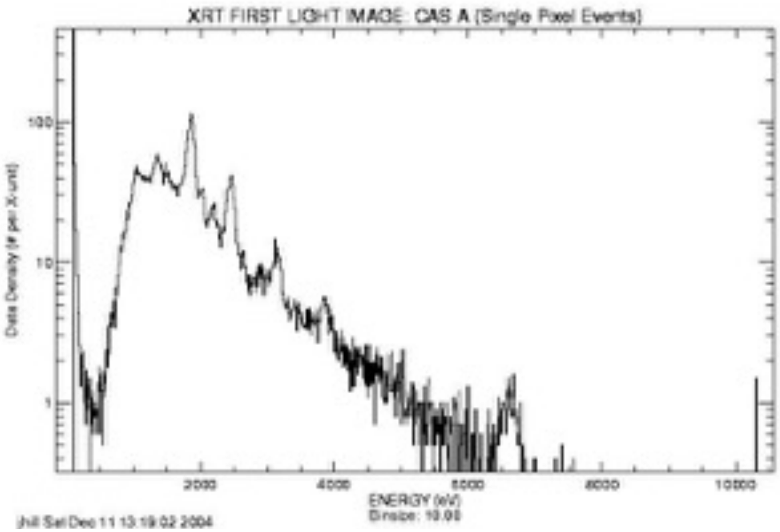






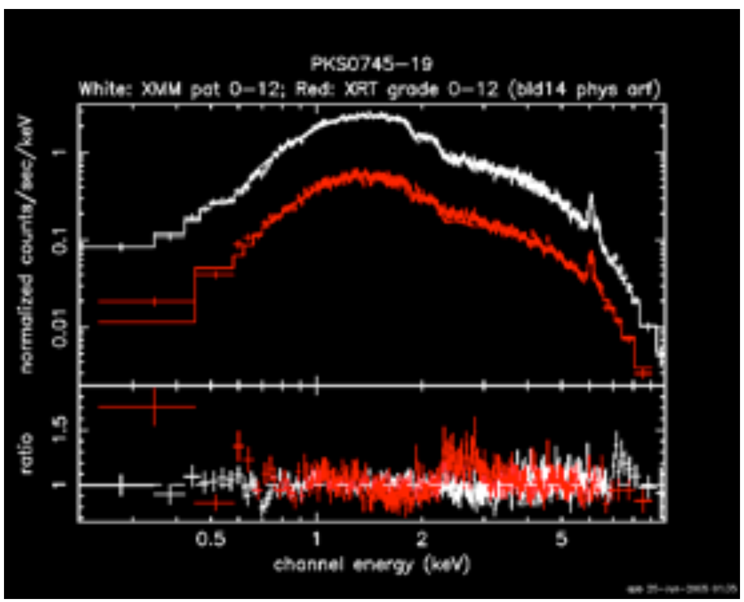


The X-Ray Telescope



Spectroscopy
(example from first light on Cas A)

