Observing the TeV Gamma Ray Sky with the VERITAS: Connections with X-rays and Neil's legacy

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Barnard College, Columbia University

Some memories and thanks

Adviser to VERITAS

VERITAS External Science Advisory Committee (ESAC)

- 2004 April, Rex Ranch, AZ**
- 2005 September, Esplendor Resort, Rio Rico
- 2007 February, Rex Ranch, Amado
- 2009 April, Argonne National Lab

*** "The committee found the progress on the prototype telescope particularly encouraging and, given the rapid development of the TeV field, the prospects for a rich VERITAS science program look strong."* *(Excerpt from 2004 ESAC Report)*

Supporter of TeV Astrophysics

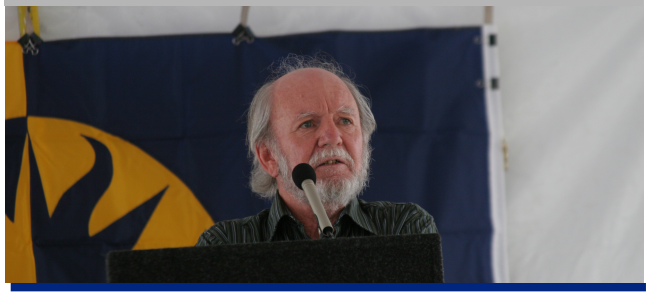
Neil was a supporter of VERITAS and of TeV astronomy particularly in the US. He believed in the need and importance of multi-wavelength observations and joint multi-missions studies of astrophysical sources.

Construction and early days of VERITAS (Fred Lawrence Whipple Observatory, AZ)

" ….I do recall that whenever I talked with Neil, he was always a strong supporter of both VERITAS and CTA. He very much recognized the close connection with VHE gamma-ray observations from the ground with what he was doing …." (David Williams, UCSC, Chair CTA-US).

10-Years VERITAS (2007 – 2017)

First light, April 2007 FLWO Basecamp



CERN COURIER

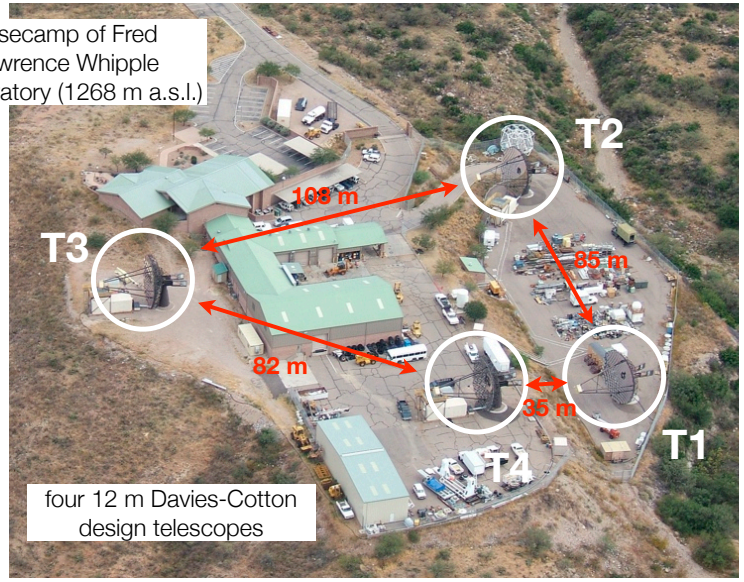
Jul 18, 2007

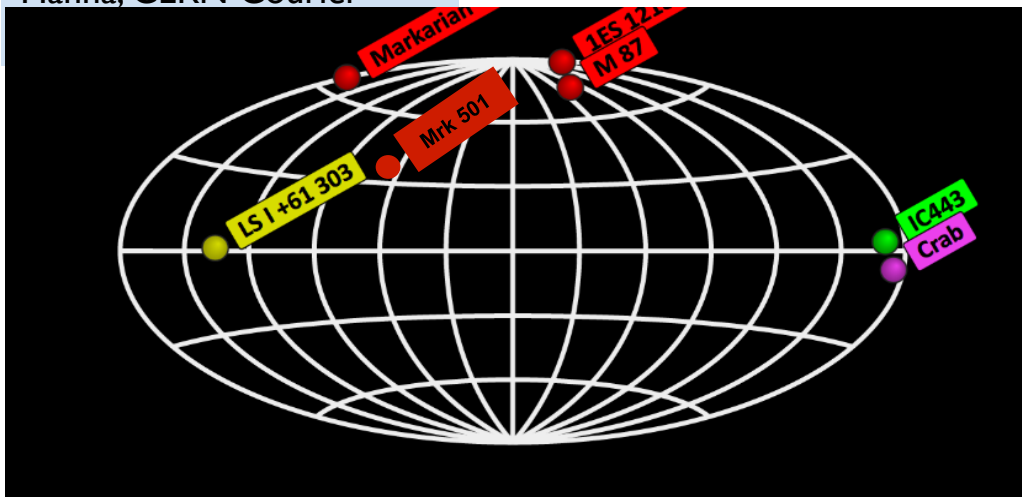
VERITAS telescopes celebrate first light

The latest in a series of VHE gamma-ray telescopes has come on line in Arizona. It will study gamma-ray sources ranging from supermassive black holes to dark matter.

Hanna, CERN Courier

basecamp of Fred Lawrence Whipple Observatory (1268 m a.s.l.)





VERITAS Skymap c. 2007

A successful Collaboration: VERITAS10-Year Celebration

VERITAS Collaboration with Friends & Supporters
Westward Look, Tucson, AZ, June 2017
http://veritasj.sao.arizona.edu/10Years/

