VERITAS Observations of Very High-Energy Phenomena

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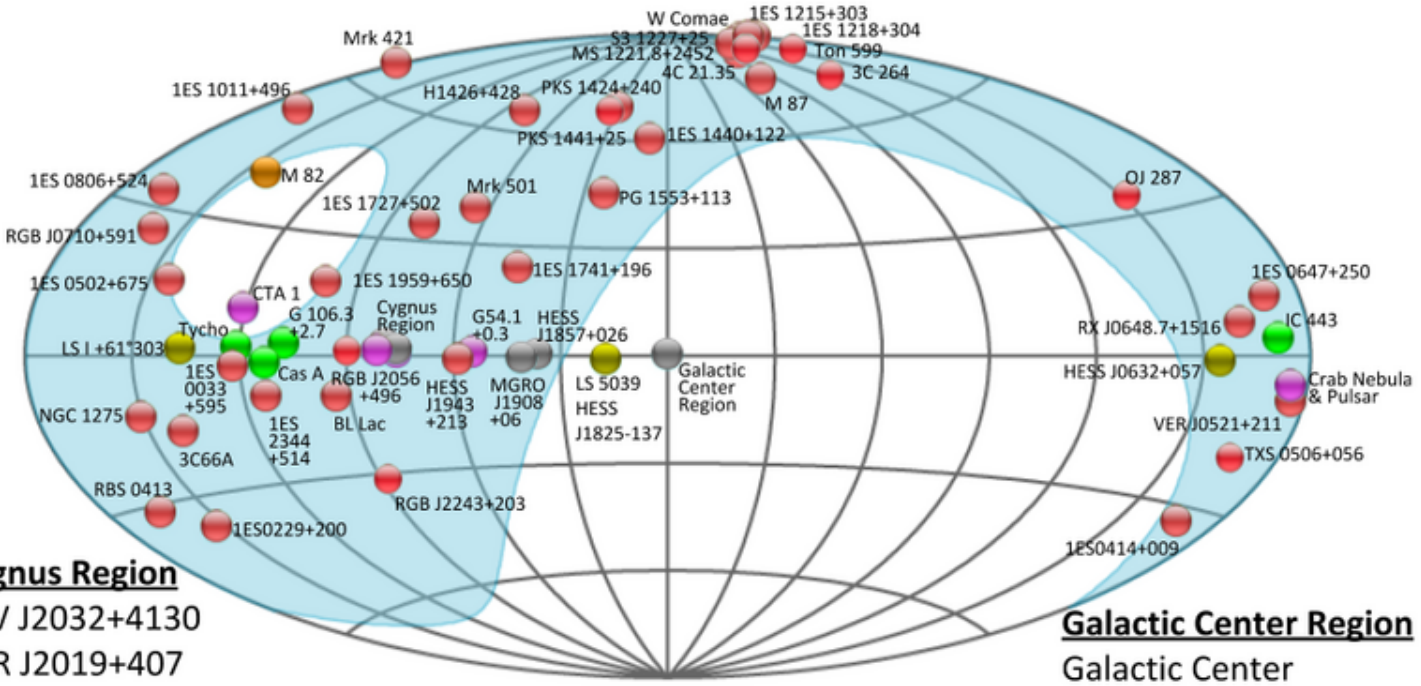
VERITAS Observatory Overview

- Study very-high-energy (~85 GeV to ~30 TeV) γ-rays from astrophysical sources
- Full-scale operations since 2007; Major upgrade completed in 2012
- Good-weather data / yr: ~950 h in “dark time” + ~250 h in “bright moon” (illum. >30%)

- Sensitivity: 1% Crab in <25 h
- Angular resolution: r_{68} ~ 0.08˚ @ 1 TeV
- Energy resolution: ~17%
- Energy Threshold: ~85 GeV
- Spectral reconstruction > 100 GeV
- Systematic errors: Flux ~20%; Γ ~ 0.1

The VERITAS Source Catalog



Cygnus Region

TeV J2032+4130
VER J2019+407
VER J2019+368
VER J2016+372
VER J2032+414

Galactic Center Region

Galactic Center
Galactic Center Ridge
VER J1746-289
G 0.9+0.1

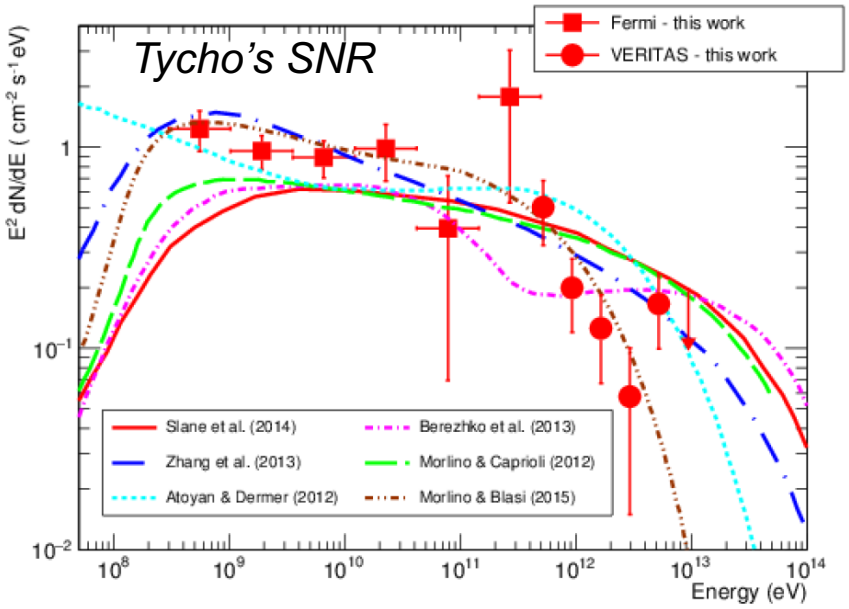
63 sources from 8 astrophysical classes

40 Extragalactic & 23 Galactic objects

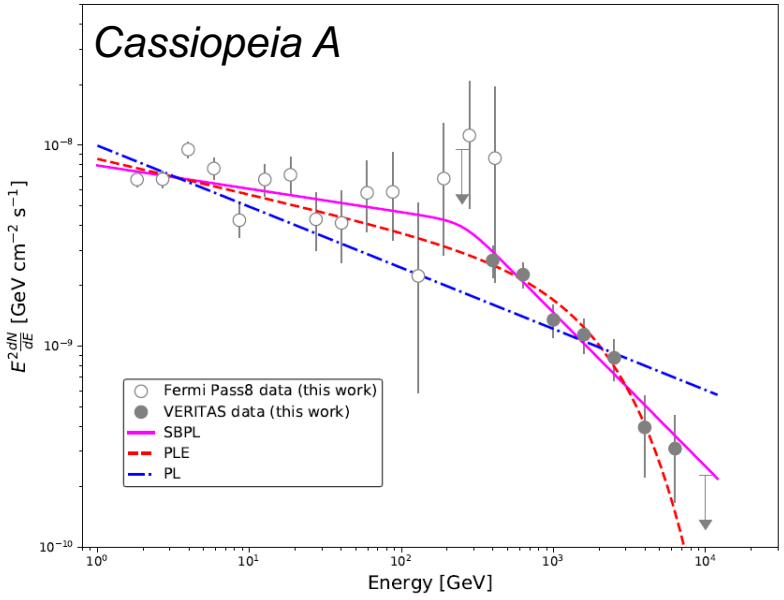
Galactic: PWNe, SNR, binaries, unidentified

Extragalactic: BL Lacs, FSRQs, radio galaxies & a starburst galaxy (M82)

Young Supernova Remnants: Tycho & Cas A



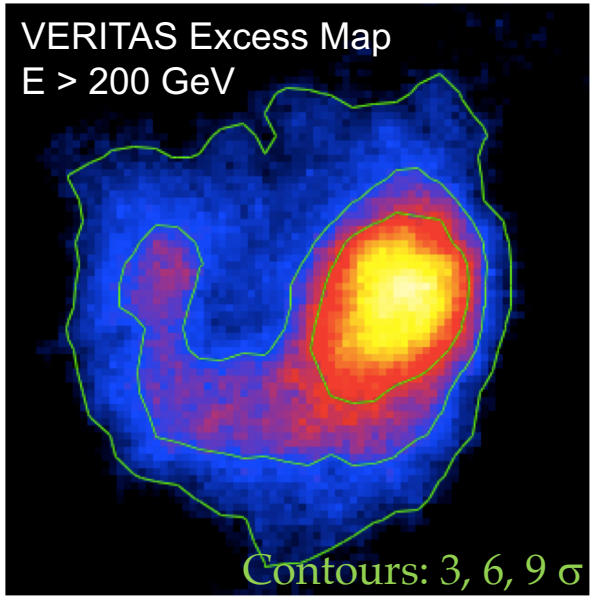
147 hr VERITAS, 84 mo Fermi-LAT
Archambault *et al.*, *ApJ,* **836**, 23 (2017)