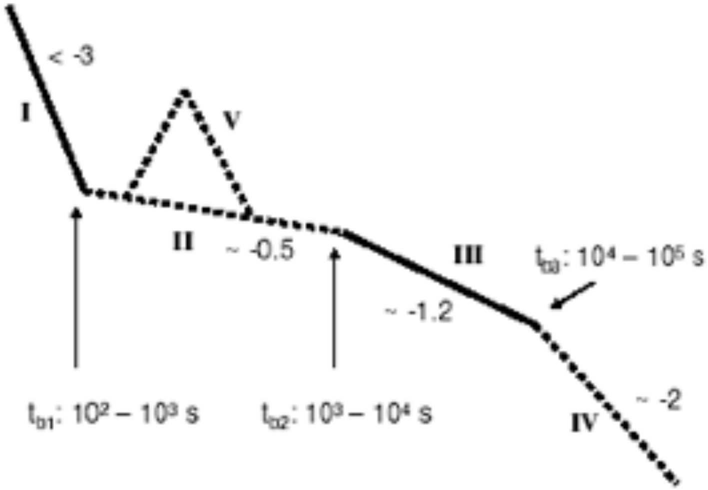
Flux limit ~10^{-15} erg/cm2/s



Example AGN spectrum

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

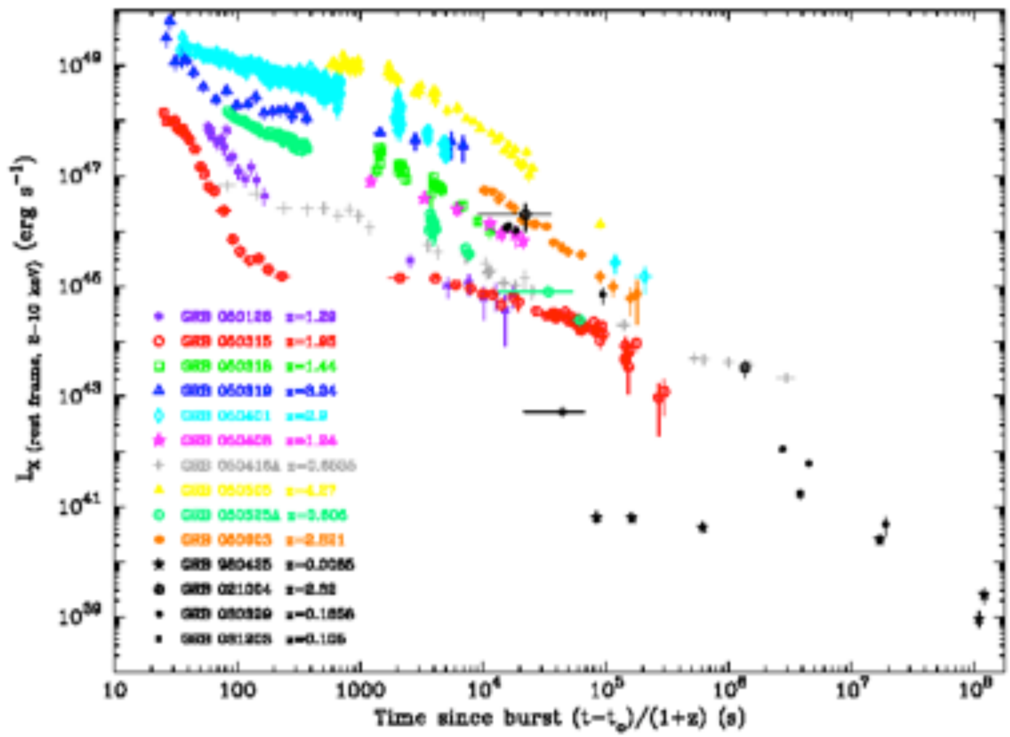
The Overall X-ray Lightcurve



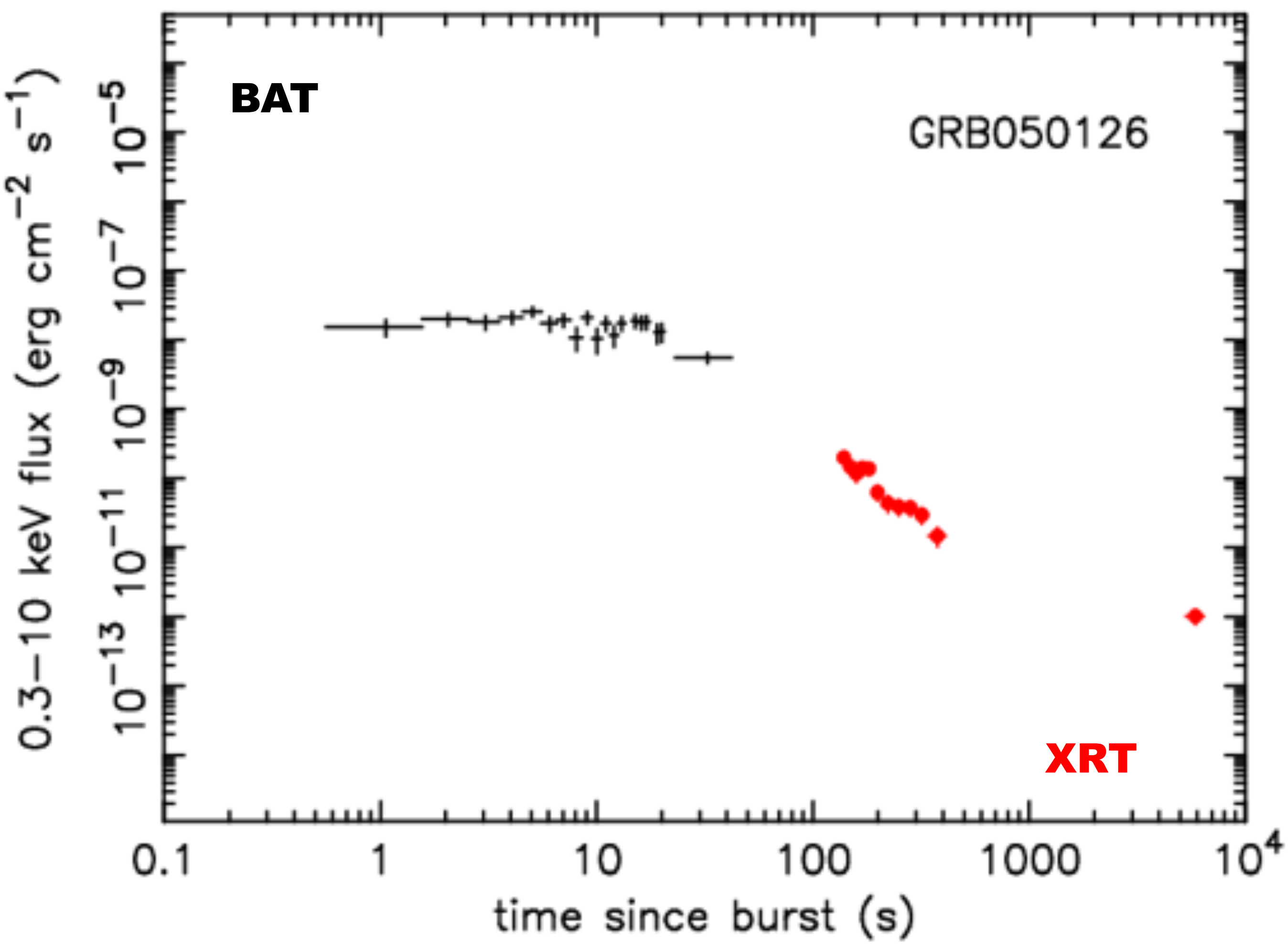
Zhang et al. 2006

Nousek et al. 2006

O'Brien et al. 2006

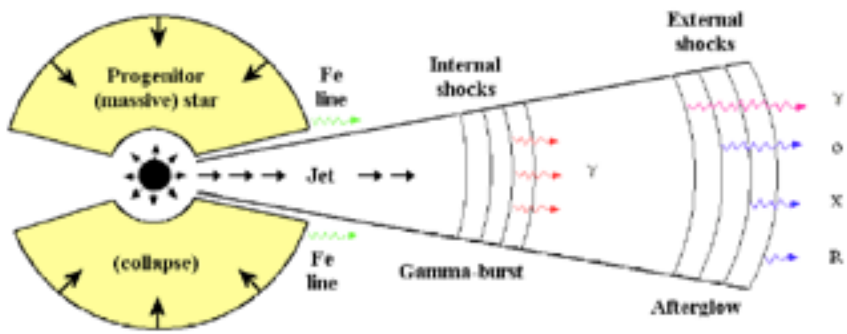


Swift Lightcurves – the Movie



Paul O'Brien / UL

Why Study GRBs at Very High Energy?

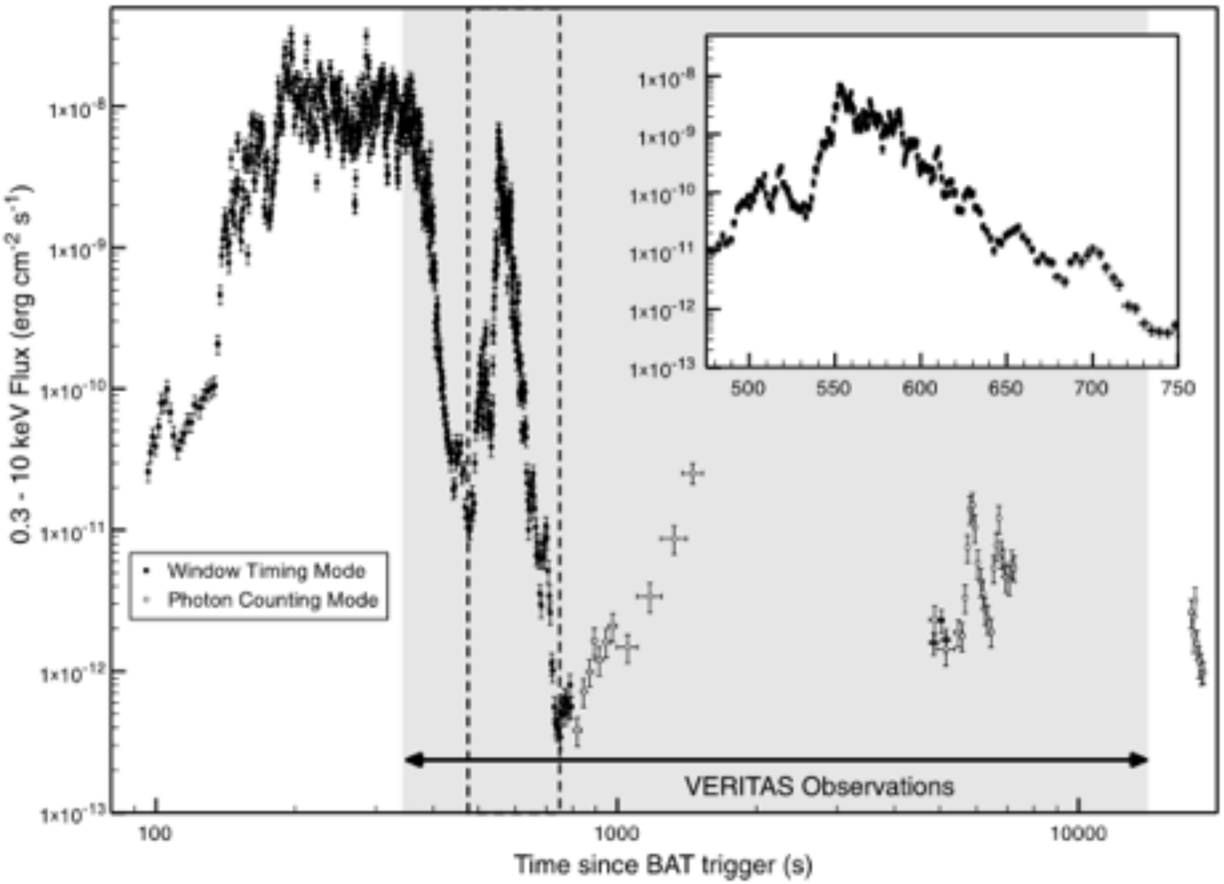


- Need to **understand acceleration mechanisms in jets**, energetics, and therefore **constrain the progenitors** and jet feeding mechanism
- Understanding progenitor then leads to an understanding of cosmology & stellar evolution required to support progenitor population
- Constrain local environment 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

- VERITAS has observed 162 gamma-ray burst positions, with more than half of those coming from Swift.

Upper limit during GRB X-ray flare

VERITAS



VERITAS observations during moderately large X-ray flare from GRB 080310 also yielded an EBL corrected upper limit of 9.8×10^{-8} photon cm^{-2} s^{-1} above 310 GeV (not very constraining). Unfortunately, the burst was at z=2.4, so EBL attenuation was large.

Acciari et al. 2011

Upper limit on GRB 150323A

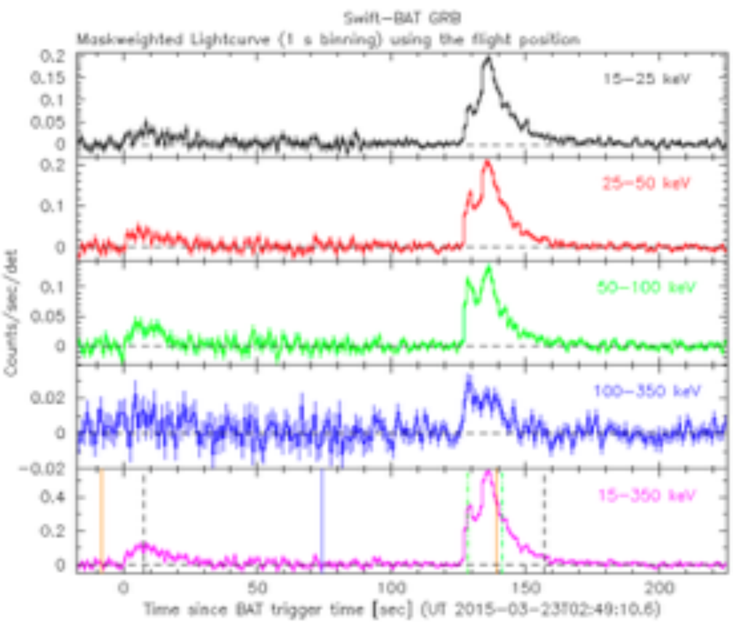


Figure 1. The *Swift*-BAT lightcurve for GRB 150323A, showing both the precursor and the main emission period. The different coloured plots correspond to various energy bands observed by BAT as indicated in each subplot. Taken from the batgrbproduct analysis page: http://gcn.gsfc.nasa.gov/notices_s/635887/BA/