Observing the TeV Gamma-Ray Sky with VERITAS

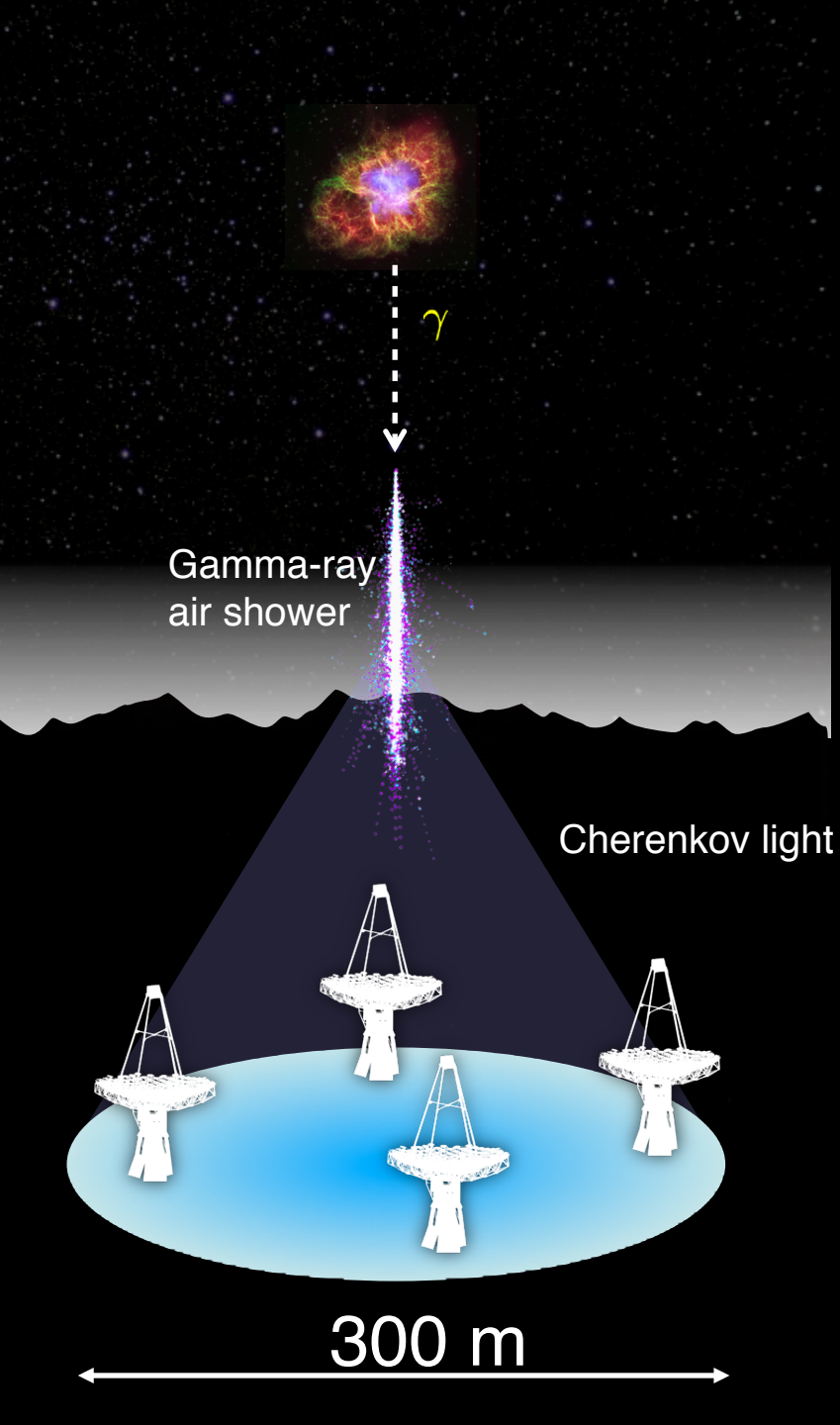
Outline

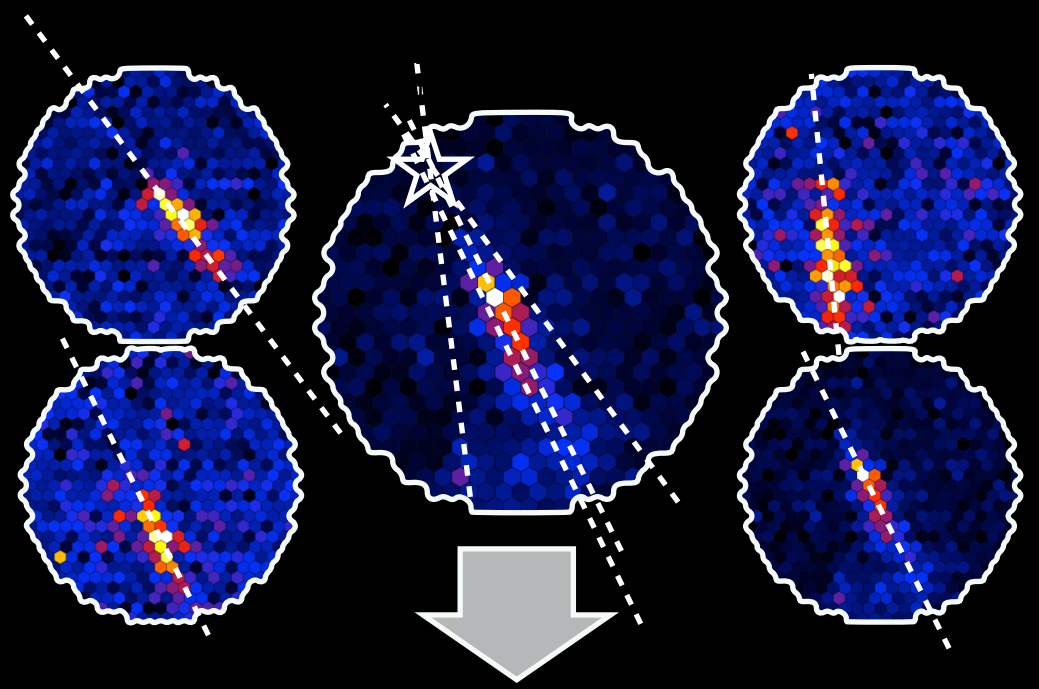
- Introduction to VERITAS
  - VERITAS instrument status
  - VERITAS skymap
- VERITAS & Swift: Why care about X-rays?
- X-ray – TeV joint studies (some results)
  - Blazars
  - Binaries
  - GRBs
- Outlook for the future

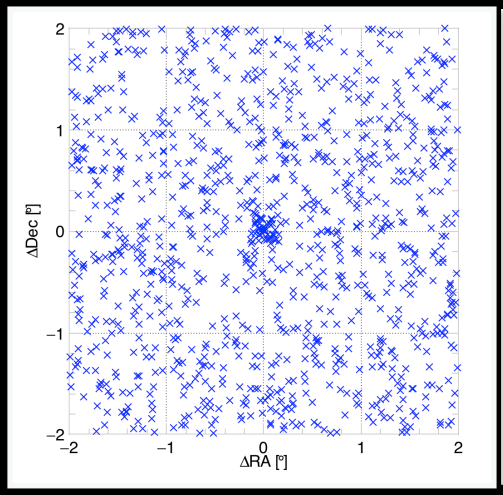
Quick Introduction to VERITAS

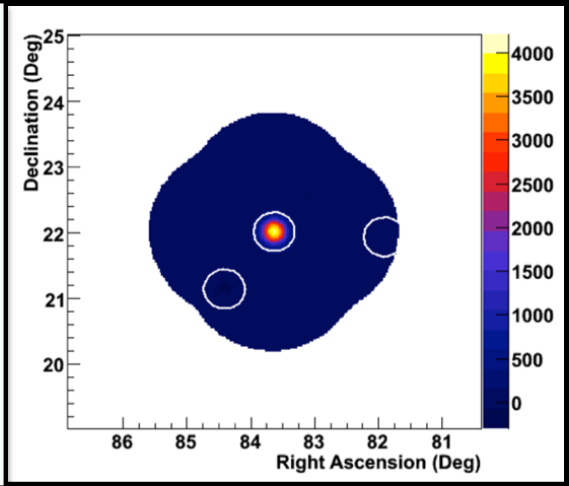
and where it fits in……

Imaging Air Cherenkov Technique



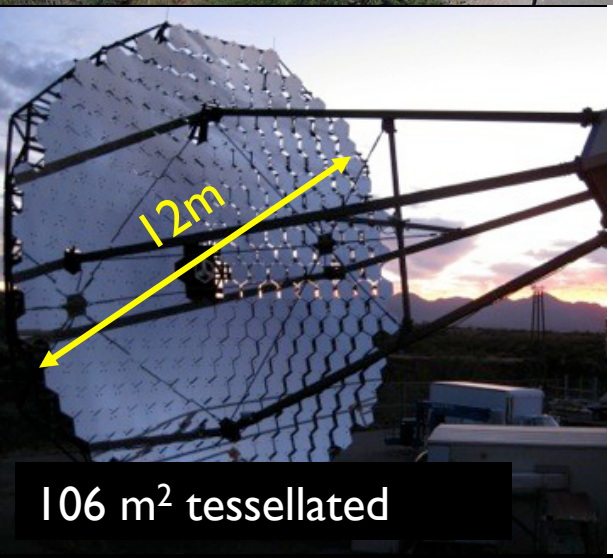




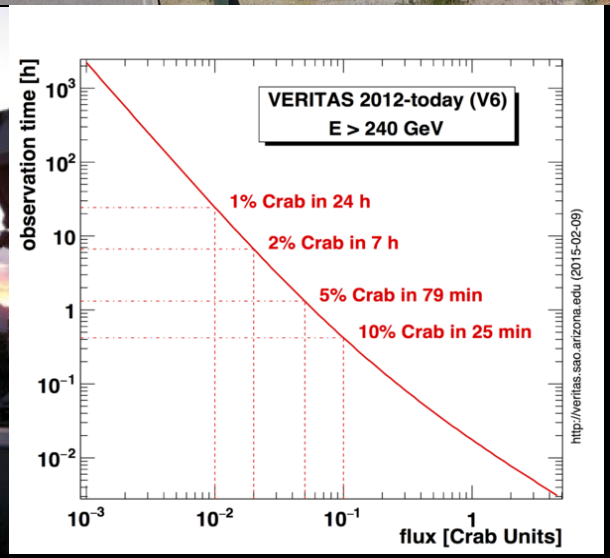


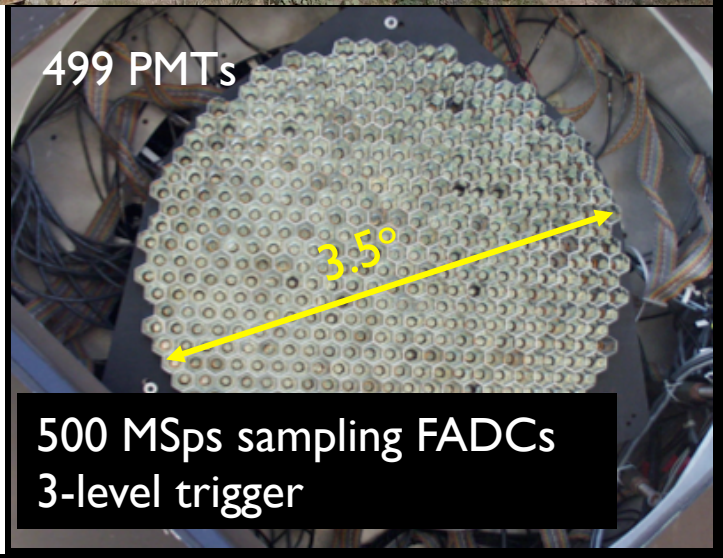
The VERITAS Array

- Sensitivity: 1% Crab in ~25 hr
- Energy range: 100 GeV to 30 TeV



106 m^2 tessellated

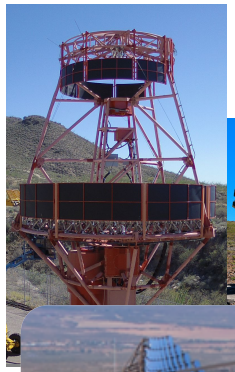




500 MSps sampling FADCs
3-level trigger

VERITAS Complementarity

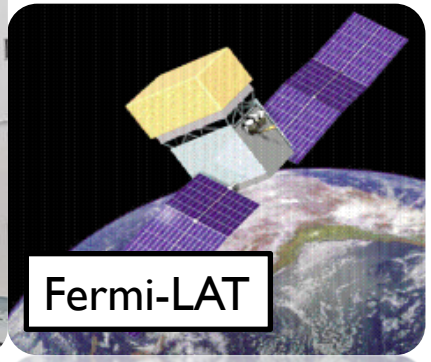
Current gamma-ray instruments
From MeV to TeV



FACT
(2011 - …)

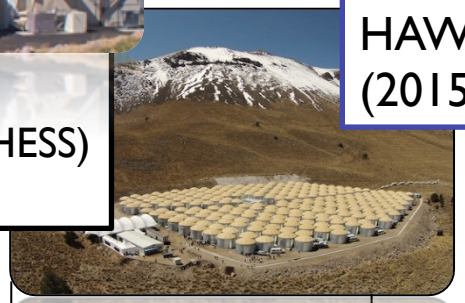
pSCT
(2018 - …)

GBM



Fermi-LAT

VERITAS
(MAGIC & HESS)
+ FACT



HAWC
(2015 - …)