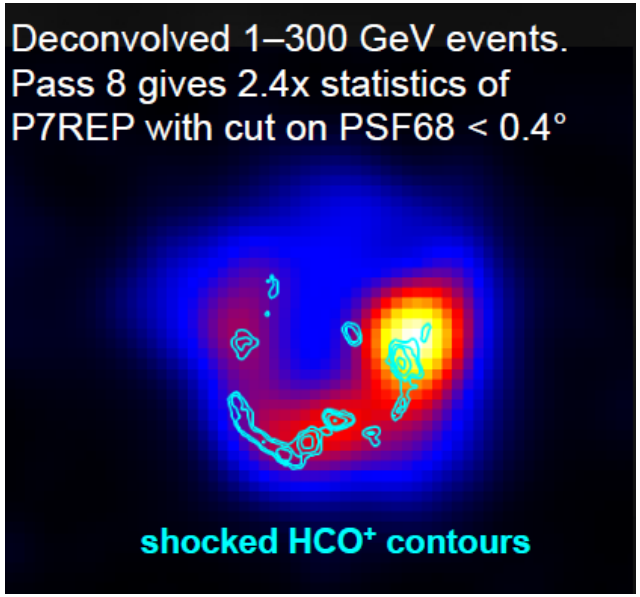


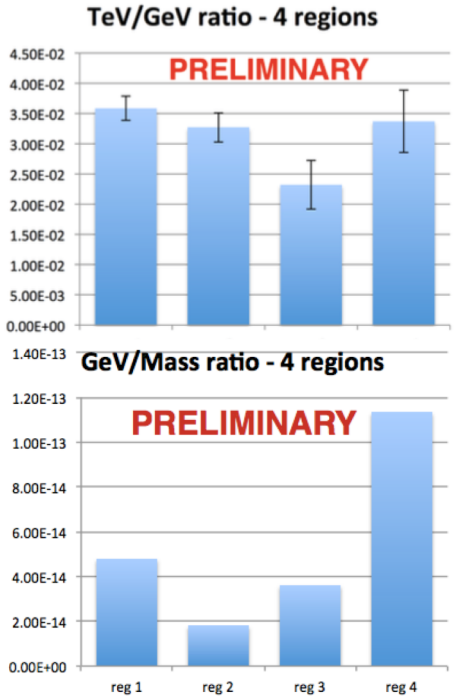
Abeysekara *et al.* (2018), in prep.

- Both Tycho and Cas A show spectral softening in the TeV range
- These are not today's PeVatrons, but they are (almost certainly) hadronic accelerators
- Any PeV particles have escaped

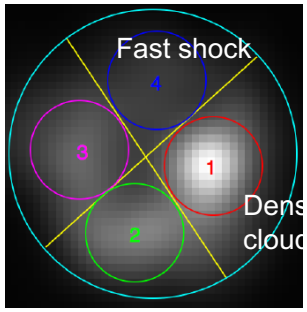
Interacting SNR: IC 443

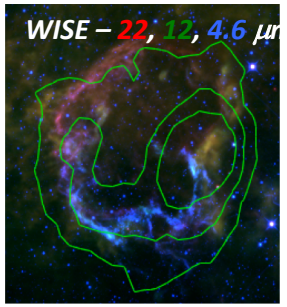






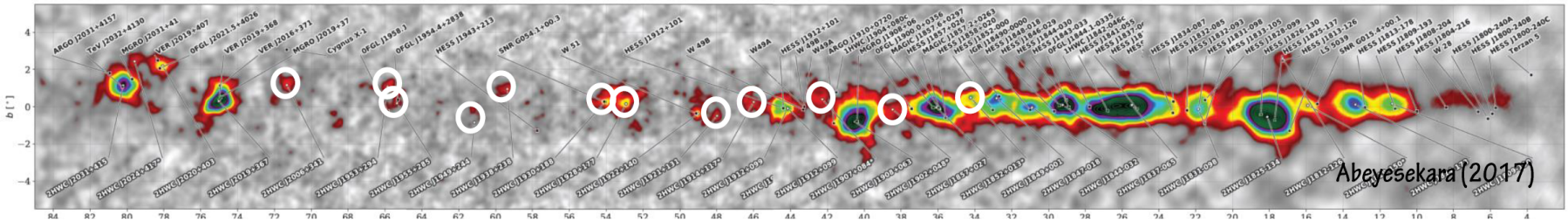
- Resolved middle-aged shell, with strong case for emission dominated by hadronic CRs
- Strong differences in environment but no clear differences in spectral shape
- Order of magnitude variation in intensity but TeV/GeV integral flux ratios consistent within errors
- Common morphology from GeV to TeV argues for single CR population





Sources from HAWC Second Catalog

507 days of observation with HAWC found 39 γ-ray sources



- 16 sources > 1° from any known TeV γ-ray sources
- **VERITAS** has 187 hrs exposure on 13 out of 16
  - Limits for 12 sources: rule out point source for 5 and require > 0.23° radius for 2
  - New detection: ***2HWC J1953+294 = VER J1952+294 = DA 495 PWN***

Park (VERITAS), arXiv:1708.05744

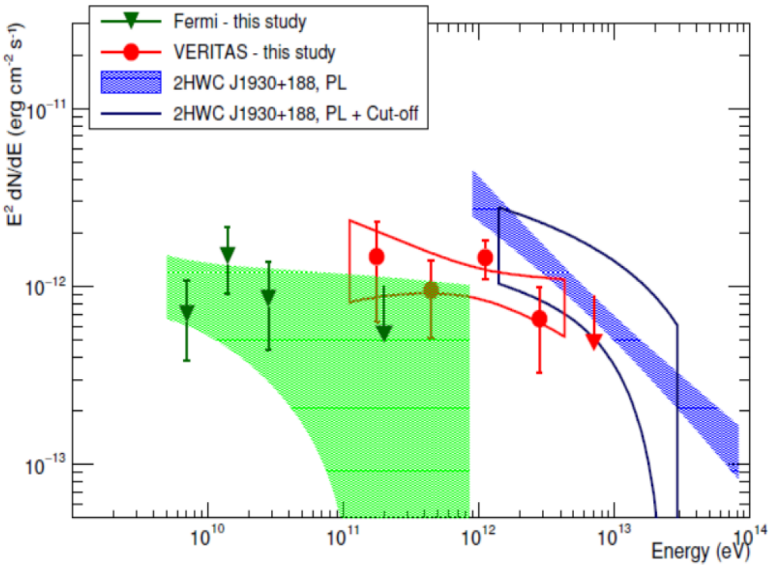
- ***Fermi*-LAT** accumulated 8.5 years of exposure over all sky, improved sensitivity with Pass 8 (E > 10 GeV)
- Non-detection for 13 sources
- New detection of known TeV source SNR G54.1+0.3, PWN of PSR J1930+1852 [Acciari *et al., ApJL,* **719**, L69 (2010)]

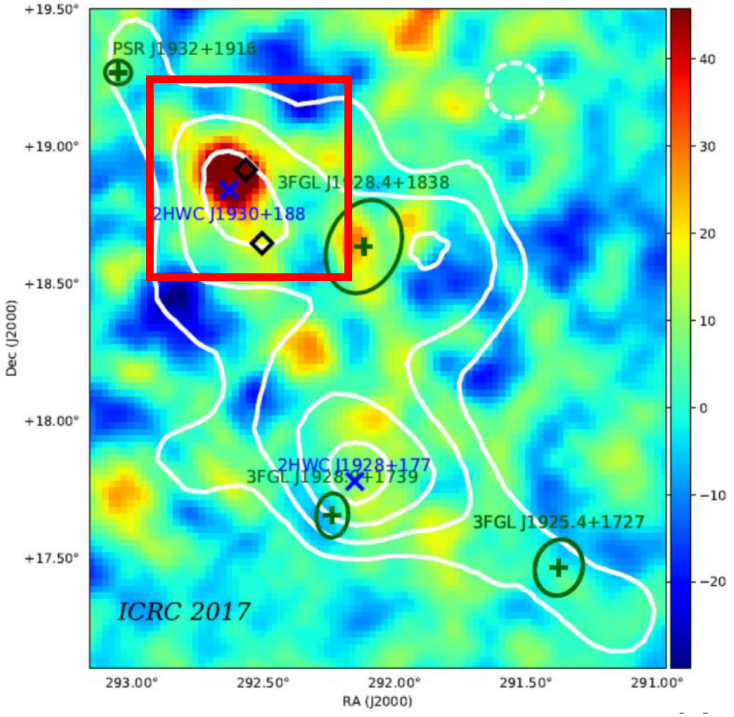
See also H. A. Ayala Solares, "The HAWC Catalog of VHE Sources" on Friday

SNR G54.1+0.3 and surroundings

Detection of Fermi coincident with known TeV source, VER J1930+188, and 2HWC J1930+188.