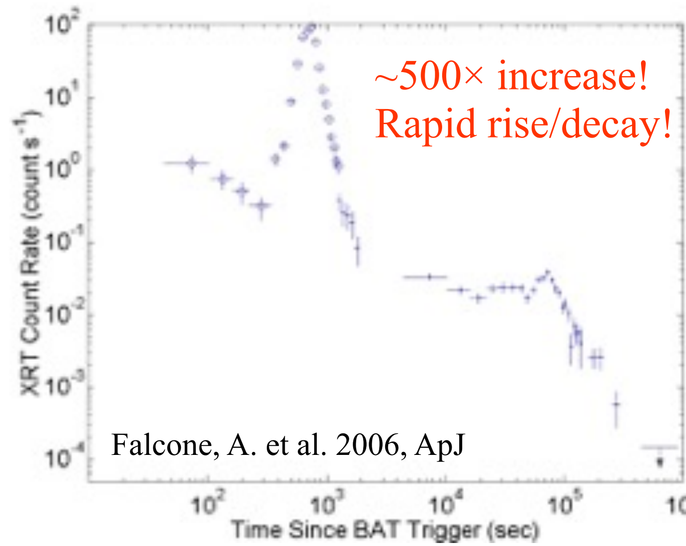
Archambault et al. 2017, in preparation

- VERITAS was on target 270 sec after Swift trigger from a precurser burst, and ~135 s after the start of the main GRB
- redshift 0.593 from Keck
- 170 min VERITAS observation
- 99% differential upper limit at 140 GeV is 3.0×10^{-6} $\mathrm{TeV}^{-1}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$
- The VERITAS upper limit corresponds to ~0.5% of the prompt fluence, which is weak relative to an extrapolation from a typical Fermi detection
- Due to this VHE upper limit, the favored models are a burst exploding into a Wolf-Rayet wind or a burst with low electron cooling due to low density ISM

see also: upper limits on GRB 130427A; Aliu et al. 2014

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, Aliu et al. 2014, Abeysekara et al. 2015, Archambault et al. 2017)
- 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 achieved exciting GRB detections at several 10's of GeV. VHE gamma ray telescopes (e.g. VERITAS & HAWC) may yet open TeV discovery space with a GRB detection, and upper limits are already constraining.

Blazars etc.
Swift Monitoring of GeV-TeV blazars and other "Sources of Interest"

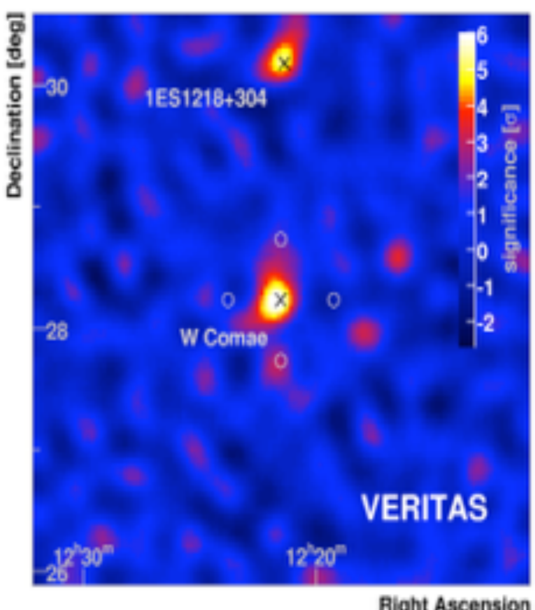
0208-512
0235+164
PKS 0528+134
PKS 0716+714
0827+243
OJ 287
Mrk 421
W Com
3C 273
3C 279
1406-076
H 1426+428
1510-089
PKS 1622-297
1633+383
Mrk 501
3EGJ1733-1313
1ES 1959+650
PKS 2155-304
BL_Lacertae
3C 454.3
1ES 2344+514
LS I +61 303

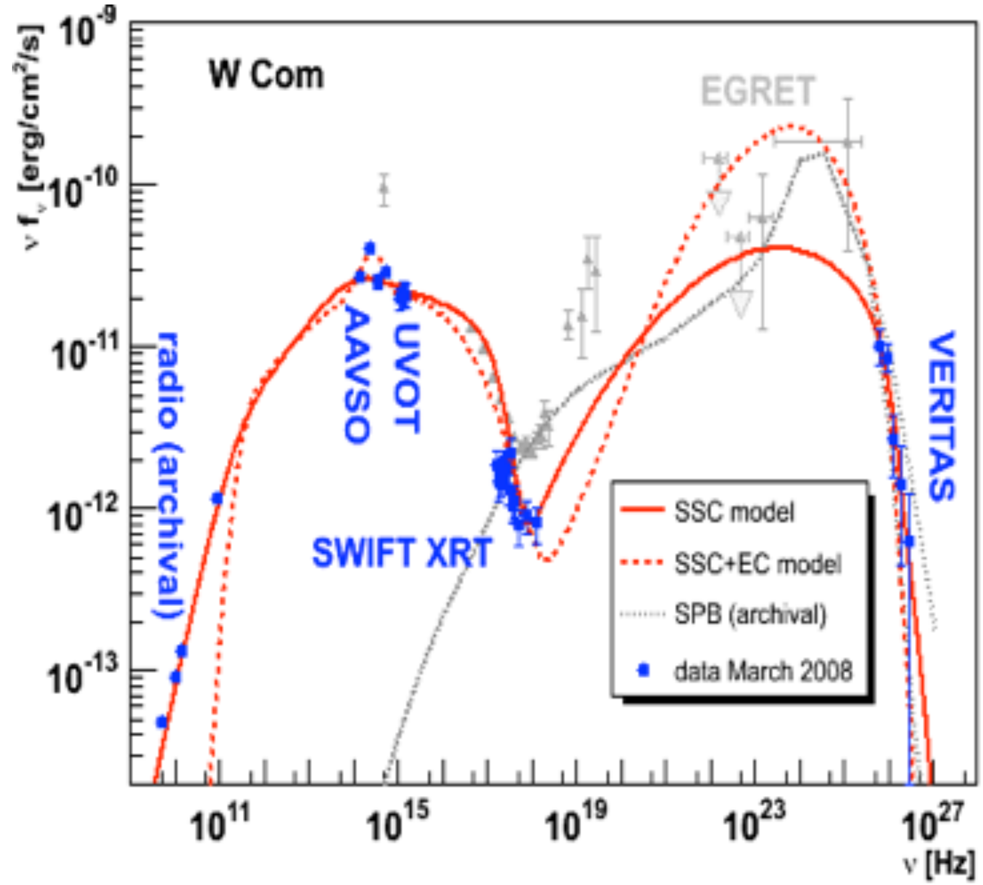
- Swift is monitoring several sources on weekly basis for 1-2 ksec per week for ~4 months per source
- Additionally, intensive Swift monitoring sometimes results as part of larger campaigns and ToOs
- This follow-up is frequently coordinated with TeV observatories, resulting in multiwavelength data from 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

W Comae: LBL/IBL blazar

- 37.8 hours of VERITAS data
- give a 4.9 σ detection
- Most of signal comes from a 0.09 Crab flare on 13Mar2008 and a second outburst on 7Jun2008
- Contemporaneous Swift data provide critical SED information

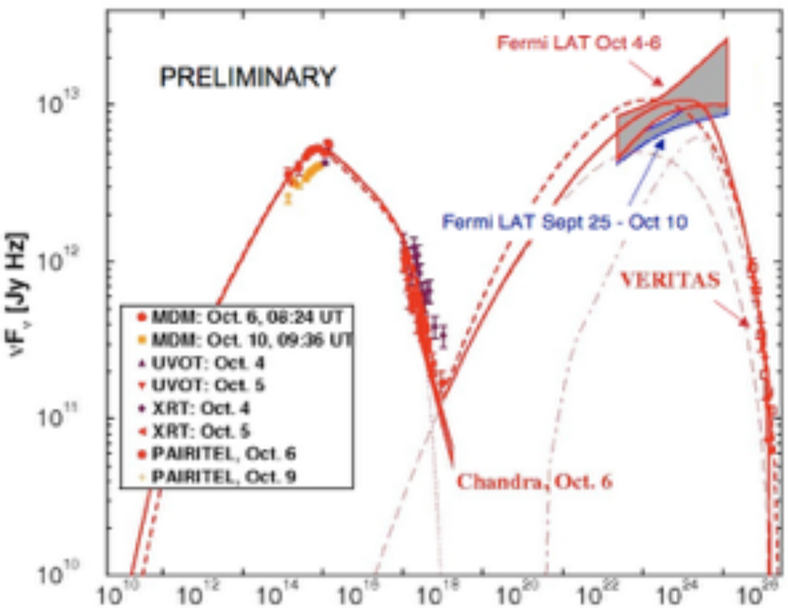




A Couple Examples

3C 66A (IBL/LBL)