10^{-12} 10^{-14} 10^{-16} 10^{-18}

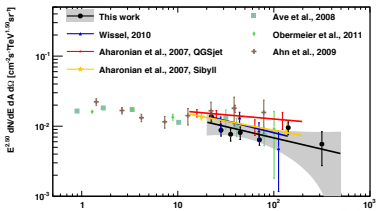
10^{-20} m

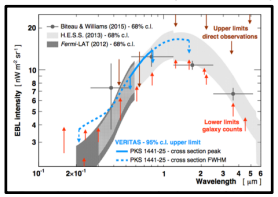
0.5 MeV

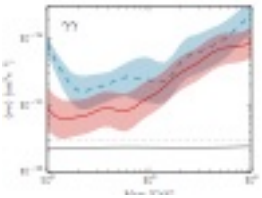
100 TeV

VERITAS Science

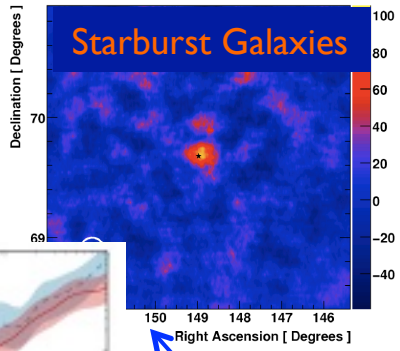
Fundamental Physics



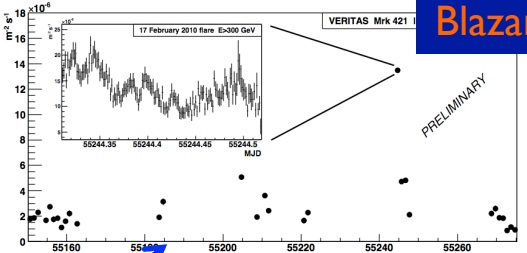


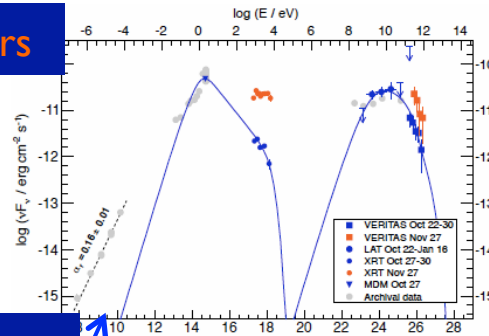


Starburst Galaxies

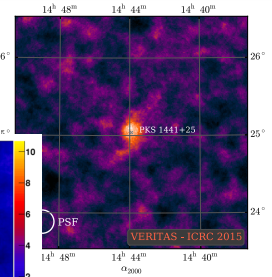


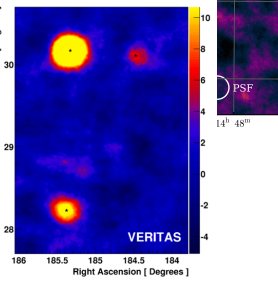
Blazars

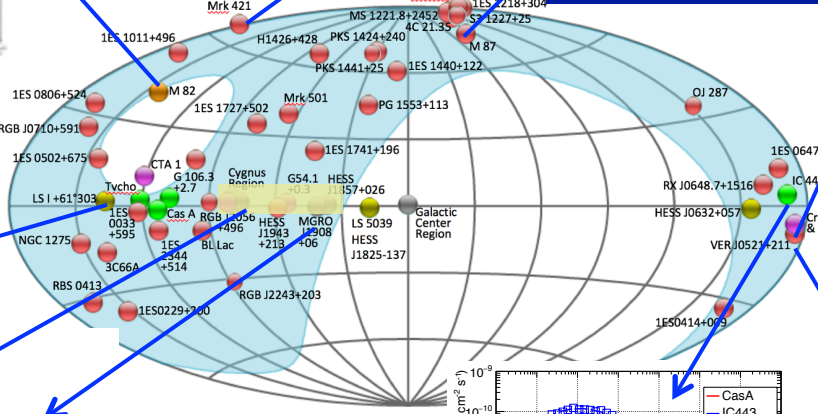




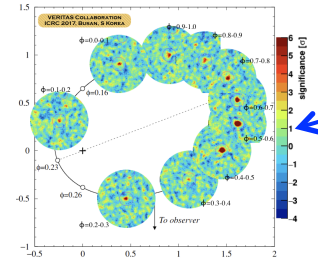
Radio Galaxies: Close, with misaligned jets



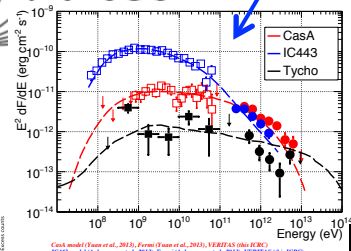


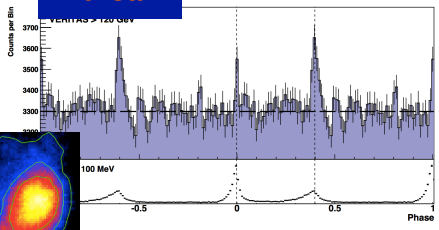


X-ray binaries

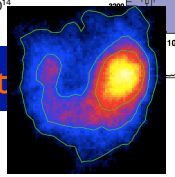


Pulsar

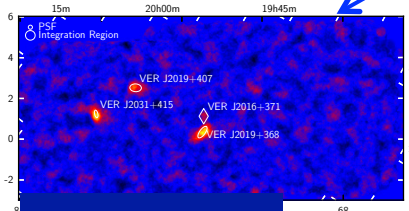




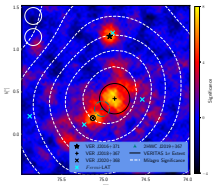
Supernova Remnant



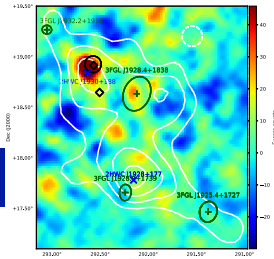
Cygnus Survey



Unidentifieds



Galactic sources

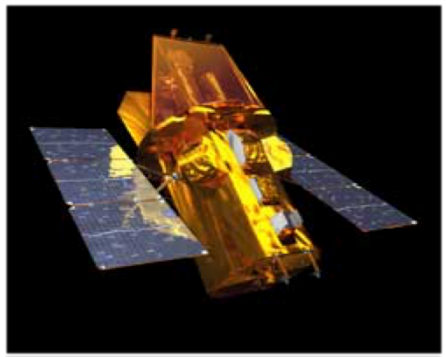


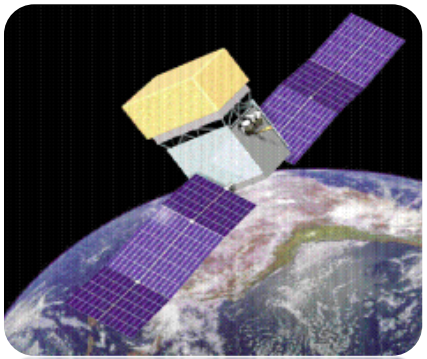
HAWC Follow-ups

VERITAS & Swift:
Why care about X-rays?

X-ray – Gamma-ray

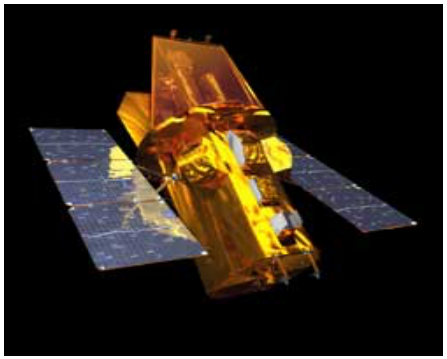
- We are at a "Golden Age" of multiwavelength astronomy.
- Gamma-ray data from ground-based TeV instruments are being complemented by Swift (X-rays) and Fermi-LAT (MeV-GeV).
- Unprecedented detailed studies of the dynamics of particle acceleration are now possible for:
    - Blazar jets
    - X-ray/TeV binaries
    - Gamma-ray bursts
    - PWNe, Supernova remnants
    - Unidentified TeV sources
    - Tidal disruption events (TDEs) ……..





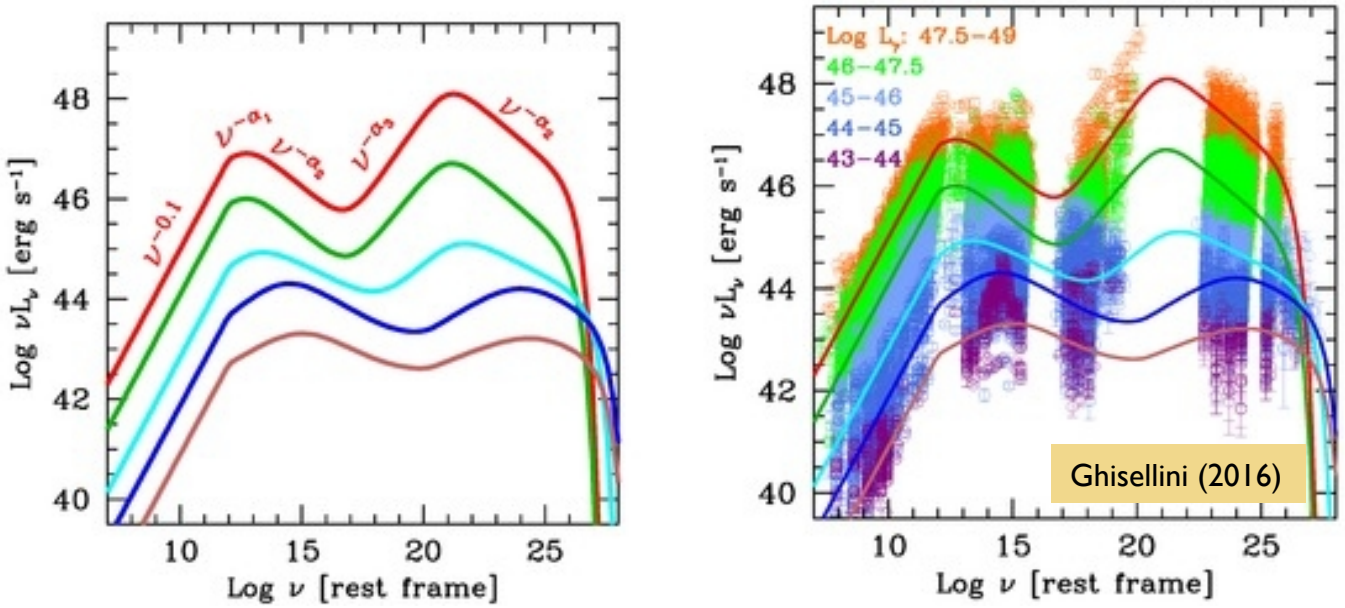
The **Power** of Swift

- Swift has a flexible observing strategy and the ability to react quickly to target of opportunity requests (ToOs).
- Swift is a great asset in multiwavelength campaigns.
- The availability of Swift Legacy observations, particularly for TeV blazars was a success story and Neil played a key role in making that instrumental.
- Data base useful for long term studies of the variability of objects. (Stroh & Falcone, arXiv:1305.4949v1)