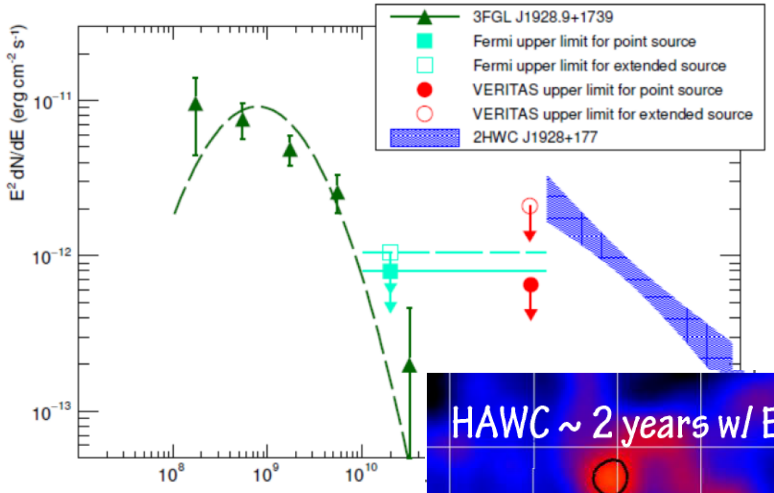
- SNR G54.1+0.3 is likely the counterpart.
- Fermi, VERITAS, & HAWC combined: the overall SED is more consistent with PL + cut-off hypothesis.

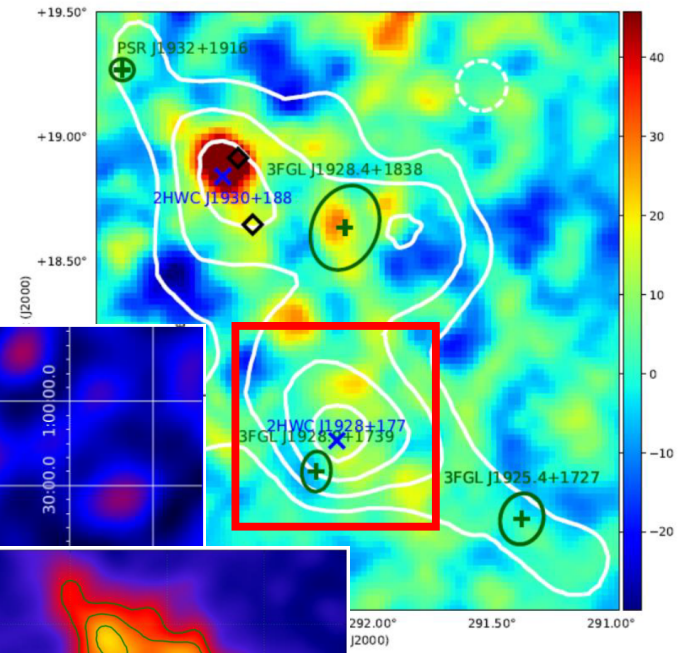


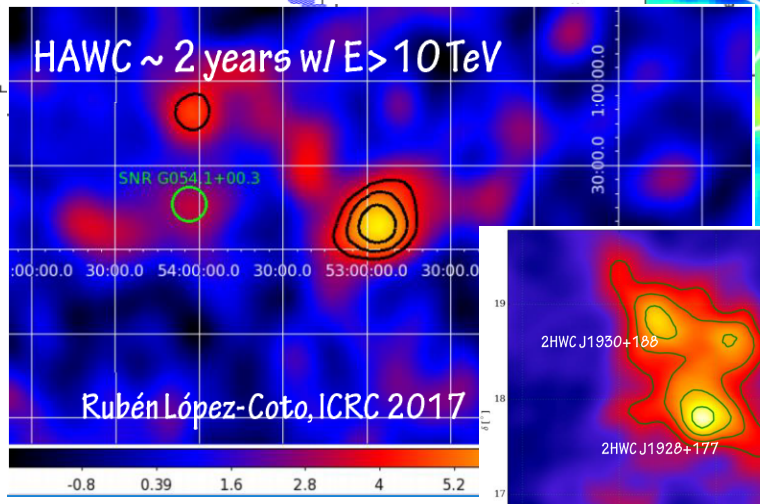


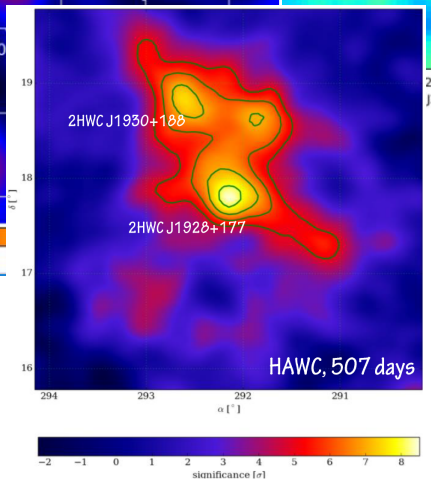
Park (VERITAS), arXiv:1708.05744

SNR G54.1+0.3 and surroundings









2HWC J1928+177

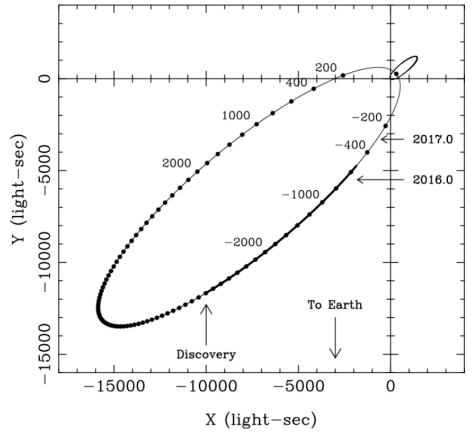
- Coincides with pulsar PSR J1928+1746
- Similar strength to 2HWC J1930+188 for HAWC
  - Stronger for E>10 TeV
- VERITAS upper limit excludes a point source hypothesis assuming the same PL spectrum

Park (VERITAS), arXiv:1708.05744

PSR J2032+4127: Counterpart of TeV J2032+4130?

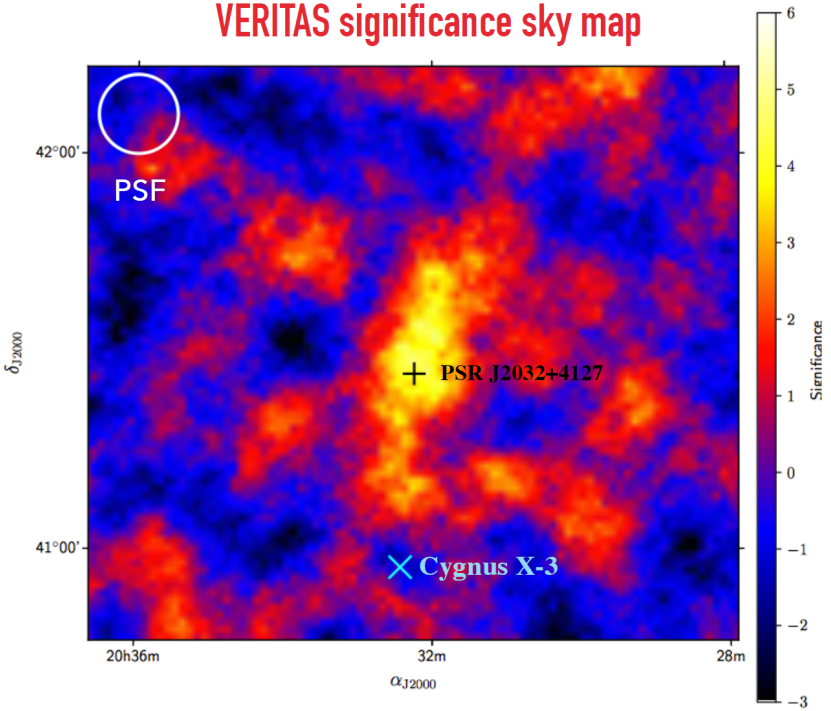
- TeV J2032+4130: the 1st "dark" γ-ray emitter
  - Discovered by HEGRA
  - 0.5° from Cygnus X-3
- Fermi-LAT discovered a pulsar 0.16° from the center of the TeV emission
  - PWN associated with the Fermi pulsar?
  - Does not explain extension
- Lyne+ 2015 suggest the pulsar is in a binary system with a Be star (MT91 213)
  - 45–50 yr period with periastron on November 13, 2017 (MJD 58070)
  - Eccentricity ~ 0.95
- Monitored thru 2016–17 in conjunction with MAGIC