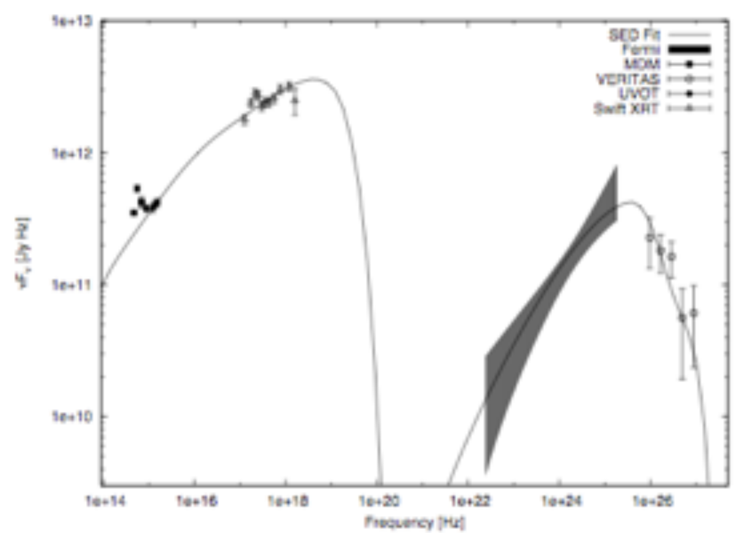
- Swift, MDM, Fermi, & VERITAS (time averaged) spectral data during high state on Oct 4-6
- Due to broadband coverage, spectrum is tightly constrained
- ***Model including an external Compton component favored***



Dashed line: pure SSC, solid line: SSC+EC
See: Reyes et al. 2009, ICRC proc.
Benbow et al. 2010

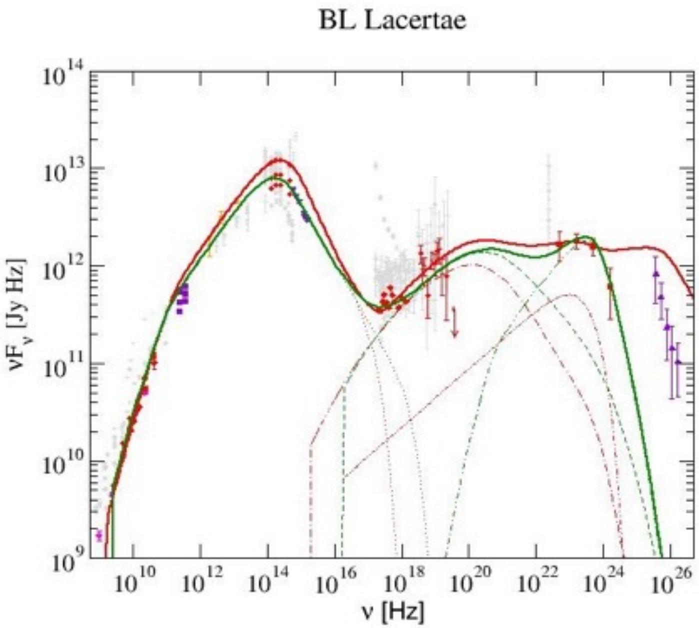
RGB J0710+591 (HBL)

- 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)**.

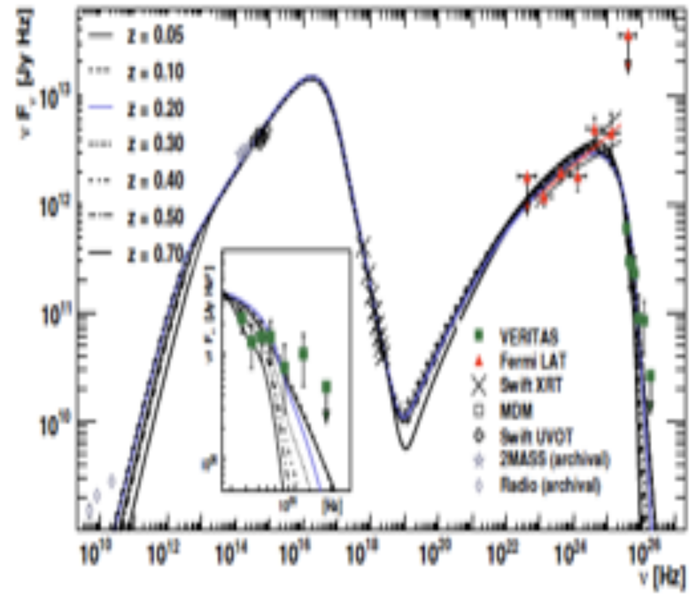


Fortin, Perkins, et al. 2010 , Acciari et al. 2010

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). [Also see Q. Feng et al. 2017 for new flare]



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).

Some other recent campaigns: OJ 287

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26 Jun 2017; 23:15 UT

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OJ 287 at its highest X-ray state since the beginning of Swift monitoring

ATel #10043; *Dirk Grupe (Morehead State University), S. Komossa (QianNan Normal University for Nationalities), & Abe Falcone (Penn State University)*
on *3 Feb 2017; 02:10 UT*
Credential Certification: Dirk Grupe (dgrupe007@gmail.com)

Subjects: Optical, Ultra-Violet, X-ray, Black Hole, Blazar

We report on an outburst of the 0.3-10 keV X-ray emission of the blazar OJ 287, which is a candidate binary black hole system. This outburst occurred on 2017 February 02, during observations at approximately 08:52 UT (MJD 57786.369975). Swift previously discovered OJ 287 in a bright X-ray and UV state on 2016 October 12 (Grupe et al., ATEL 9629). We have followed OJ 287 since October 2016 with a two day cadence. Although it remained bright, its X-ray flux seemed to suggest an end of the flaring state. However, about a week ago OJ 287 started to become brighter again in X-rays. Further observations were triggered last night, which resulted in the detection of an outburst at a level of 2 counts/s, the highest count rate seen since the start of the monitoring program by Swift in 2005 May. The 0.3-10 keV spectrum of the current outburst can be fitted by a single power law model with a photon index of Gamma = 2.62+/-0.06. The observed flux in the 0.3-10 keV band currently is (3.83+/-0.10)e-14 W m-2 (or e-11 ergs/s/cm2). In the optical and UV band, OJ 287 has become brighter compared with the observation during the last few weeks. The optical and UV magnitudes found in the most recent observation from February 02 are (not corrected for Galactic reddening): V: 14.09+/-0.04, B: 14.43+/-0.04, U: 13.56+/-0.05 UVW1: 13.53+/-0.05, UVM2: 13.48+/-0.05, UVW2: 13.66+/-0.05. We are planning to continue monitoring OJ 287 with Swift and encourage observers to obtain multi-wavelength observations in order to cover this brightest X-ray outburst since 2005.

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VERITAS Detection of VHE Emission from OJ 287

ATel #10051; *Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration*
on *5 Feb 2017; 02:02 UT*
Credential Certification: Reshmi Mukherjee (muk@astro.columbia.edu)

Subjects: Gamma Ray, TeV, VHE, AGN, Blazar

We report the detection of VHE emission (>100 GeV) from OJ 287 with VERITAS. The source was observed by VERITAS between 1 February and 4 February 2017 (UTC), for a total exposure of 13.0 hours. OJ 287 is an optically bright quasar, known to display quasi-periodicity with roughly 12-year optical cycles (Shi et al., Ap&SS 310, 59, 2007), and is believed to host a binary supermassive black hole (Valtonen et al., ApJ, 643L, 9, 2006). The VERITAS observations were carried out in response to a rising X-ray flux, noted in the X-ray light curve measured by Swift-XRT; see http://www.swift.psu.edu/monitoring/source.php?source=OJ287 (Stroh & Falcone, ApJS, 207, 28, 2013). A preliminary analysis of the VERITAS observations yields an excess of 141 events above the background at the position of the blazar, corresponding to a statistical significance of 5.7 standard deviations. The corresponding flux observed above 100 GeV is (18 +/- 3) x 10^-12 cm^-2 s^-1, or 3% of the Crab Nebula flux above the same threshold. VERITAS measurements of possible enhanced gamma-ray activity on 2017 Feb 1, led to Swift observations on Feb 2 and 3, which showed the source to be in a remarkably high X-ray state at, or near, the same time (Grupe et al., ATel 10043). VERITAS will continue to observe OJ 287; multi-wavelength observations are encouraged. Questions regarding the VERITAS observations should be directed to Reshmi Mukherjee (muk@astro.columbia.edu). Contemporaneous target-of-opportunity observations with the Swift satellite have also been scheduled. VERITAS (Very Energetic Radiation Imaging Telescope Array System) is located at the Fred Lawrence Whipple Observatory in southern Arizona, USA, and is most sensitive to gamma rays between ~85 GeV and ~30 TeV (http://veritas.sao.arizona.edu).