BAT: 15 keV - 150 keV
XRT: 0.2 keV – 10 keV
UV/Optical: 650 nm - 170 nm

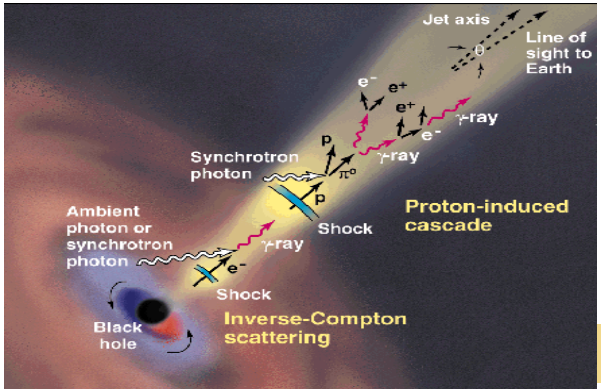
Understanding Blazar SEDs: The X-ray – γ-ray connection



Blazar SEDs: From low to high-frequency peaked sources. Simultaneous X-ray spectrum is crucial in interpretation of blazars from FSRQs to "Extreme" HBLs.

Coverage: VHE (HESS, MAGIC, VERITAS): 100 GeV – 50 TeV
MeV-GeV (Fermi/AGILE): 30 MeV – 300 GeV all sky
UV-Optical-X-ray (Swift/NuSTAR): up to 150 keV

Why Study VHE Blazars with X-rays?



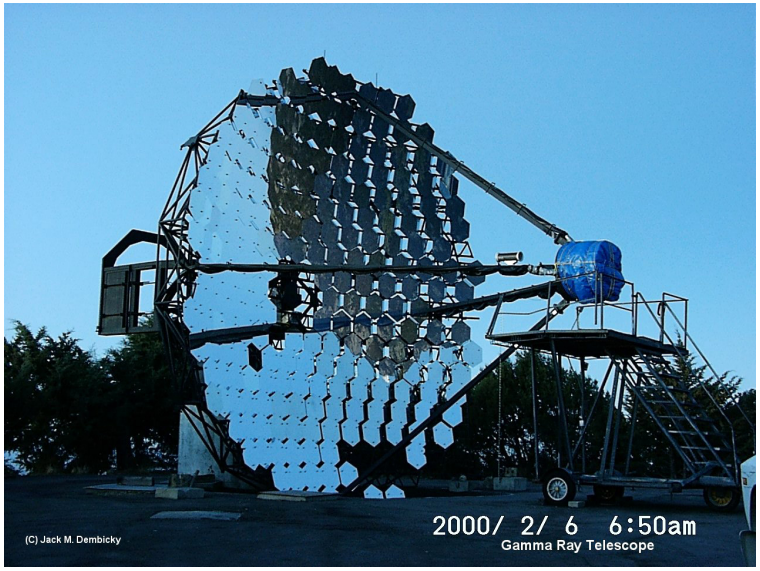
J.Buckley 1998

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

- 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.

Slide from Abe Falcone, VERITAS 10-Yr Meeting

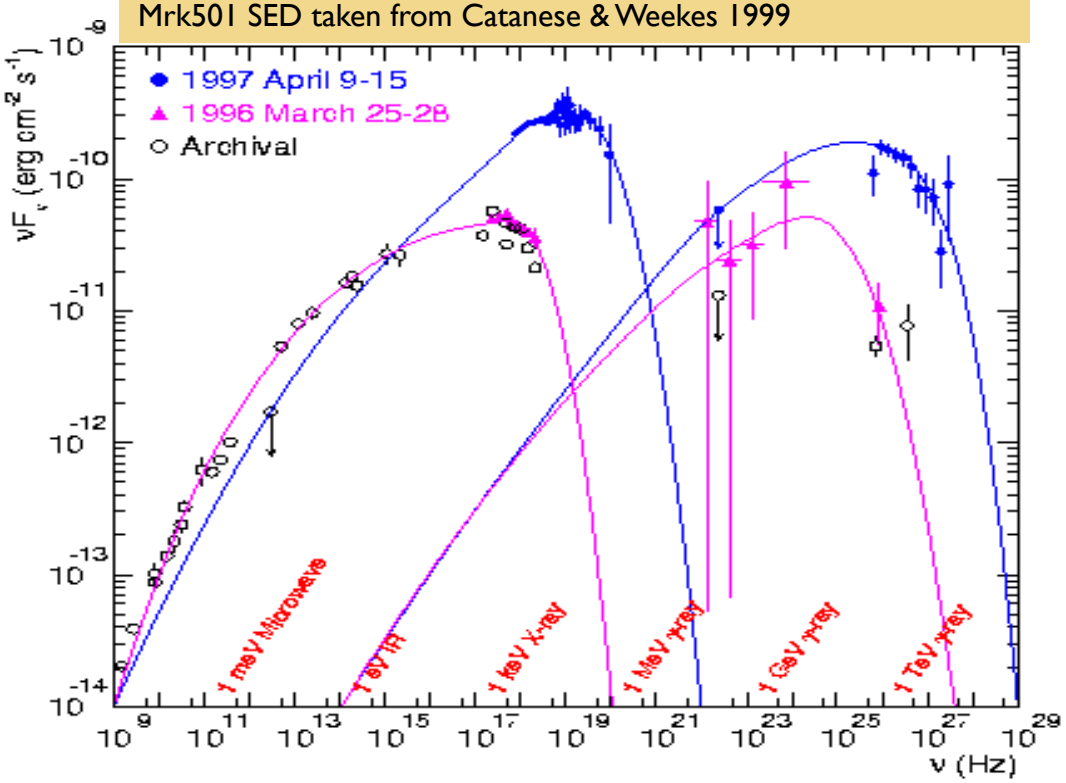
Blazars: Where were we before VERITAS & Swift?



- Whipple: Limited 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)