Bird (VERITAS), arXiv:1708.04718



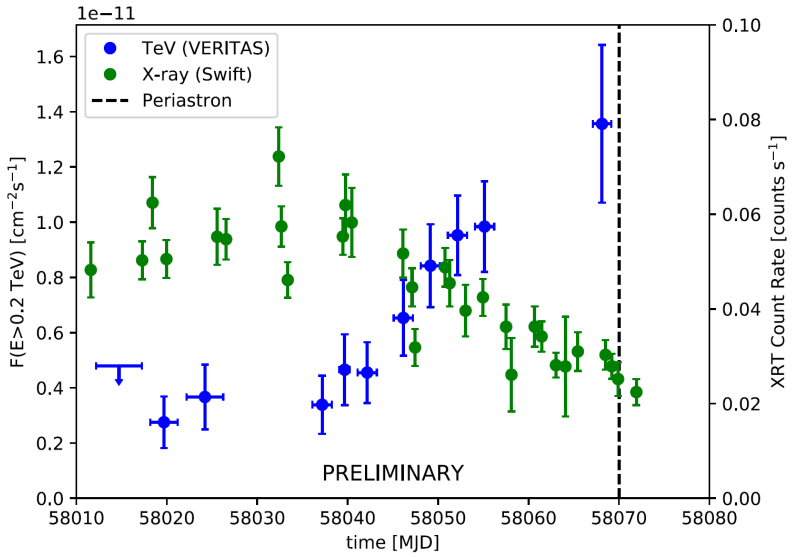
Lyne+ 2015, Ho+ 2017

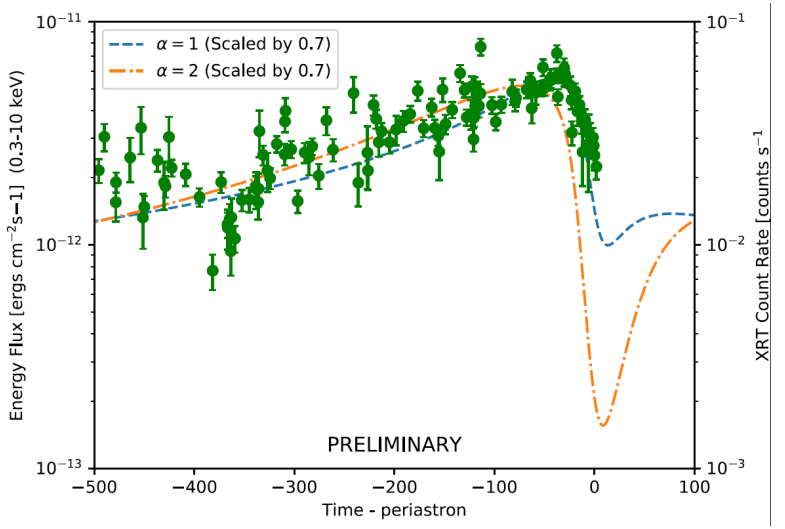
VERITAS significance sky map



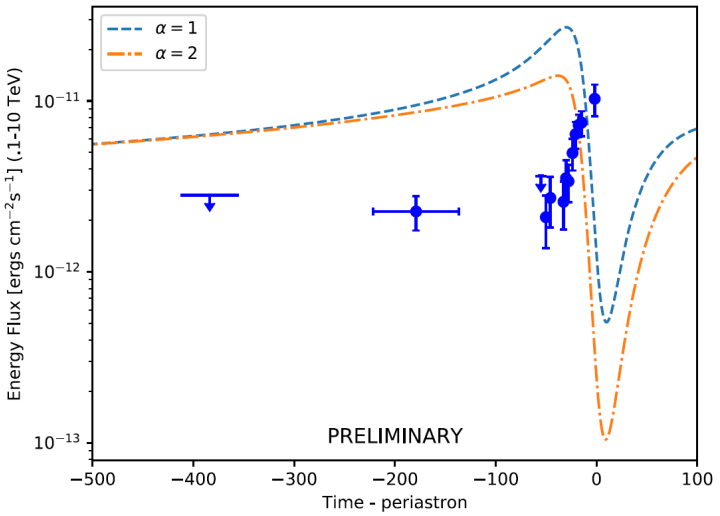
PSR J2032+4127: Flux Rising Towards Periastron

- Enhanced flux detected beginning in September 2017
- Comparison to X-ray monitoring (Swift) and previous modeling



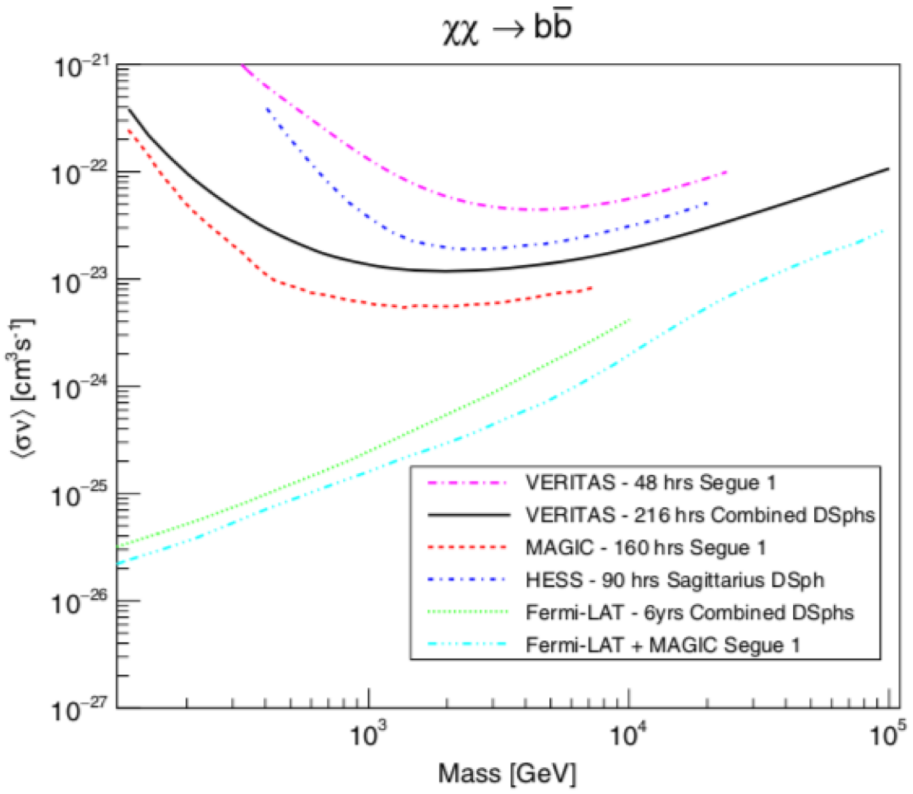


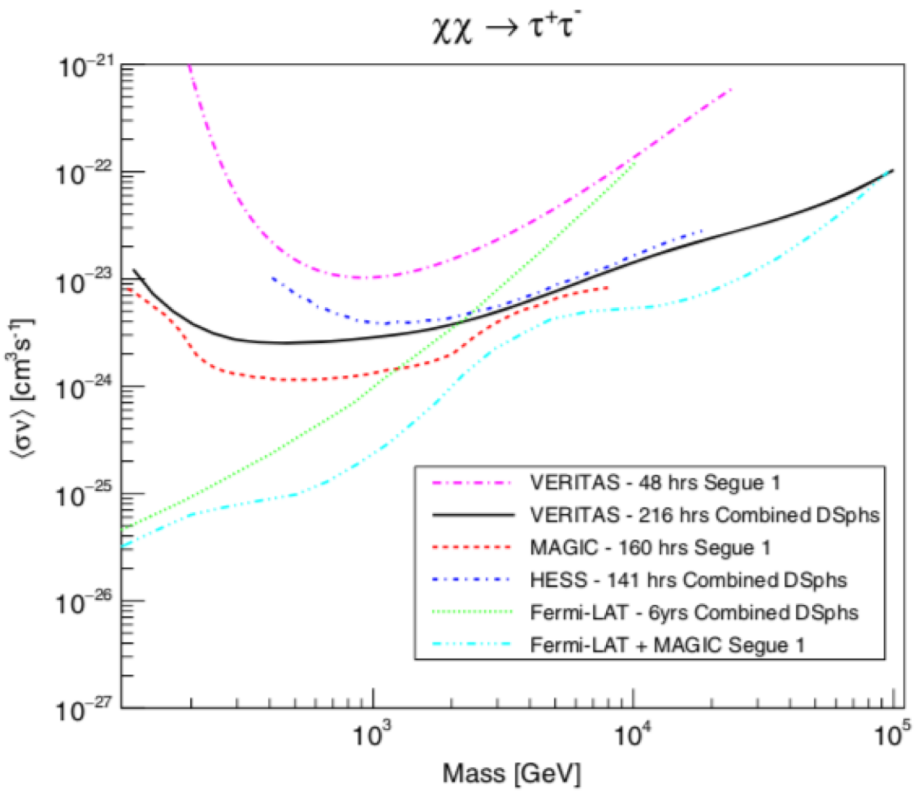
Model: Takata *et al., ApJ,* ***836,*** 241 (2017)



- X-rays, TeV not well correlated
- System geometry, timing not completely understood?
  - Pulsar wind interacting with disk? γ–γ absorption? Geometry will improve when pulsar timing solution during periastron is released