(O'Brien, S. et al. 2017 for details)

Some other recent campaigns:

1ES 1959+650

BL Lac

RGB J2056+496

S5 0716+714

PG 1553+113

PKS 1441+25

Mrk 421 & 501

MS 1221.8+2452

3C 279

... and many more with 100’s of ksec of simultaneous coverage over multiple epochs .... !

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

To compare to the rapid TeV blazar flares (~2 min doubling times):

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)

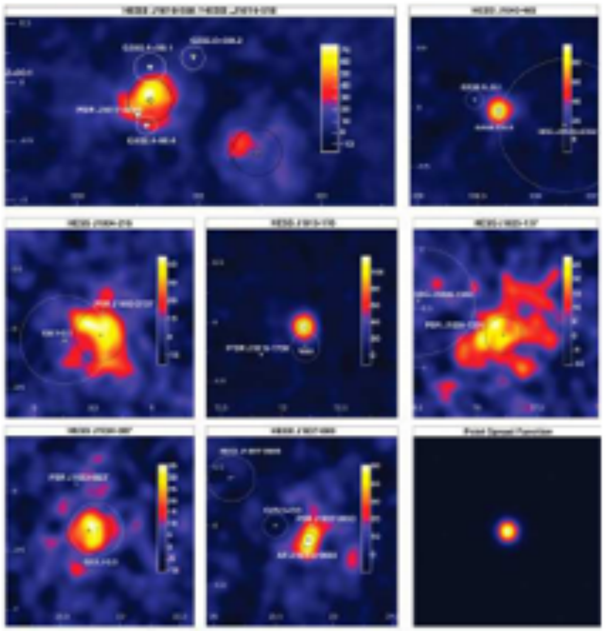
What Has Been Learned about blazars?

- 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***
- Some intriguing SEDs have more than 2 components; hadrons+electrons? multi-zone?
- 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!*

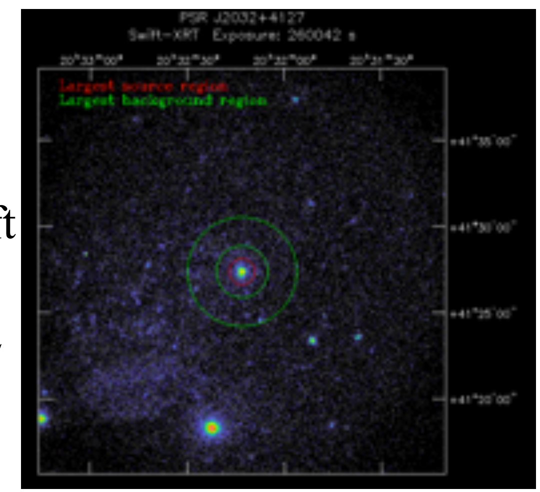
Some other Swift/GeV/TeV Programs on Astroparticle accelerators



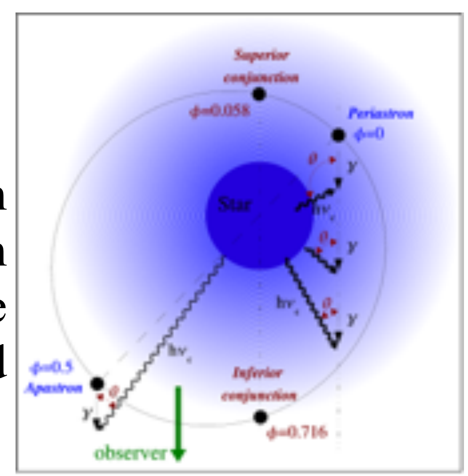
Selected TeV UnID sources, Aharonian et al. 2008

Swift is searching for counterparts **to *MeV/GeV and TeV Unassociated sources***. We have executed a program to spend ~1 Msec searching many Fermi unassociated sources and some TeV unidentified sources.

Skymap with many X-ray sources that have long-term Swift observations in vicinity of TeV2032



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



HESS J0632+057

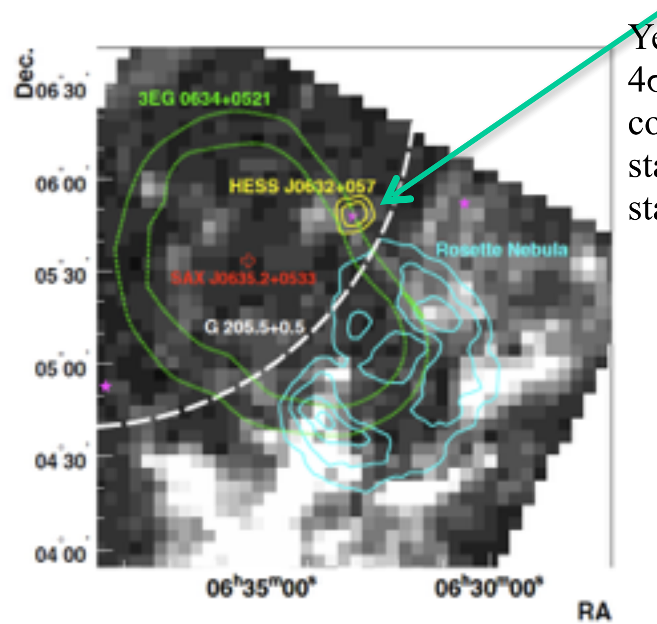
• TeV unidentified point source from HESS survey of Galactic plane (Aharonian et al. 2007)

• Combined observations from HESS and VERITAS imply TeV variability

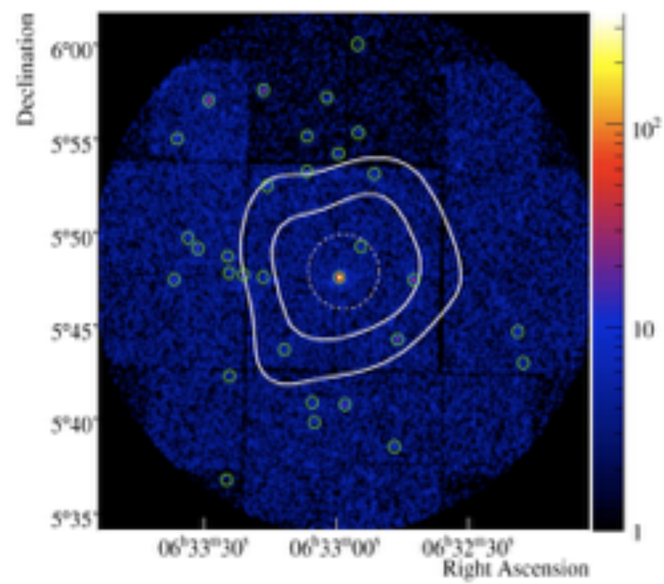
• spectrum is similar to TeV binaries

• Position is consistent with X-ray emitting Be star MWC 148

• Speculation that it could be a new binary system, but radial velocity measurements or binary-like periodicity are needed for confirmation (Hinton et al. 2009, Falcone et al. 2010)