Slide from Abe Falcone, VERITAS 10-Yr Meeting

Mrk501 SED taken from Catanese & Weekes 1999

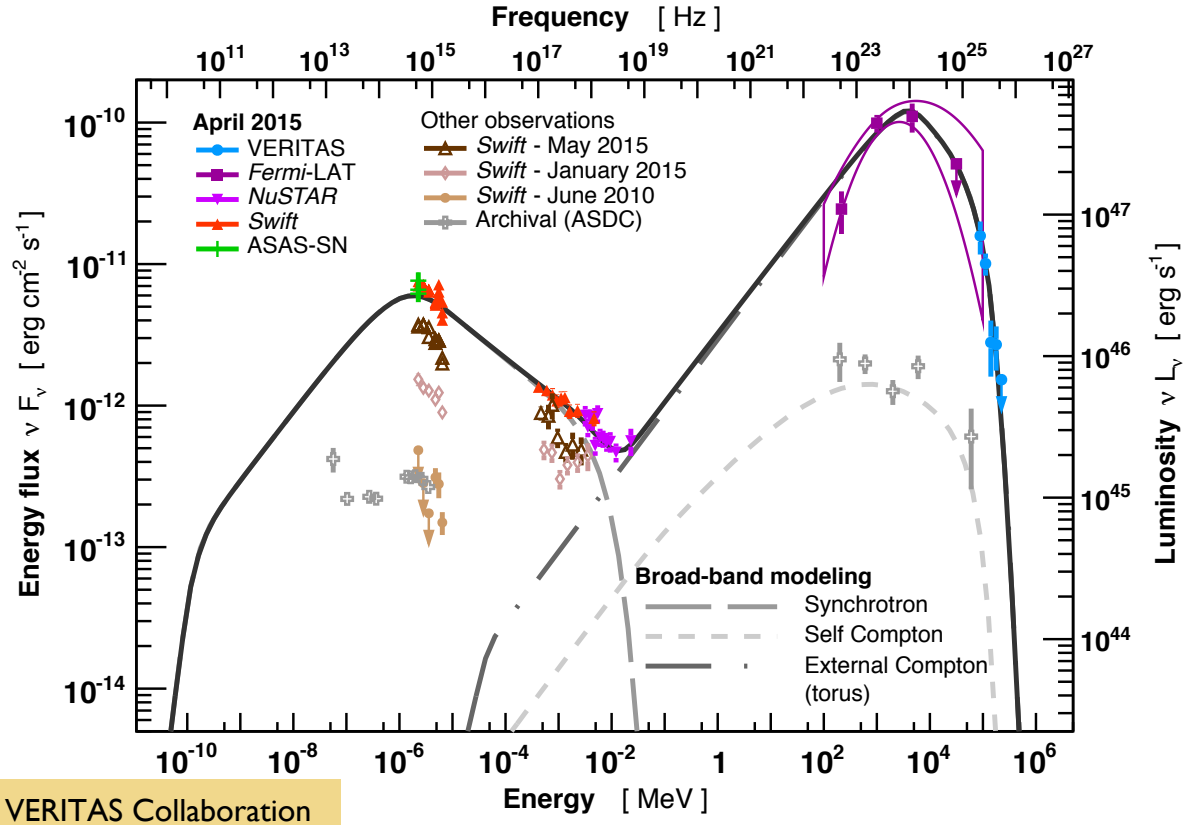


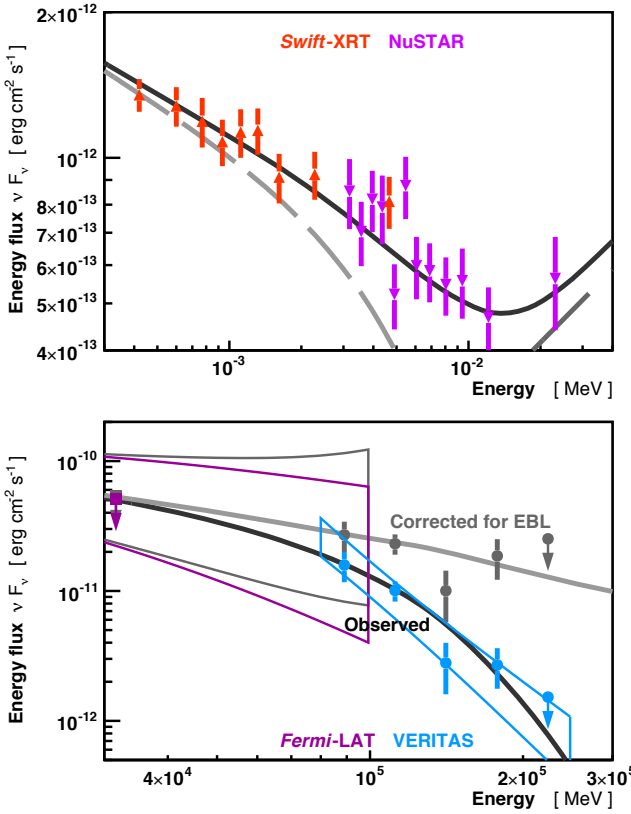
- Very few simultaneous multi-wavelength campaigns, coupled with difficult observing constraints with large slewing overhead for typical space telescopes, led to sporadic coverage of the critical spectral regions below the peak of the 2nd bump.
- Most transient studies involved the use of archival data.

Blazars: Now we have ……

Simultaneous multi-frequency monitoring of blazars to look for flares and their and relation to events in the relativistic jets.

Detection of γ rays (~200 GeV) from PKS 1441+25 (z = 0.939) during April 2015.

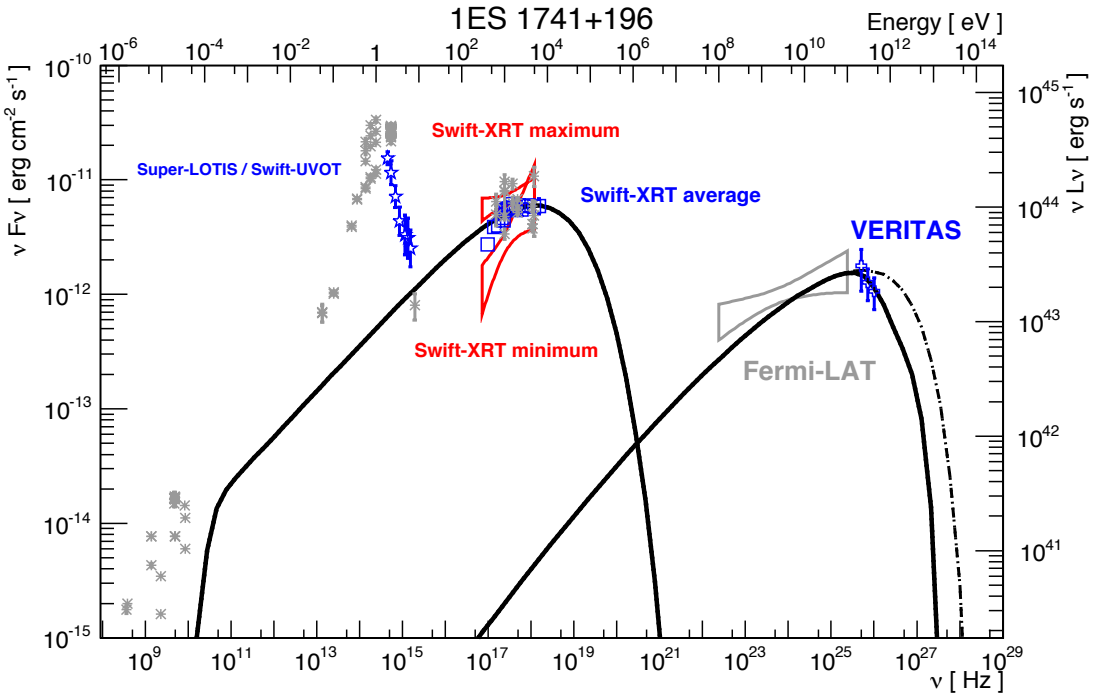




VERITAS Collaboration
1512.04434

Blazars: Now we have ……

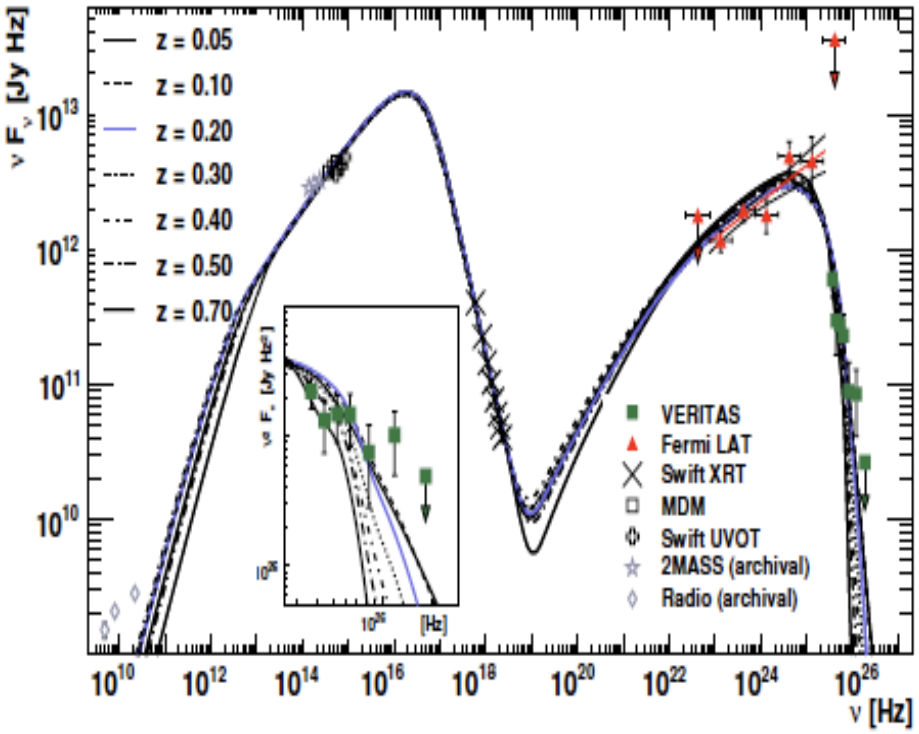
SED studies: An "extreme" HBL, 1ES 1741+196



VERITAS Collaboration
1603.07286

- Synchrotron peak-frequency constrained by average Swift–XRT spectrum: best-fit by broken-power-law with $\Gamma \sim 1.99$, $E_{break} \sim 1.20$ keV, indicating synchrotron peak-frequency located above 10.0 keV.
- SED of 1ES 1741+196 suggests VHE blazar may belong to the extreme-HBL class.
- VERITAS spectrum corrected for EBL absorption consistent with $\Gamma \sim 2.3$, indicating an IC peak-frequency above 100 GeV.

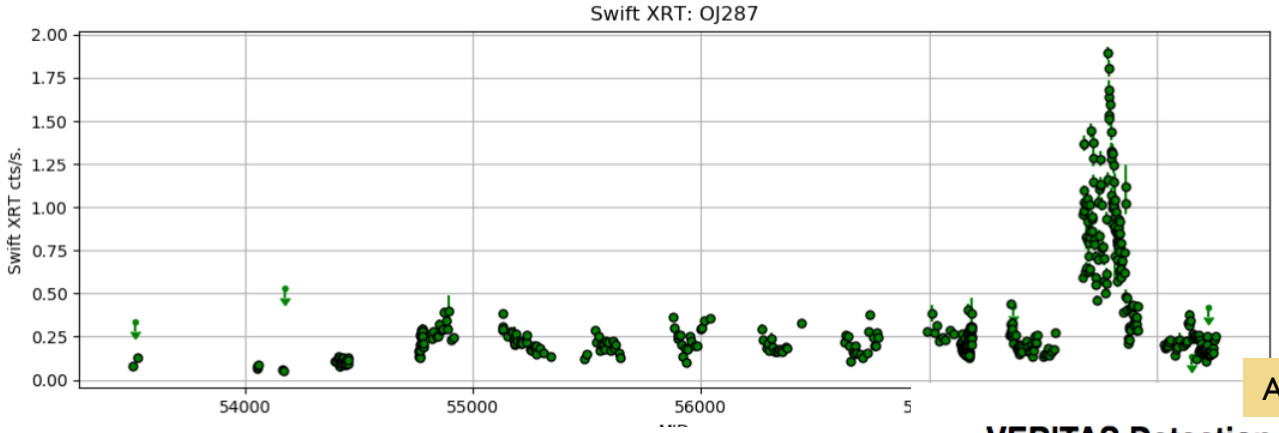
Blazar SED Studies … More Examples



VERITAS Collaboration
0912.0730

- SED of PKS1424+240 with constraints on redshift and emission mechanisms from data using Swift, Fermi, VERITAS, and others….
- 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).