Dark Matter Limits

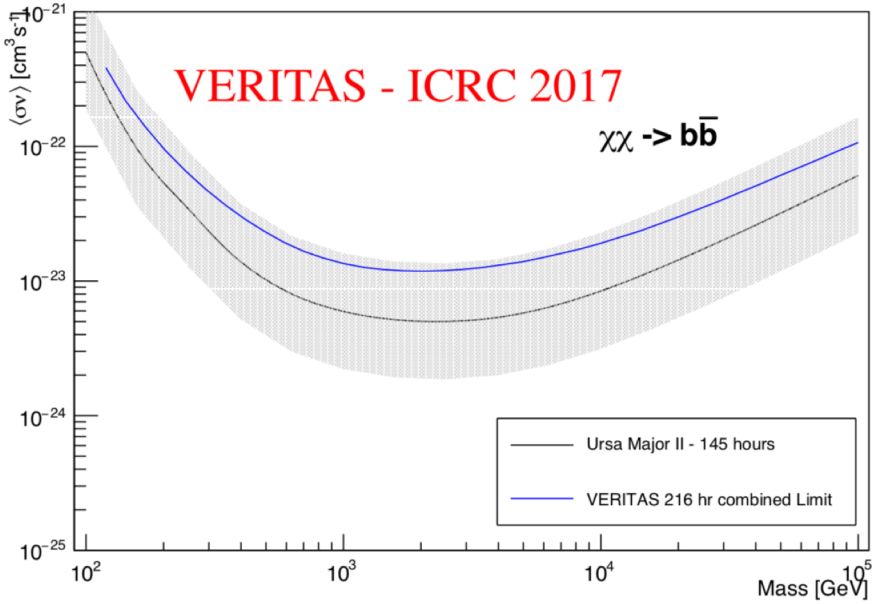


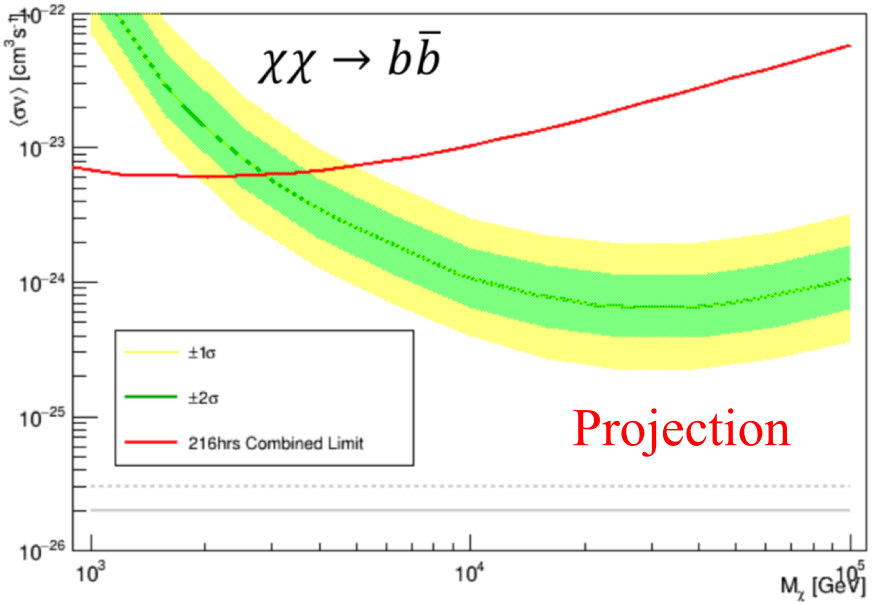


- Combined result from four dwarf galaxies: Segue 1, Ursa Minor, Draco, Boötes
- IACT dwarf results similar
- Fermi-LAT dominates for low-mass WIMPs

Archambault *et al., PRD*, **95**, 082001 (2017)

Dark Matter Search Prospects





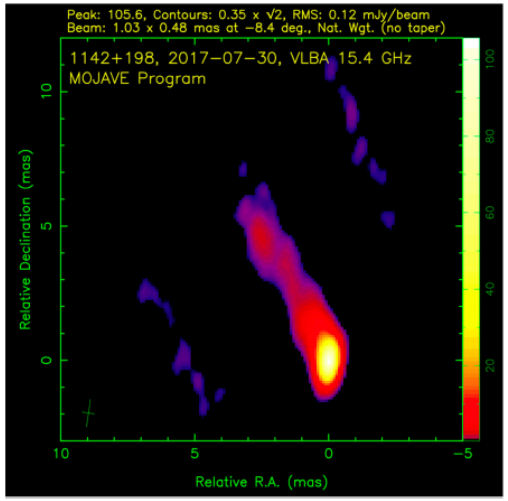
- Preliminary limit from 145 hours observing Ursa Major II

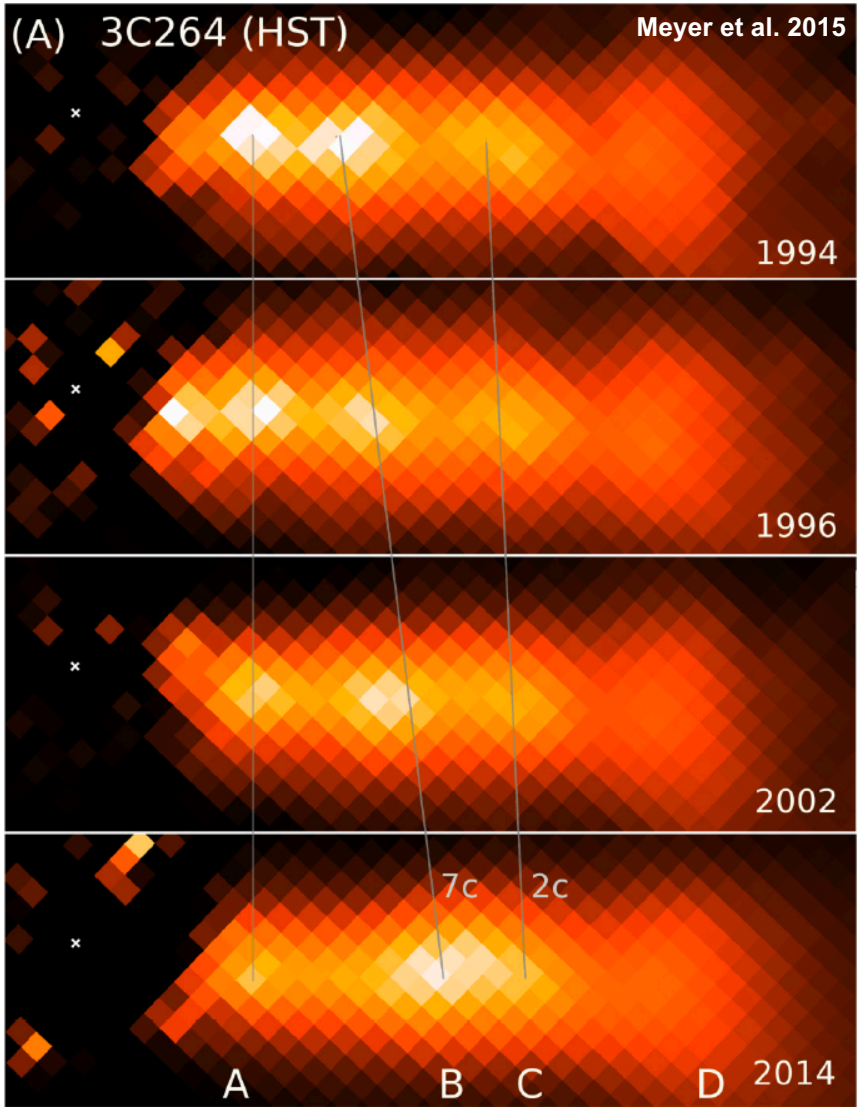
Zitzer (VERITAS), arXiv:1708.07441

- Projected sensitivity of Galactic Center observations through mid-2018

VERITAS Observations of 3C 264

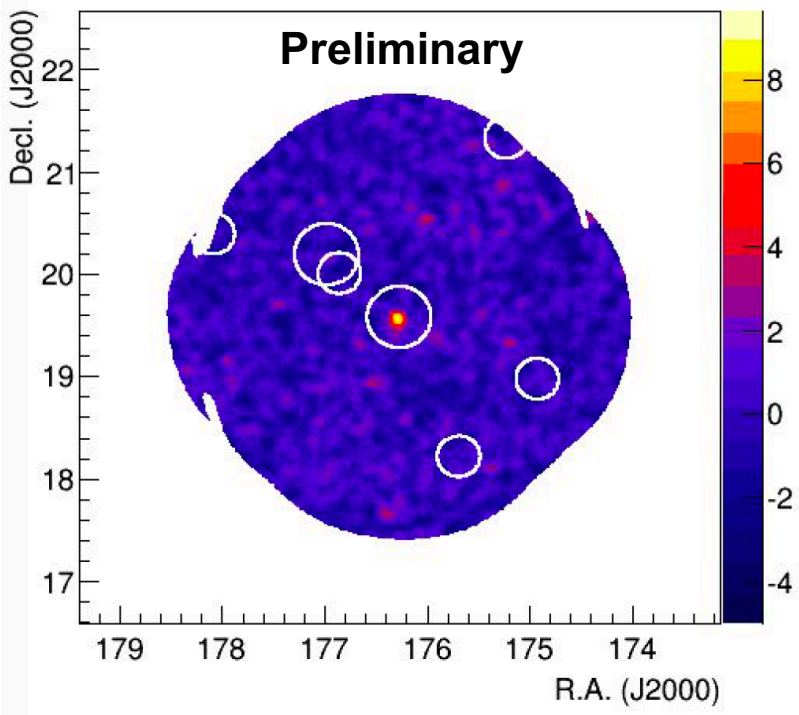
- More distant (~6x) “M87” analog
  - FR-I radio galaxy, z = 0.0216
- Rapidly evolving knot-structure
- MeV-GeV source: 3FGL, 2FHL & 3FHL
  - Γ_{3FHL} ~ 1.65 => F(>200 GeV) ~ 1.6% Crab
- VERITAS ~10 h observation in 2017
  - ~2σ excess => 2018 follow-up