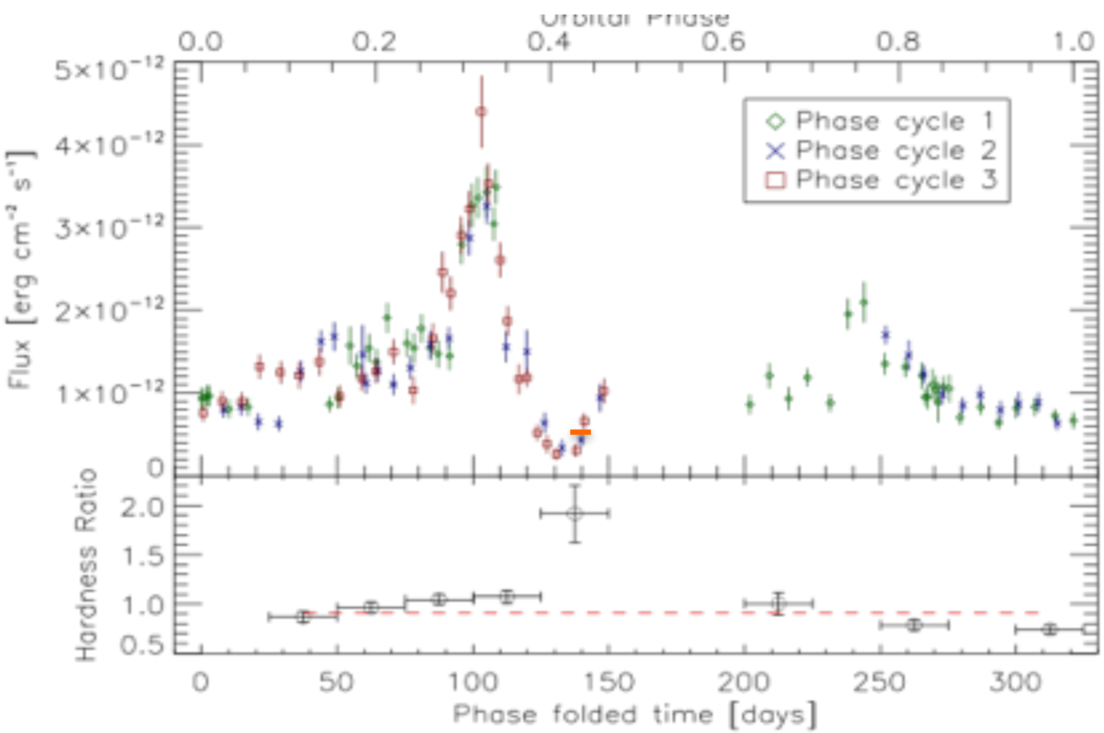
Yellow contours are 4σ & 6σ HESS contours and pink star in center is Be star MWC 148



XMM image

Bright spot in center is X-ray source corresponding to MWC 148. It is in the center of the HESS contours and the center of the upper limit on the angular extent (dashed circle)

Variable TeV 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**).

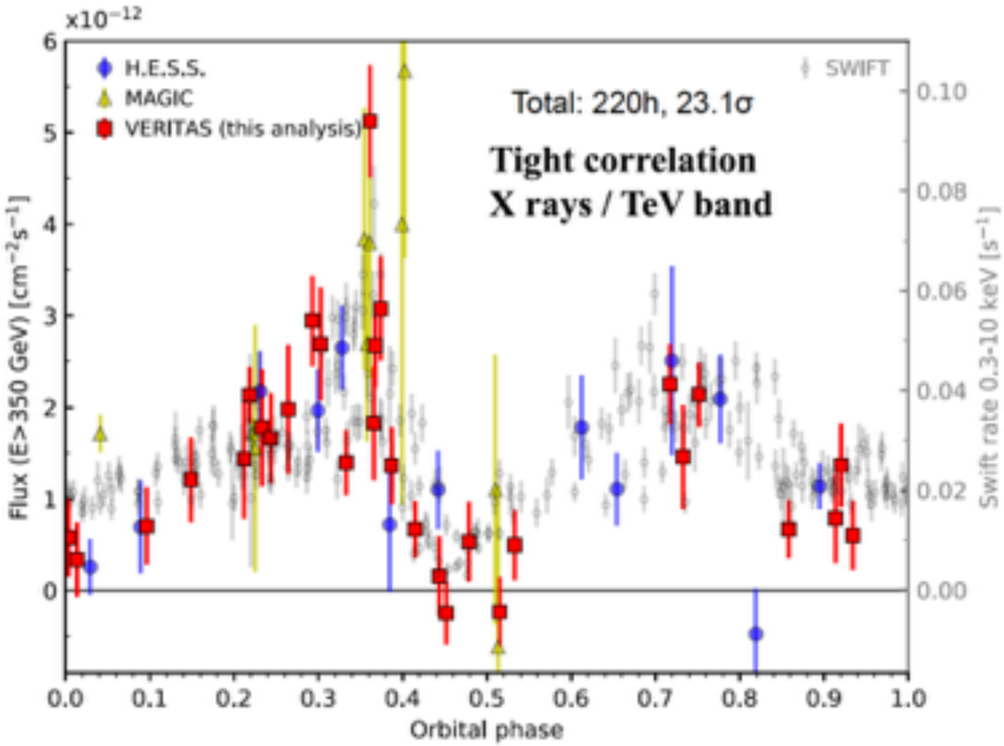
(Different color data points are offset by 321 days, i.e. from different cycles)

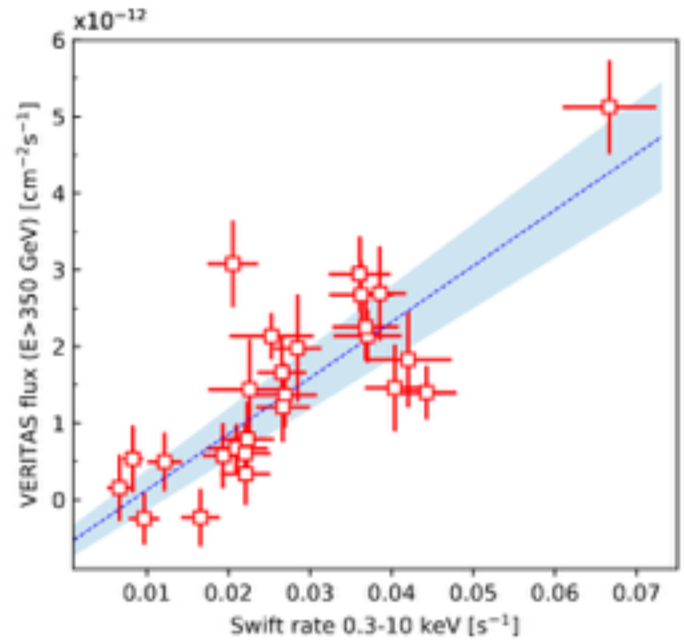
Note the hardening of the spectrum during "the dip."

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

LSI+61303 shows extra-orbital variability in X-rays; we should look for that in this binary.

X-ray / TeV correlation





Maier et al. 2017

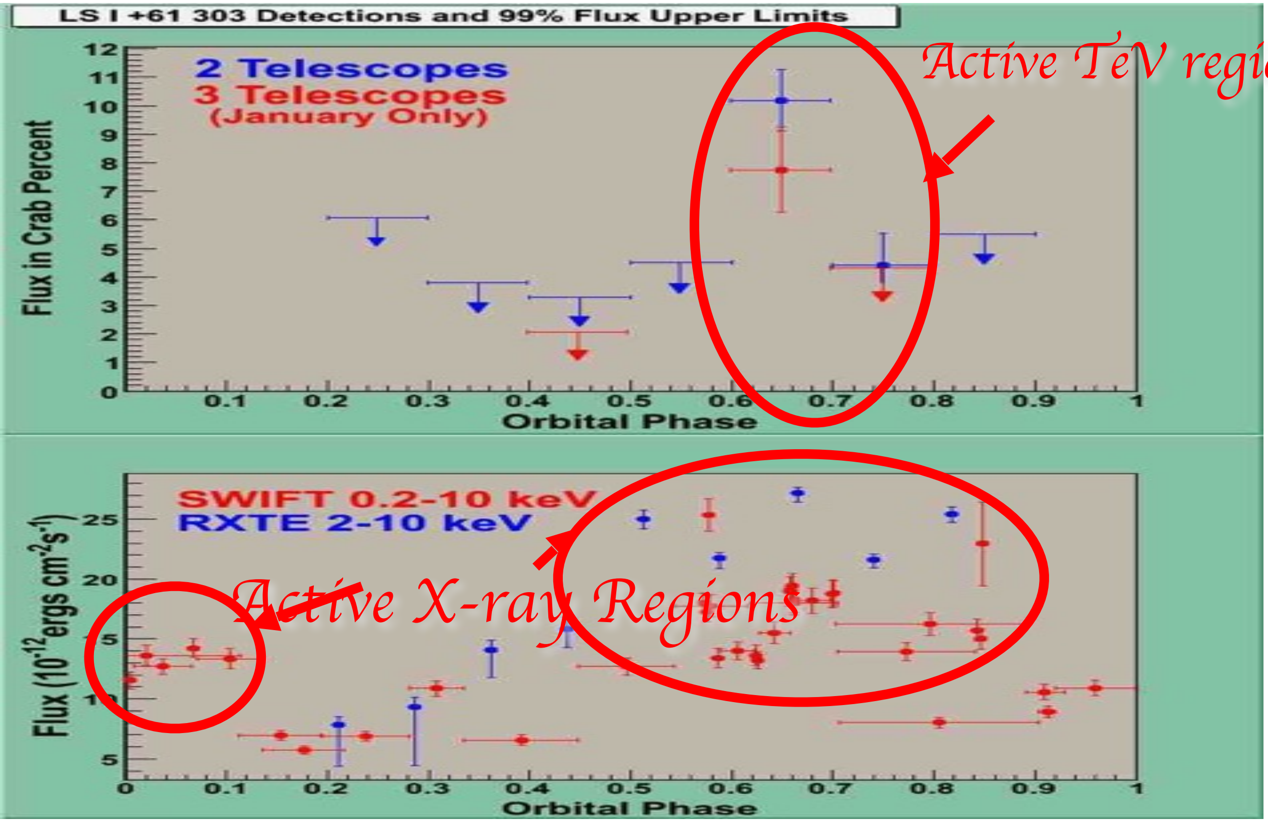
TeV data points from different epochs with VERITAS (red), HESS (blue), and MAGIC (yellow) compared to Swift XRT data from multiple epochs folded over a 315 day period (gray open data points).