Blazars at TeV Discoveries: OJ 287

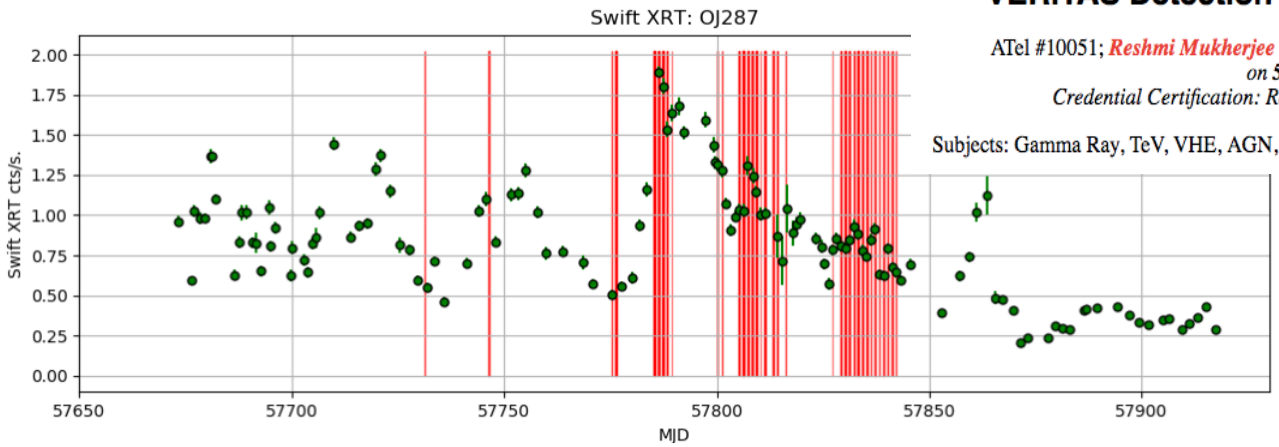


ATEL # 10051

VERITAS Detection of VHE Emission from OJ 287

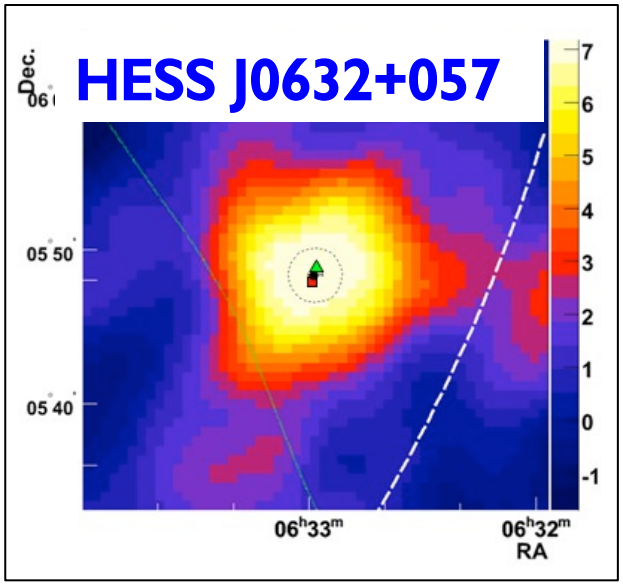
ATel #10051; *Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration*
on 5 Feb 2017; 02:02 UT
Credential Certification: Reshmi Mukherjee (muk@astro.columbia.edu)

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

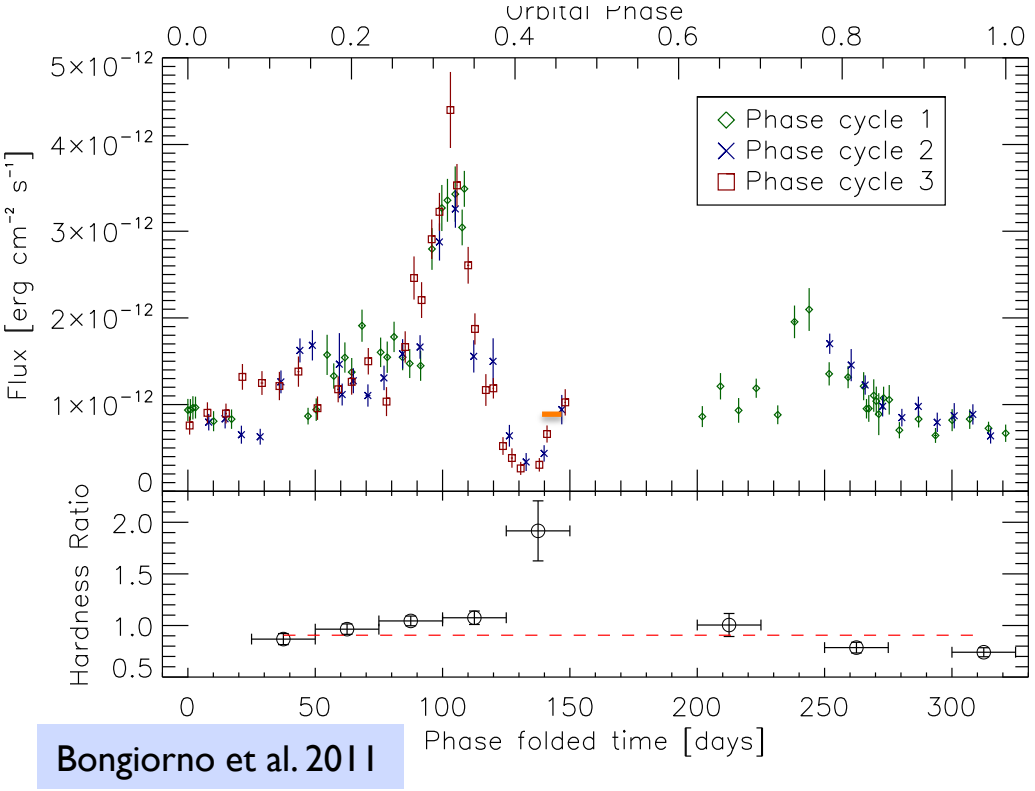


- Blazar OJ 287 (z ~ 0.3) detected by VERITAS during high X-ray activity/low Fermi-band activity.
- Proposed as a source with a binary supermassive black hole system.
- VERITAS triggered by high Swift state, which subsequently triggered Swift observations. .

Identification of a Gamma-Ray Binary



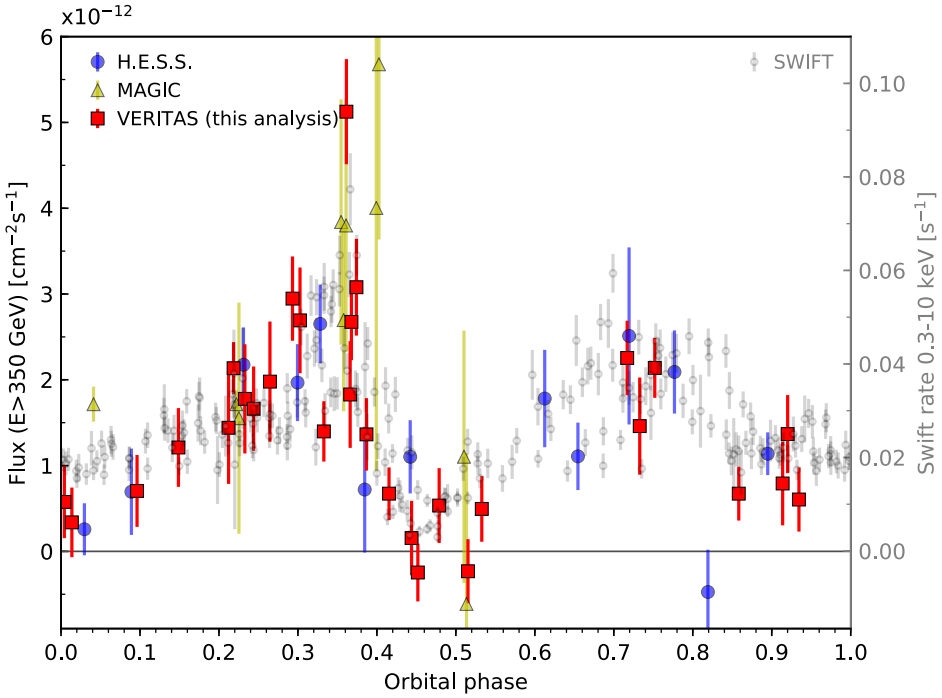
H.E.S.S. Collaboration 2007

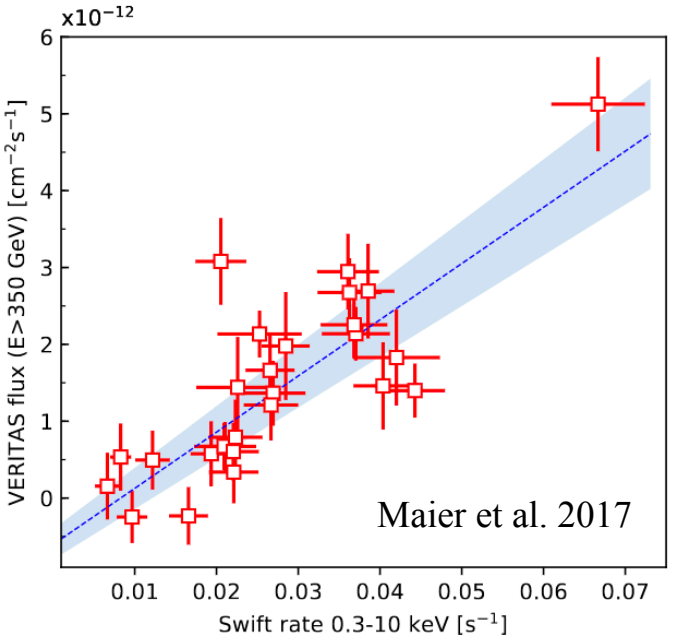


Bongiorno et al. 2011

- HESS J0632+057: variable, unidentified TeV source, located in the Monoceros region.
- Associated with massive Be star MWC 148.
- 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)
- Swift observations used to discover a new and enigmatic γ-ray binary (Falcone et al. 2010).