VERITAS VHE Discovery of 3C 264

Significance map for 3C 264



VERITAS discovery of VHE emission from the FRI radio galaxy 3C 264

ATel #11436; *Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration*
on 17 Mar 2018; 00:25 UT
Credential Certification: Reshmi Mukherjee (muk@astro.columbia.edu)

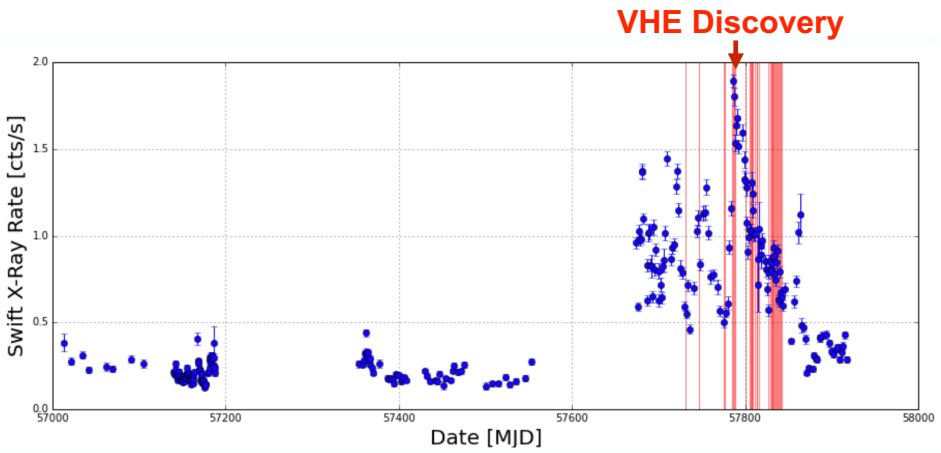
Subjects: Gamma Ray, TeV, VHE, Request for Observations, AGN, Blazar

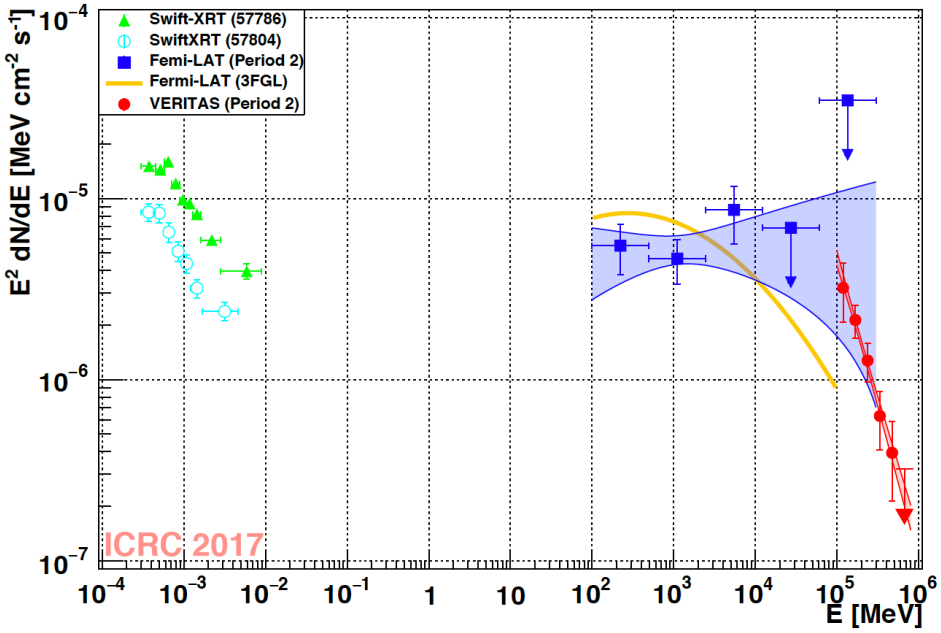
We report the VERITAS discovery of very-high-energy emission (VHE; >100 GeV) from the FRI radio galaxy 3C 264, also known as NGC 3862. Nearly 12 hours of quality selected data, collected by VERITAS between 09 February 2018 and 16 March 2018 (UTC), were analyzed. Preliminary results yield an excess of 60 gamma-ray events above background at the position of the source, corresponding to a statistical significance of 5.4 standard deviations. Our preliminary flux estimate (E>300 GeV) is (1.3 ± 0.2)e-12 cm^-2 s^-1, or approximately 1% of the Crab Nebula flux above the same threshold. The Fermi-LAT 3FHL catalog (Ackermann et al. 2017 ApJS 232, 18) lists a photon index of 1.65 ± 0.33 for 3C 264 which, when extrapolated to the VHE band, is consistent with the VERITAS detection. At a redshift of 0.0217, 3C 264 is a more distant analog to M87, with superluminal motion of ~7c (Meyer et al. 2015, Nature 521, 495) detected in its kpc-scale optical jet. With this discovery, 3C 264 is the most distant radio galaxy detected at VHE so far. VERITAS will continue to observe 3C 264; multi-wavelength observations are encouraged. Questions regarding the VERITAS observations should be directed to Reshmi Mukherjee (rm34@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).

- Strong, hard-spectrum detection: ~8σ in ~44 h; Γ ~ 2.3
- Low, weakly variable VHE flux: ~0.5% Crab; ~Month-scale variations
- Major VERITAS + MWL effort: Radio (e.g. VLBA), Optical (HST, ground-based), X-ray (Chandra + Swift), Fermi-LAT => No major activity in knot sub-structure

OJ 287: VERITAS VHE Discovery

- Optically bright blazar @ z = 0.306
  - Classification uncertain
  - TeV candidate: Costamante & Ghisellini 2002
- "Periodic" optical behavior: T ~ 12 yr
  - Binary black hole system? Helical jet?
  - Next optical outburst in 2019
- VERITAS limit in '07: 10 h, <2.6% Crab
- Swift XRT flaring => 2016-17 ToO
- VHE discovery in Feb. '17: ATel #10051
- 2016-17: ~50 h, 9.7σ, Γ = 3.49 ± 0.28
  - F(>150 GeV) = (4.61± 0.61) x 10^{-12} cm^{-2} s^{-1}; 1.3% Crab
- Copious MWL data: SED shifts
  - Possible contemporaneous birth of radio knot near BH

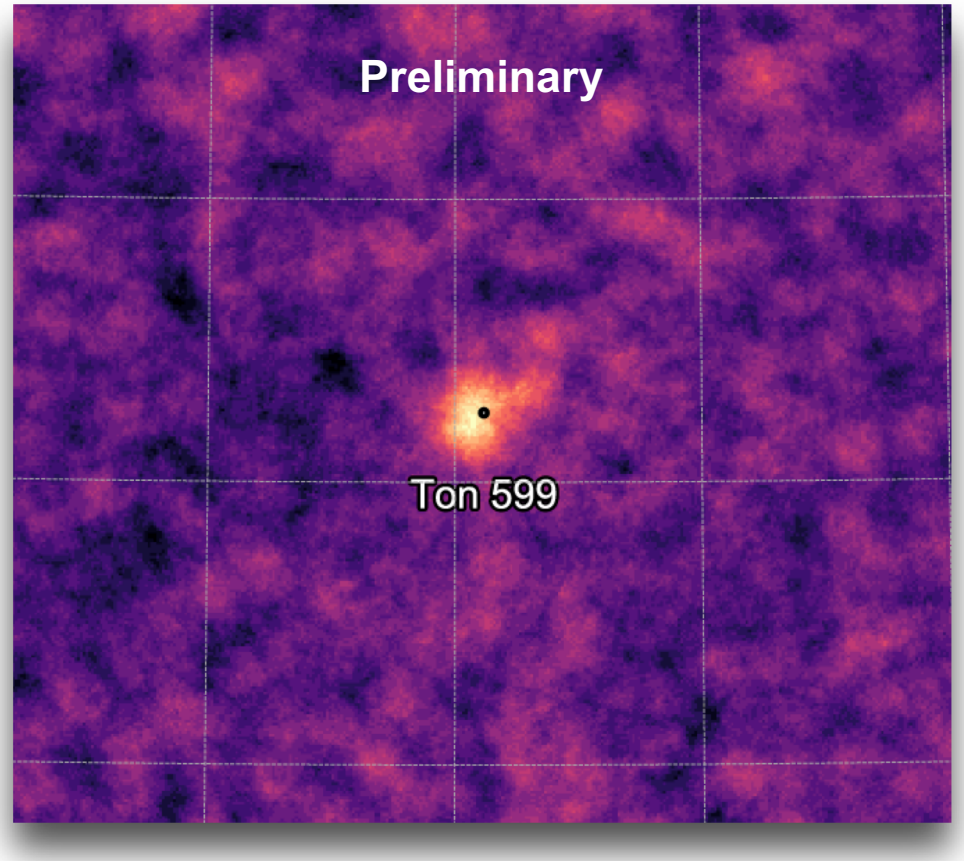




Ton 599: Third Highest *z* VHE Source

- FSRQ @ $z = 0.72$
- Fermi-LAT flare in early Nov. 2017
  - ATel #10931: ~20x 3FGL flux
- Exceptional NIR flares in Nov. 2017
  - ATel #10949: 0.5 mag. after 10x flux
- VERITAS observes on 12/15-16
  - ~8σ in ~2 h; Γ ~ 5
  - F(>100 GeV) ~ 12% Crab
- MAGIC also detects on 12/15: ATel #11061