VERITAS data currently at ~220 hours resulting in >23sigma detection, with a photon index of ~2.6-2.7 throughout all detected phases (only the dip is not detected by VERITAS)

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

Abe Falcone, Penn State

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

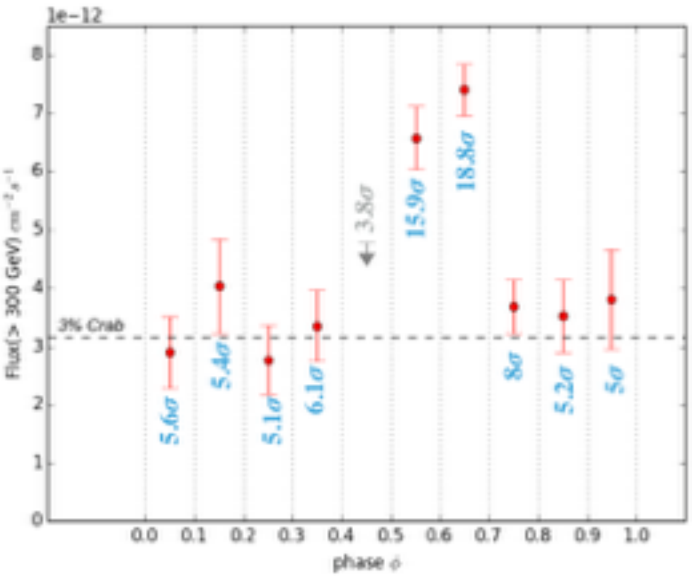


26.5 day period enigmatic binary system

Holder, Falcone, Morris 2007; Acciari et al. 2009; Smith et al. 2009; Esposito et al. 2007; Anderhub et al. 2009, Acciari et al. 2011, Aliu et al. 2013,

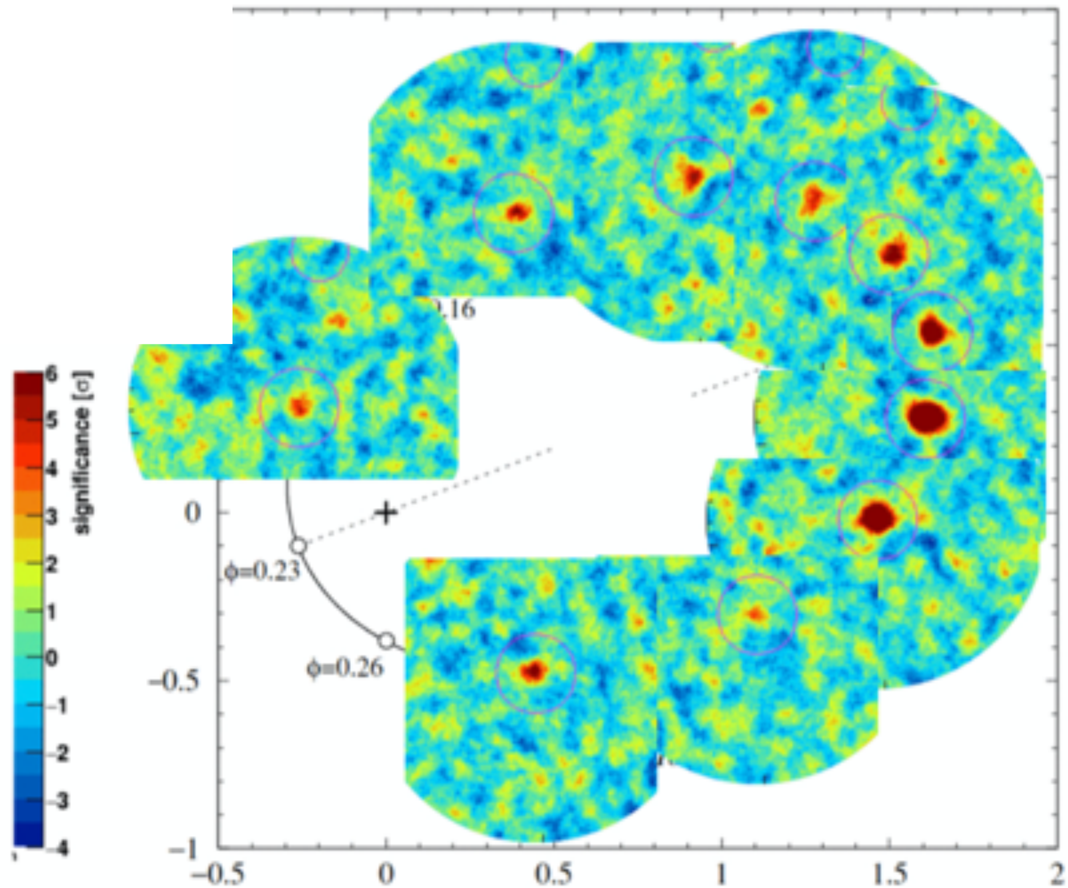
- Variable TeV emission, particularly when measured in 2006/2007 (peaks at ~15% Crab)
- All data from 2006 to 2009:
  ~apastron, roughly 3%-4% Crab
  ~periastron, roughly 1%-2% Crab
- Incredibly fast (seconds) X-ray flare events (Smith et al. 2009) → Magnetar?

LS I +61 303: More recent results



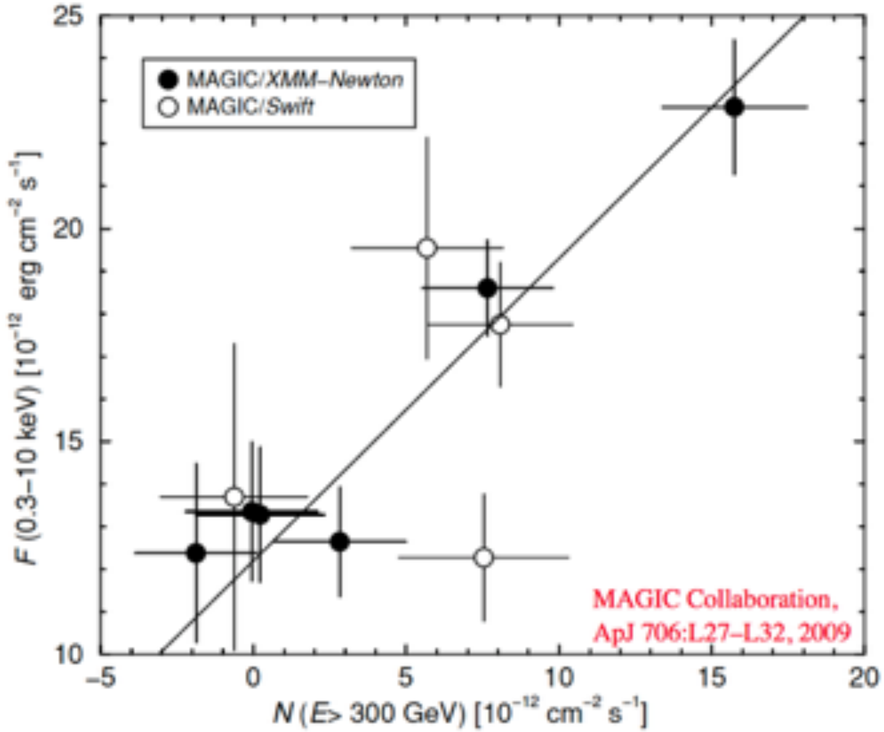
Phase-binned flux and significance maps at different phases of LS I +61 303, with apastron at phase ~ 0.73