HESS J0632+057: Correlation of TeV & X-rays

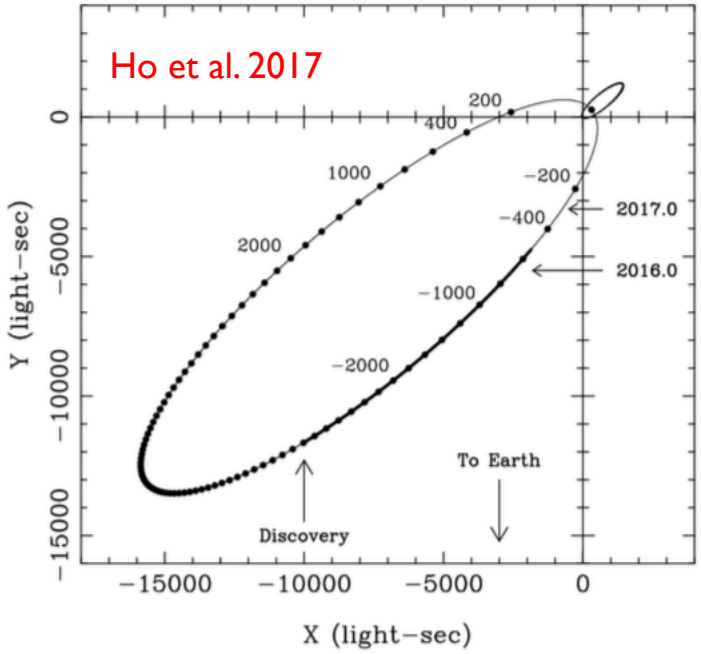


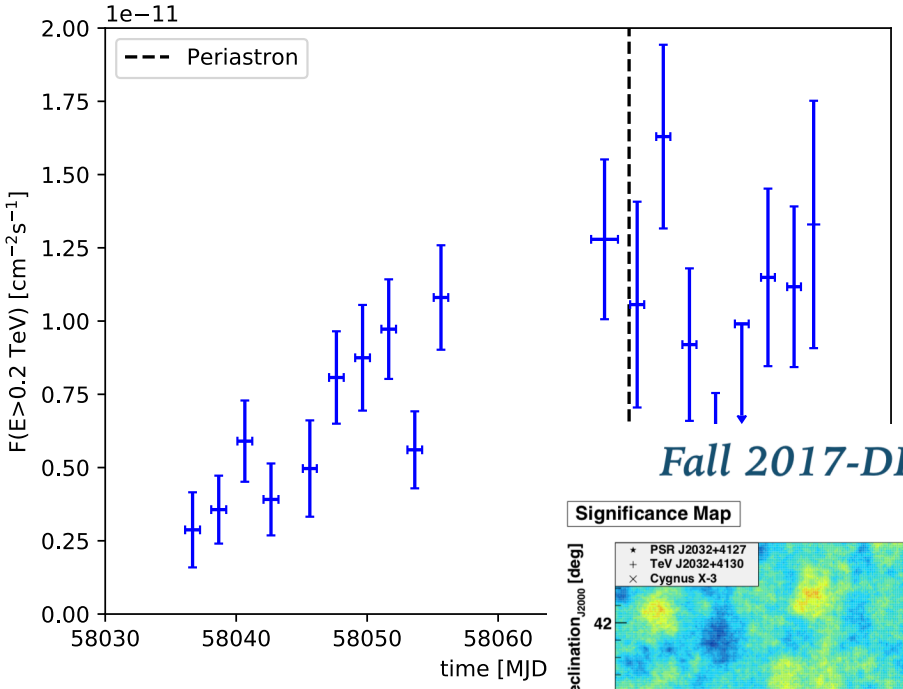


- VHE & Swift X-ray data indicate that the source is a binary period of 315 days.
- Tight correlation between X-ray and TeV.
- First binary discovered via γ-rays.

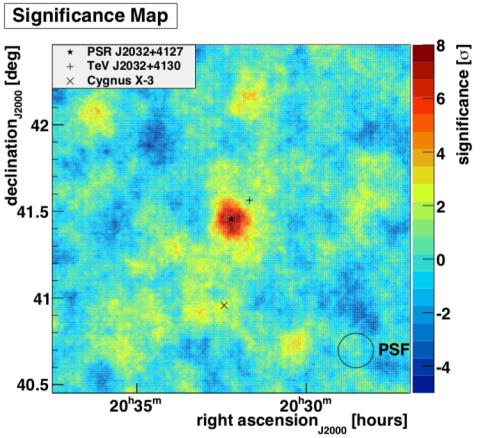
New TeV Binary: TeV J2032+4130

- Linked with the first unidentified TeV source TeV J2032+4130, dubbed the "dark accelerator."





Fall 2017-DR 1

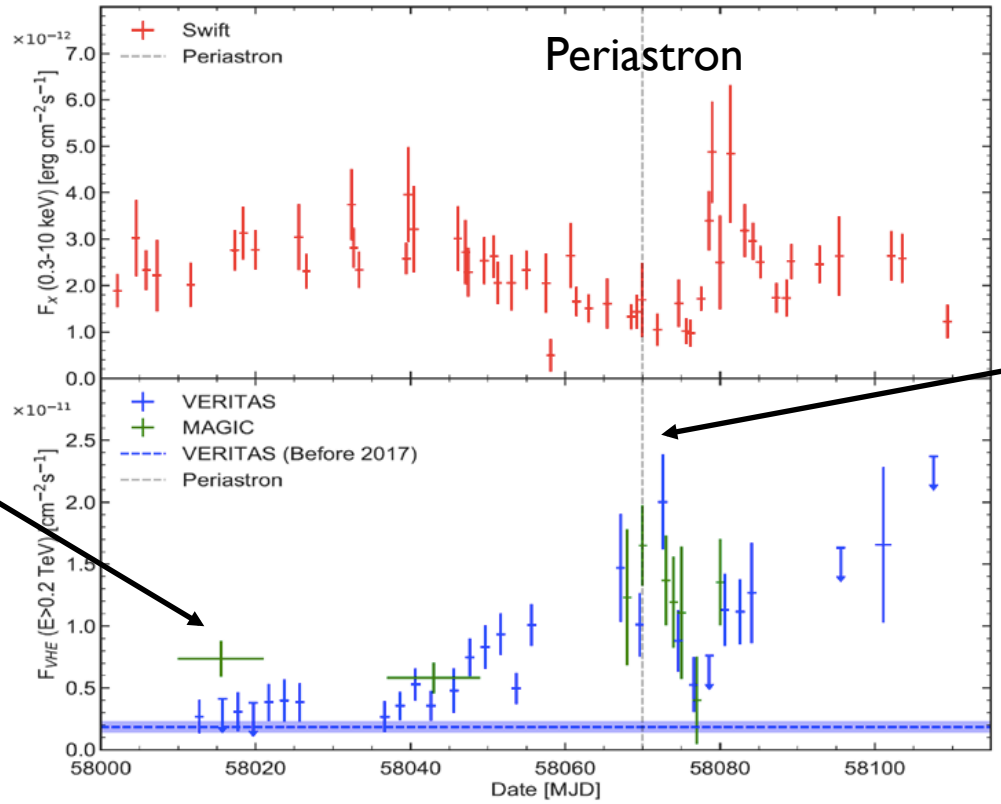


6.8 σ in 18.7 hrs

- The 50-year orbit of PSR J2032+4127/ MT91-213 binary system. Periastron predicted for November 2017.
- We have been watching the source. Thorough campaign carried out, long baseline, including pre-periastron.

New TeV Binary: TeV J2032+4130

- Swift X-ray monitoring during TeV flare.
- TeV light curve shows steady rise over 2 months up to periastron. Short dip & rebound after periastron.
- Ongoing studies to understand TeV and X-ray light curves and spectrum.