Significance map for Ton 599

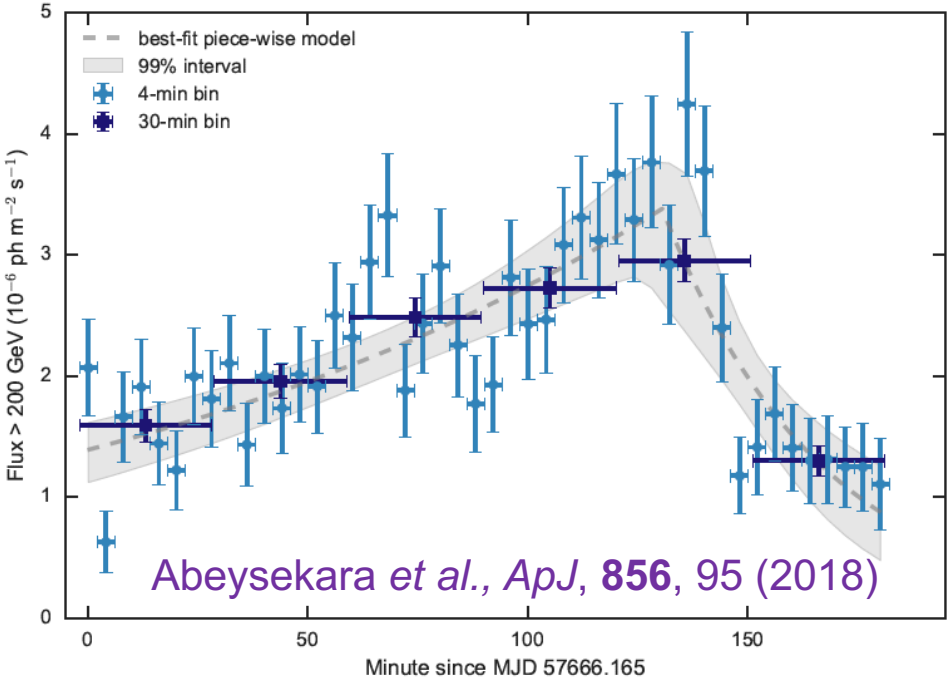


VERITAS's 3rd FSRQ & 7th in VHE

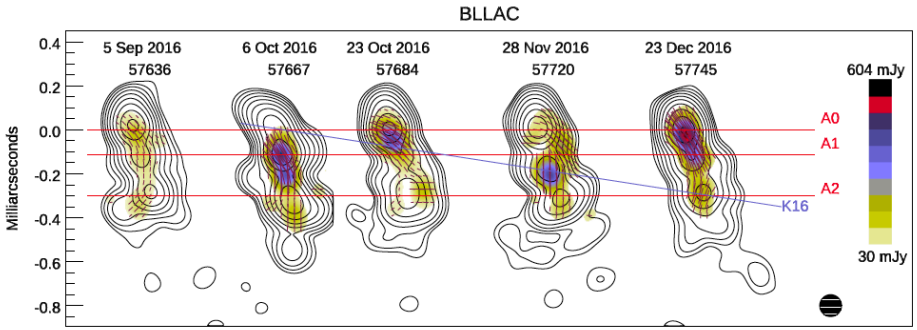
PKS 1441+25 (z ~ 0.94) & 4C +21.35 (z ~0.43)

BL Lac: Flares & Superluminal Knots

- MAGIC flare in 2005 (3% Crab)
- VERITAS: 70 h of data since 2010
  - 4 flares, but not usually detected at VHE
- Brief flare in 2011: Arlen *et al.*, *ApJ*, **762**, 92 (2013)
  - Peak: ~125% Crab; Exp. decay: $\tau = 13 \pm 4$ min
  - Associated w/ birth of superluminal radio knot
- Two, single-night flares in 2015
  - 16% Crab on June 21 & 9% Crab on November 30
- Major flare on Oct. 5, 2016
  - Monitoring => 2.6 h, 71σ, Peak ~ 180% Crab
  - Slow rise (t_{rise} ~ 140 min) & rapid fall (t_{fall} ~ 36 min)
  - Another candidate superluminal knot appears



VLBA 43 GHz Maps: Sept - Dec 2016



TXS 0506+056: A Multi-Messenger Blazar?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TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino
candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of
Maryland) report on behalf of the IceCube Collaboration
(http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a
high probability of being of astrophysical origin. The event was identified by
the  Extremely High Energy (EHE) track event selection. The IceCube detector
was in a normal operating state. EHE events typically have a neutrino
interaction vertex that is outside the detector, produce a muon that traverses
the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon
/50579430_130033.amon), more
sophisticated reconstruction algorithms have been applied offline, with the
direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a
possible astrophysical source for the candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector
operating at the geographic South Pole, Antarctica. The IceCube realtime alert
point of contact can be reached at roc@icecube.wisc.edu
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- AMON / GCN neutrino alert on Sept. 22
  - E > 100 TeV, P_{astro} ~ 0.5
- VERITAS: No detection in 1 h on Sept. 22
- LAT ATel: 6x 3FGL flux in ±1 week period

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
*on **28 Sep 2017; 10:10 UT***
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430, 11489

Tweet Recommend 3

We searched for Fermi-LAT sources inside the extremely high-energy (EHE) IceCube-170922A neutrino event error region (https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3, see also ATels 10773, 10787) with all-sky survey data from the Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope. We found that one Fermi-LAT source, TXS 0506+056 (3FGL J0509.4+0541 and also included in the 3FHL catalog, Ajello et al., arXiv:1702.00664, as 3FHL J0509.4+0542), is located inside the IceCube error region. The FAVA (Fermi All-sky Variability Analysis) light curve at energies above 800 MeV shows a flaring state recently (https://fermi.gsfc.nasa.gov/ssc/data /access/lat/FAVA/SourceReport.php?week=477&flare=27). Indeed, the LAT 0.1--300 GeV flux during 2018 September 15 to 27 was (3.6+/-0.5)E-7 photons cm-2 s-1 (errors are statistical only), increased by a factor of ~6 compared to the 3FGL flux, with nearly the same power-law index of 2.0+/-0.1. We strongly encourage multiwavelength observations of this source. We also encourage optical spectroscopy for this source, because the redshift is still unknown. According to NED, the R-band magnitude is reported as 15.1 (Healey et al. 2008, ApJS 175, 97). Radio observations show that this blazar has had increasing flux during the past year: http://www.astro.caltech.edu /ovroblazars/data.php?page=data_query, http://www.physics.purdue.edu/astro/MOJAVE /sourcepages/0506+056.shtml.

The IceCube Collaboration *et al.*, *Science*, **361**, 1378 (2018)

TXS 0506+056: A Multi-Messenger Blazar?

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
*on **4 Oct 2017; 17:17 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet | Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

- MAGIC weakly detects: ~12 h; 9/28–10/3
- VERITAS does not: ~5 h; 9/28–9/30

VERITAS follow-up observations of IceCube neutrino event 170922A

ATel #10833; ***Reshmi Mukherjee***
*on **9 Oct 2017; 22:32 UT***
Credential Certification: Reshmi Mukherjee (muk@astro.columbia.edu)

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

Referred to by ATel #: 10838, 10844, 10845, 10861

Tweet | Recommend 15

The VERITAS gamma-ray telescope array was used to perform follow-up observations of the high-energy neutrino event detected by the IceCube collaboration on September 22nd, 2017 20:54:30 UTC (GCN Circular #21916).