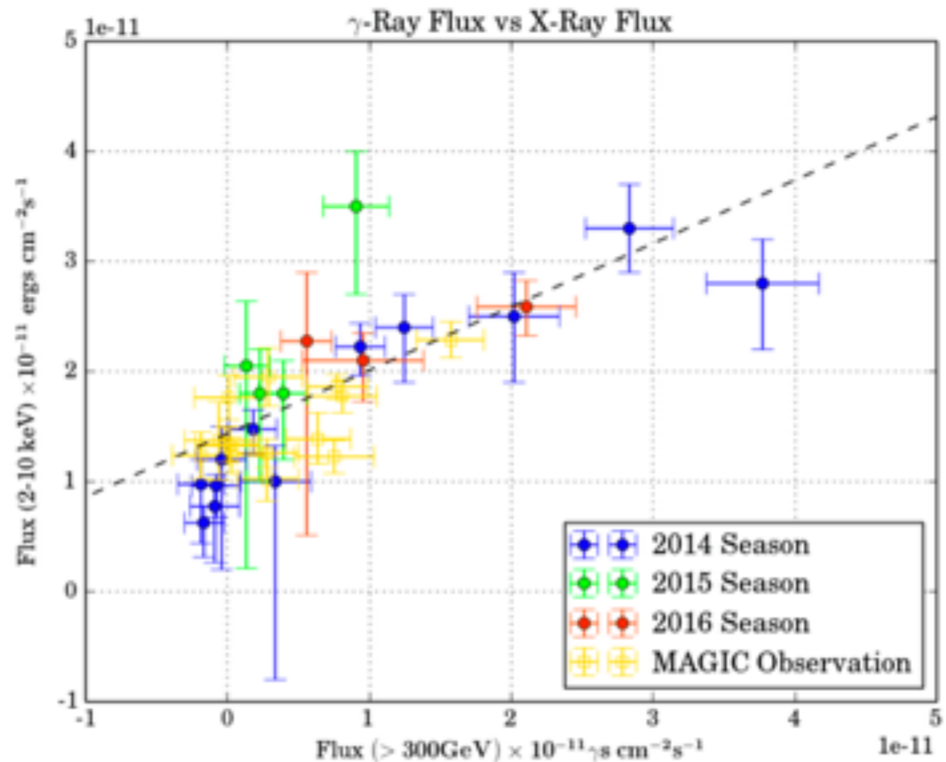
(Kar, P. et al. 2017)



Using Swift and VERITAS data from the past 3 seasons, a clear and significant X-ray/TeV correlation is found to extend over all detected flux states.

LS I +61 303





10 observations with XMM-Newton(6) and Swift(4)

MAGIC ⟶ $r = 0.81^{+0.06}_{-0.21}$

19 obs Swift VERITAS ⟶ $r = 0.756^{+0.09}_{-0.13}$

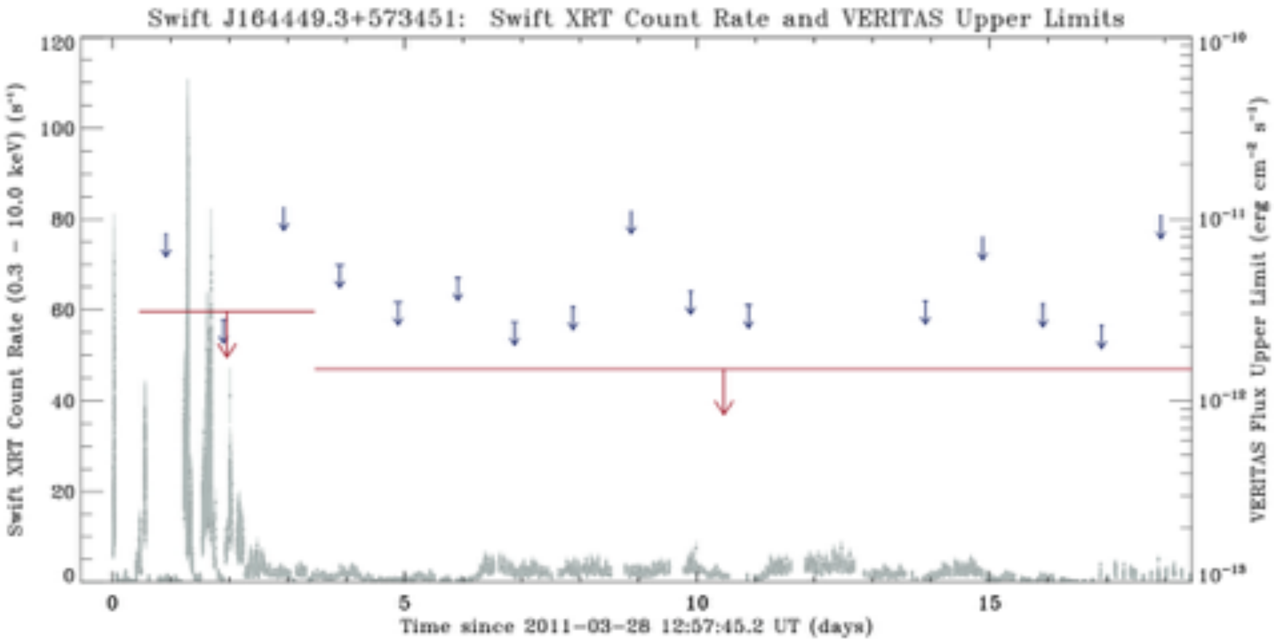
VERITAS + MAGIC ⟶ $r = 0.773^{+0.07}_{-0.09}$

Kar, P. et al. 2017

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 ~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 2/3 and 5/3, depending on where/how you fit the decay.
- Post-burst decaying lightcurve shows some evidence for periodicty on timescales of 0.36, 5.2, & 10.4 days

Swift J1644+57



These upper limits strongly disfavor synchrotron emission in a particle dominated jet, unless the jet had a very large (>100) Doppler factor. Therefore IC scattering is preferred.

Aliu, E. et al., *VERITAS Observations of the Unusual Extragalactic Transient Swift J164449.3+573451*, Astrophysical Journal Letters, **738**, L30, 2011

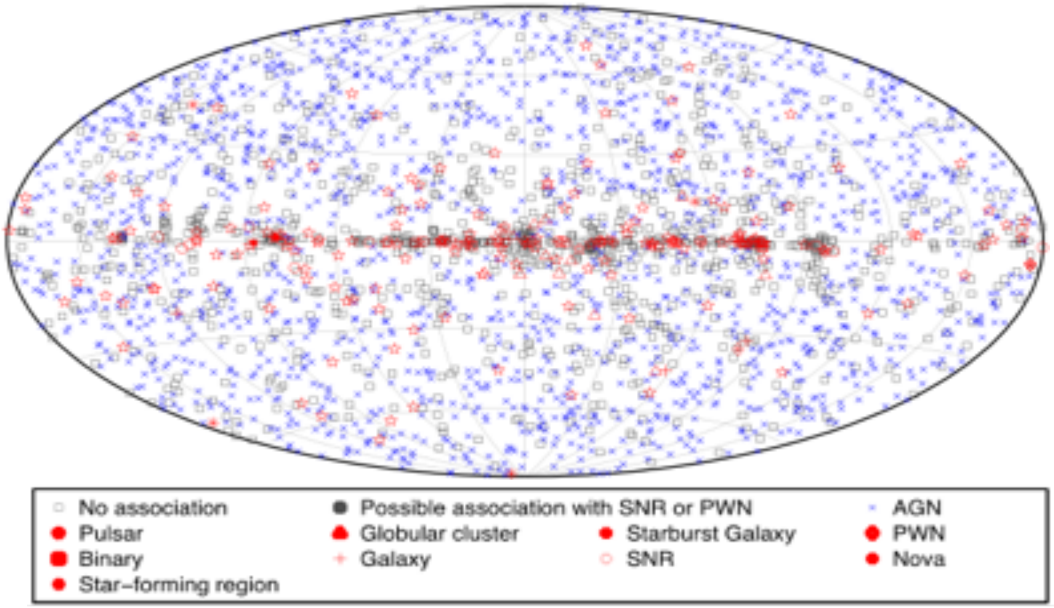
Burrows, D.N. et al., *Onset of a Relativistic Jet from the Tidal Disruption of a Star by a Massive Black Hole*, Nature, **476**, 421, 2011

Other Transient Sources

- In addition to the AGN/blazars, GRBs, TDEs, and X-ray binary variability that is studied by Swift, there are multiple programs to follow-up other types of transients and steady sources:
  - Neutrino multiplet events
  - Gravity wave triggers
  - other galactic transients
  - Unidentified Gamma-ray sources
  - high state triggers from myriad other instruments

Swift-XRT real-time analysis of many GeV/TeV Sources

The Fermi point source catalog is dominated by blazars and unassociated sources, many of which are of interest to VERITAS.



You can see the reduced results at:
(automatically updated in nearly real-time)

http://www.swift.psu.edu/monitoring (lightcurves of most TeV sources)

http://www.swift.psu.edu/unassociated/ (images of many LAT unassociated's)

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, rather than having multiple simple models that ambiguously fit data! Progress!***

- 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.

- This is a "Golden Age" of multiwavelength data to complement VHE gamma-ray telescope data, and this is the start of such an age for transients. We may not have this for most of the 2020's so let's continue to capitalize on it as long as possible over the coming several years.