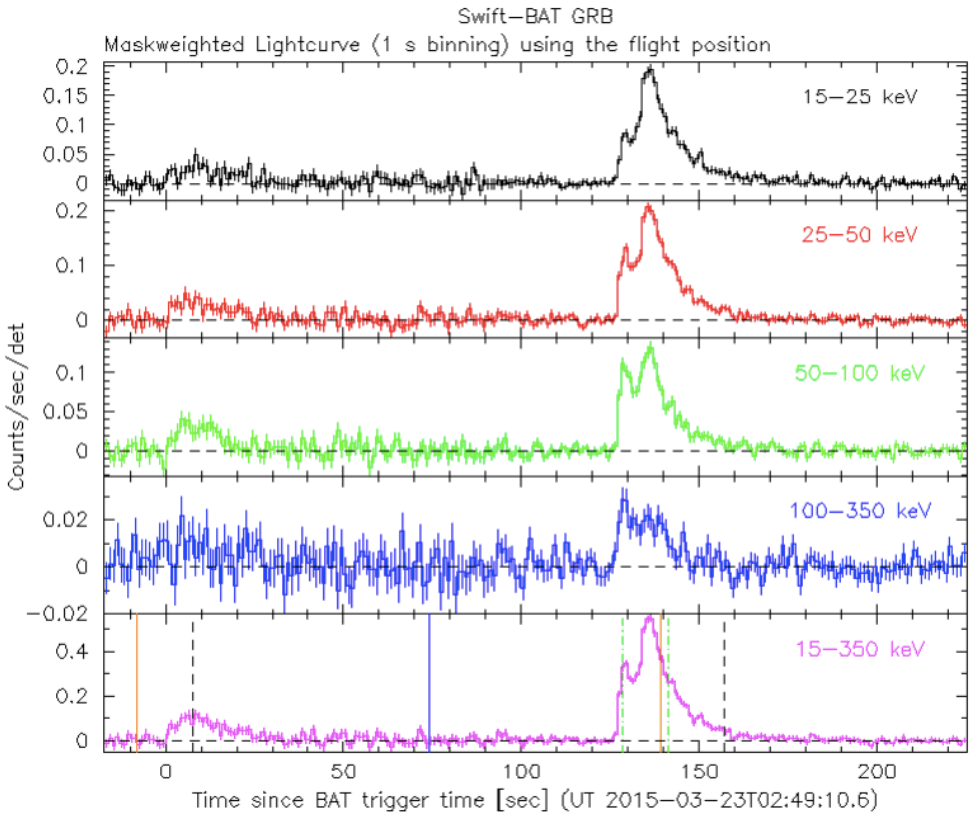


ATels #10810

ATels #10810

GRB 150323A: Constraints on the Environment

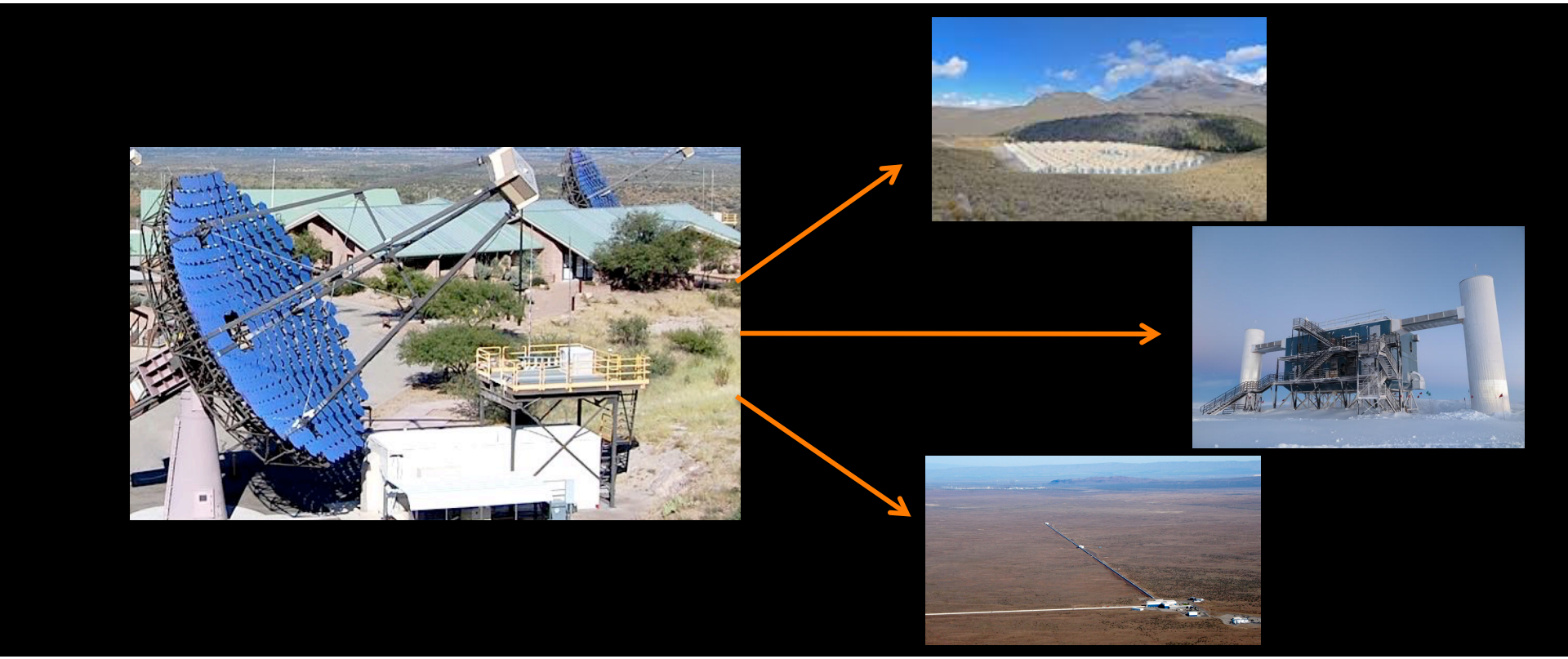
"A strong limit on the very-high-energy emission from GRB 150323A"



VERITAS Collaboration, ApJ (1803.01266)

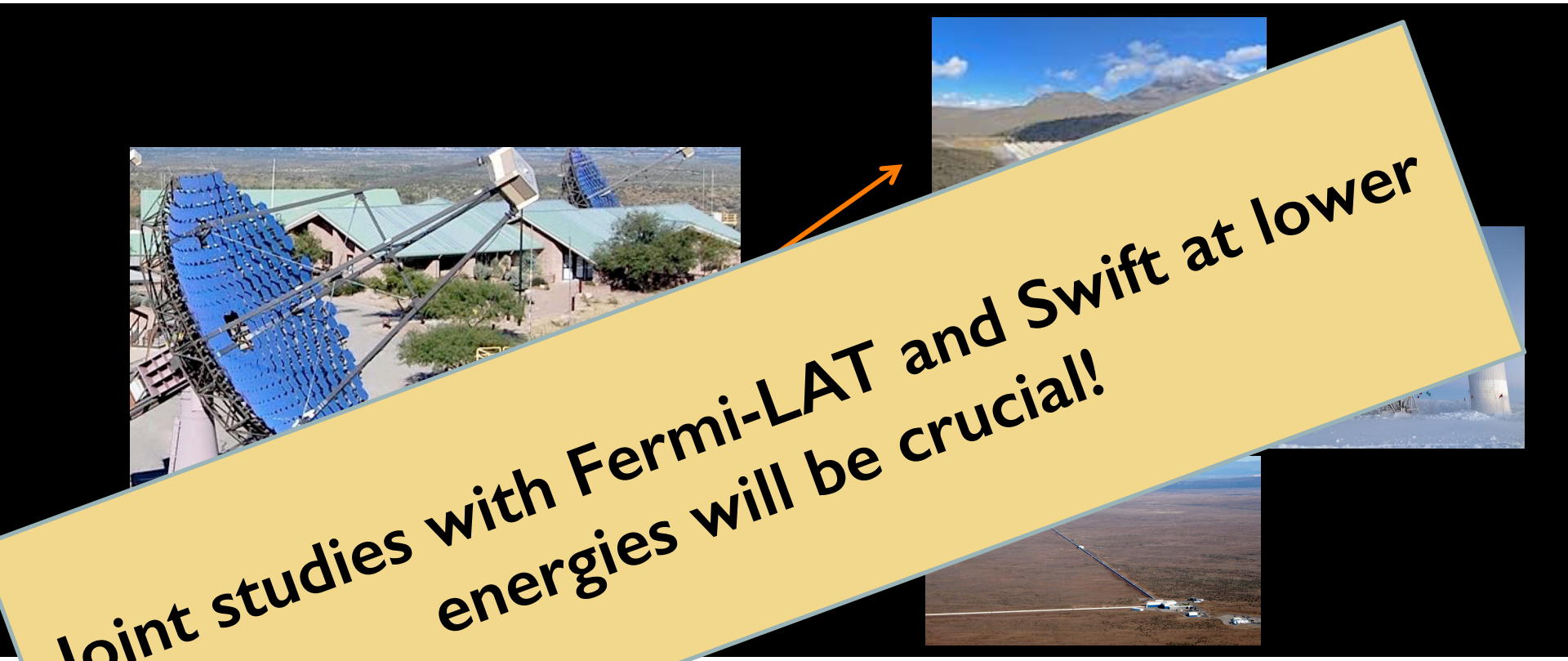
- Swift BAT burst at z ~ 0.6. VERITAS was on target 270 sec after Swift trigger from a precurser burst, and ~135 s after the start of the main GRB
- TeV UL at <1% prompt fluence.
- Weak VHE emission favors explosion into the stellar wind of dense progenitor (Wolf-Rayet star), or a weak blast wave with low electron cooling due to a tenuous ISM.
- EBL attenuation not a significant factor.

Looking to the Future: VERITAS Multi-Messenger Program



- **Cosmic ray sources:** Follow up of HAWC sources of TeV γ rays.
- **Astrophysical Neutrinos**: Observation of IceCube neutrino positions. Prompt follow-up of neutrino alerts.
- **Gravitational Waves:** Planned follow-up observations of LIGO-VIRGO alerts.

Looking to the Future: VERITAS Multi-Messenger Program



Joint studies with Fermi-LAT and Swift at lower energies will be crucial!

- ...low up of HAWC sources of TeV γ rays.
- ...**eutrinos**: Observation of IceCube neutrino positions. Prompt f... of neutrino alerts.
- **Gravitational Waves:** Planned follow-up observations of LIGO-VIRGO alerts.

Thank you

Neil was always incredibly supportive of VERITAS, and of gamma-ray astronomy in general, and his support really came through when Swift gave us the opportunity to obtain a legacy of multiwavelength campaign data.

The VERITAS Collaboration would like to thank the Neil Gehrels Swift Observatory Team for enabling excellent collaborative work and successful scientific studies. The scientific legacy from these joint studies will benefit generations of future scientists and will help them take our discoveries to higher levels.