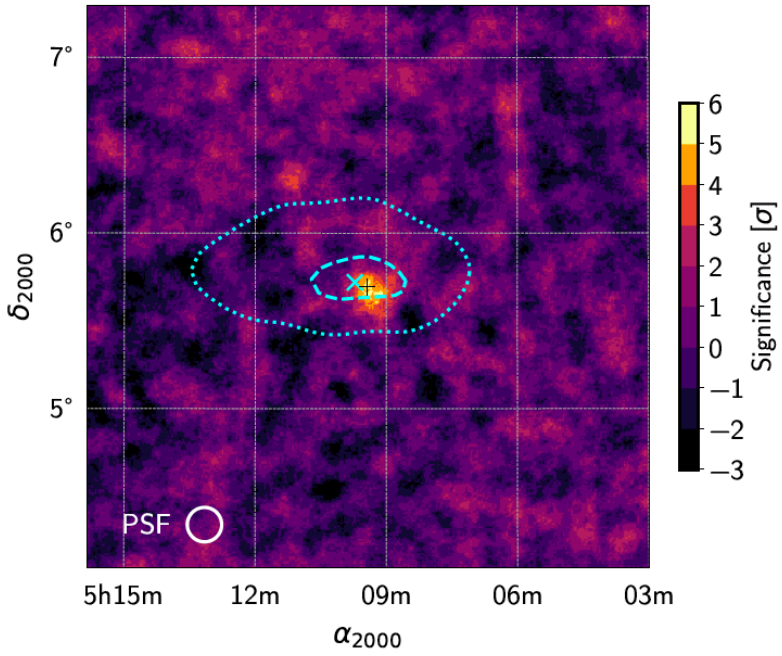
VERITAS observed the location around the initial position reported by IceCube in the GCN/AMON Notice dated Fri 22 Sep 17 20:55:13 UTC (RA = 77.29 deg, Dec = 5.75 deg in J2000 coordinates) under partial cloud coverage for one hour. Observations started on September 23rd, 2017 09:06 UTC, 12.2 hours after the IceCube detection. No gamma-ray source was detected at the neutrino position or anywhere else in the 3.5-degree VERITAS field of view.

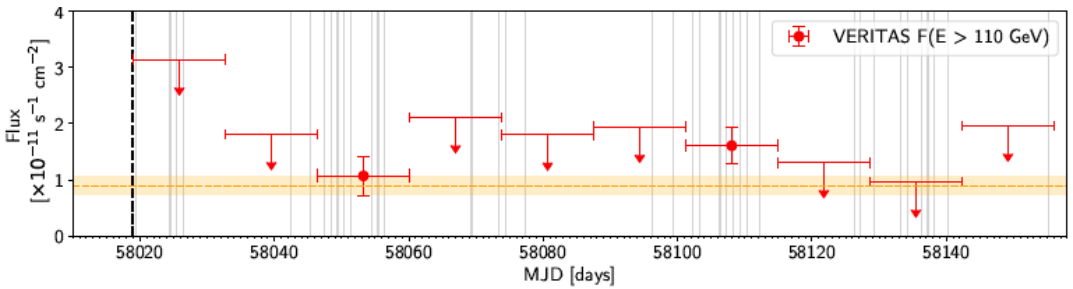
Additional VERITAS observations were collected following the report by the Fermi LAT collaboration (ATel #10791) of the detection of a strong, hard GeV flare from the blazar TXS 0506+056 (RA = 77.358 deg, Dec = 5.693 deg in J2000 coordinates) located within the neutrino error region.

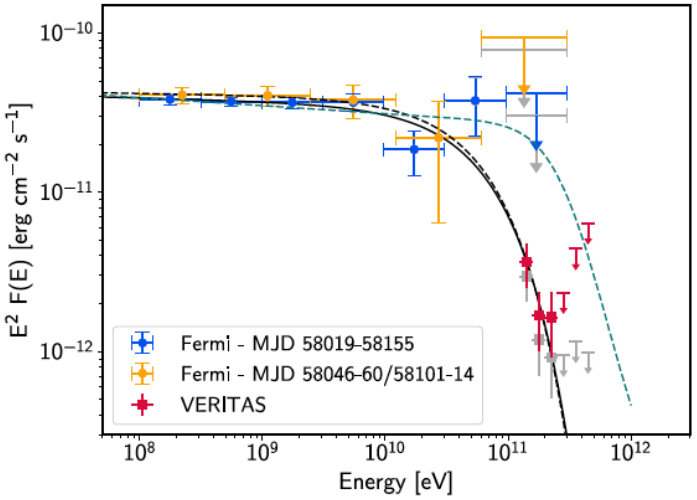
A total of five hours of additional observations centered on the blazar location were collected between September 28th 08:57 UTC and September 30th 11:04 UTC. A preliminary analysis of the data optimized for soft-spectrum sources shows no evidence of gamma-ray emission at the blazar location. The integral gamma-ray flux upper limit derived from these observations at the TXS 0506+056 position is 6.80 x 10^-12 cm^-2 s^-1 at 99% CL above an energy threshold of 160 GeV for an assumed spectral index of -2.7. Null VHE gamma-ray observations were also reported by the H.E.S.S. (ATel #10787) and HAWC collaborations (ATel #10802), while the MAGIC collaboration reports the detection of a gamma-ray source coincident with the blazar position above a 100 GeV energy threshold in 12 hours of observations taken between September 28 and October 3 (ATel #10817).

The IceCube Collaboration *et al.*, *Science*, **361**, 1378 (2018)

Nevertheless, VERITAS Persisted…







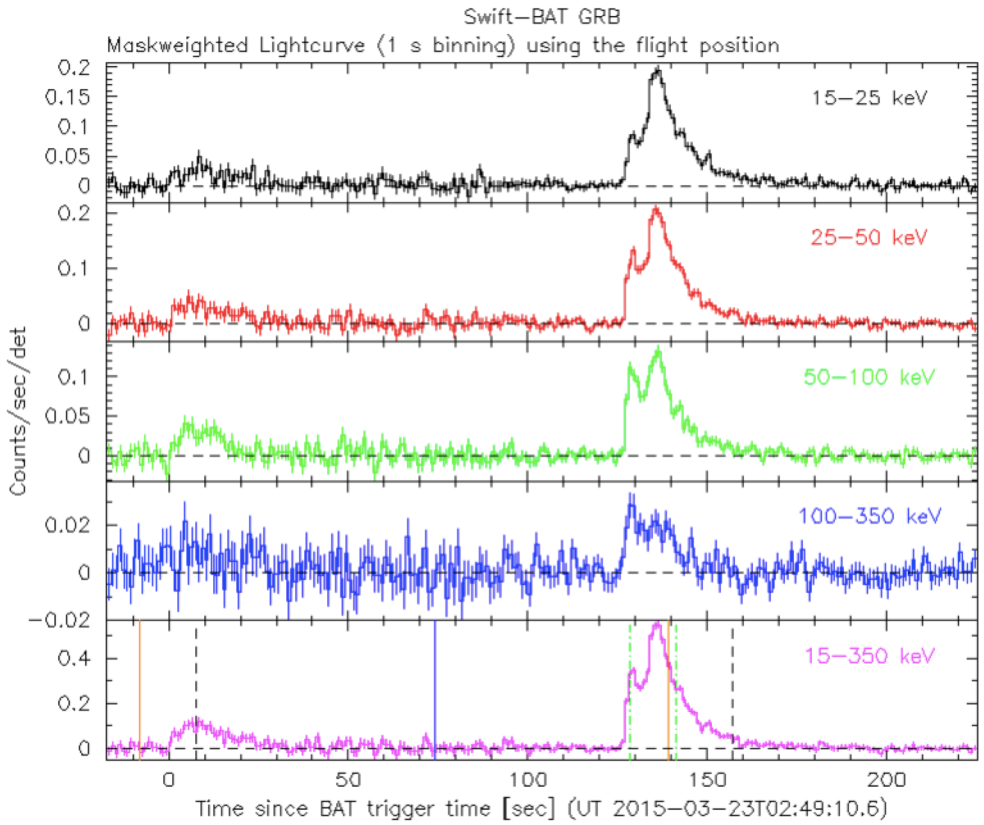
Abeysekara *et al., ApJL*, **861**, L20 (2018)

- VERITAS detects blazar (5.8σ) in 35 h of good-quality data from Sept. ’17 - Feb. ’18
- Weak flux: F(>110 GeV) ~ 1.6% Crab; Soft VHE spectrum: Γ = 4.8 ± 1.3
- If LAT flare & VHE detections associated with neutrino –> Cosmic-ray implications
  - VERITAS is already performing neutrino follow-up: Expect deeper VERITAS campaigns in the future!

GRB 150323A

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

Abeysekara *et al.*, *ApJ*, **857**, 33 (2018)



- Swift BAT burst at z ~ 0.6. VERITAS observation 2 min after the BAT emission peak.
- Upper limit at <1% prompt fluence.
- Lack of >100 GeV emission favors explosion into the stellar wind of dense progenitor (Wolf-Rayet star), or into a low-density ISM (inefficient radiative cooling).
  - Can constrain emission models even with no detections.
- Provide a strong test of EBL models in the case of detection.

Summary

- VHE observations are revealing the processes of cosmic-ray acceleration and transport
- Multi-messenger programs are opening new windows into extreme environments
  - VERITAS detection of TXS 0506+056 following IceCube HE neutrino alert: Expect more deep campaigns
  - Synergy with HAWC, Fermi-LAT, IceCube, ANTARES, LIGO/Virgo, …
- Probing connection between radio knot structure and AGN activity
  - Multiwavelength observations can help pinpoint location of TeV emission
  - BL Lac: Fast γ-ray flare coincident with emergence of a radio knot
  - 3C 264: New TeV-detected radio galaxy with no strong activity from the radio knot or core
- VERITAS is running very well & is funded to operate until at least 2019
  - Source catalog is now at 63 sources from 8 classes
  - Exploring the possibility of further operations (e.g. until ~2022)
- We are always looking to collaborate! https://veritas.sao.arizona.edu/
  - Ideas are welcome!
  - Observing proposals due September 5. Contact Science Working Group Coordinators.