

Particle Accelerators in Space: Recent News from VERITAS

BRIAN HUMENSKY, COLUMBIA UNIVERSITY Cosmic Ray International Seminar, June 17, 2018

Outline



Introduction

- Galactic Science: Supernova Remnants, HAWC Follow-Up, PSR J2032+4127
- Extragalactic Science: Fast Flares from BL Lac, Radio Galaxy 3C 264
- Multi-Messenger Studies: IceCube and LIGO/Virgo followup campaigns

Summary

VERITAS Overview



- Array of 4 Davies-Cotton Imaging Air Cherenkov Telescopes, 1st light in 2007
- ► <u>Energy range:</u> ~ 80 GeV 30 TeV
- **Effective area:** ~ 10^5 m^2
- Observing time: ~ 900 hr dark + 300 hr moon
- ► <u>Angular resolution:</u> $< 0.1^{\circ}$ for E > 1 TeV

Location: Whipple Observatory, Arizona Status & Highlights: arxiv/1609.02881





Cas A

- ► 350-yr-old core-collapse supernova remnant, at distance of 3-4 kpc
- Broken power law, exponential cutoff models favored over a single power law (~3.5 σ after accounting for syst. uncertainties)
 - Cut-off at 2.5 ± 0.6 TeV
- ► Ahnen+ 2017 (MAGIC Collab) measure significant spectral cut-off at 3.5 TeV





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Young Supernova Remnants: Tycho & Cas A



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

>PeV particles have escaped – where can we find them?

VERIT

Interacting SNRs: IC 443



Deconvolved 1–300 GeV events. Pass 8 gives 2.4x statistics of P7REP with cut on PSF68 < 0.4°



shocked HCO⁺ contours

- 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 B. Humensky, Particle Accelerators in Space: Recent News from VERITAS, CRIS 2018



Interacting SNRs: IC 443



Fermi-LAT reports a second, hard-spectrum extended source encompassing IC 443 (FGES J0619.6+2229, Ackermann+ 1702.00476)

> CR escape signature? Or a separate SNR?

Follow-up of 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

*See also T. Weisgarber, "Highlights from the HAWC Observatory" B. Humensky, Particle Accelerators in Space: Recent News from VERITAS, CRIS 2018

- 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.* 2010)

Park+ VERITAS - arXiv:1708.05744 $_{\circ}$

SNR G54.1+0.3 and surroundings Two 2HWC sources -2HWC J1930+188 & 2HWC J1928+177







Park+ VERITAS - arXiv:1708.05744 9

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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.





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SNR G54.1+0.3 and surroundings

3FGL J1928.9+1739 Fermi upper limit for point source (erg cm⁻² s +19.50 Fermi upper limit for extended source VERITAS upper limit for point source VERITAS upper limit for extended source E² dN/dE 2HWC J1928+177 +19.00* 30 11928.4+1838 10-12 $+18.50^{\circ}$ HAWC ~ 2 years w/ E>10 TeV 10 10¹⁰ -10 3FGL J1925.4+1727 SNR G054 1+00.3 -20 :00:00.0 30:00.0 54:00:00.0 30:00.0 53:00:00.0 30:00.0 292.00 291.50° 291.00° A (12000) 2HWC J1930+ Rubén López-Coto, ICRC 2017 2HWC J1928+17 -0.8 0.39 1.6 2.8 4 5.2 HAWC, 507 days rXiv:1708.05744

2HWC J1928+177

- Coincides with pulsar PSR J1928+1746
- Equally strong source as 2HWC J1930+188 for HAWC
 - Stronger than 2HWC J1930+188 for E>10 TeV
- VERITAS upper limit excludes a point source hypothesis assuming the same PL distribution

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

TeV J2032+4130: the 1^{st} "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?





Bird+ VERITAS - arXiv:1708.04718

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

10000

5000

- TeV J2032+4130: the 1^{st} "dark" γ -ray emitter
 - Discovered by HEGRA
 - ► 0.5° from Cygnus X-3
- Fermi-LAT discovered a pulsar 0.16° from the 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

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PSR J2032+4127: Flux Rising Towards Periastron

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





int Rate



- 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

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Knots and the Blazar Sequence



48 TeV HBLs (the majority of TeV jets)

- 10 TeV IBLs/LBLs
- 7 TeV FSRQs
- 4 TeV radio galaxies (misaligned jets)



48

47

45 vLv

43

42

Bog 44

 s^{-1} 46

[erg

VERIT

VERITAS >85 GeV

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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
 - ► $\Gamma_{3FHL} \sim 1.65 \rightarrow F(>200 \text{ GeV}) \sim 1.6\% \text{ Crab}$
- VERITAS ~10 h observation in 2017
 - ► Curious ~ 2σ excess \rightarrow 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

Tweet Recommend 49

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 $(1.3 \pm 0.2)e-12$ 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: $\sim 8\sigma$ in ~ 44 h; $\Gamma \sim 2.3$

The VERITAS Collaboration+ E. Meyer... 2018, in prep

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*

BL Lacertae: A Blazar with Fast TeV Flares • Intermediate-peaked blazar at redshift z = 0.07

- ► A powerful, fast TeV flare on October 5th 2016
- ► Rise time ~140 minutes; decay time of ~36 minutes → ~12 R_Schwarzschild
 - ► Typical flare structure expected to be fast rise/slow decay → opposite observed with BL Lac
- Possible coincident superluminal radio knot ejection
- ► Curved spectrum, index ~3.6
- Similar behavior in 2011



Milliarcseconds

Multi-Messenger Astronomy

- Searching for VHE Transients
 - □ Astrophysical neutrinos
 - **Gamma-ray Bursts**
 - **Gravitational waves**





TXS 0506+056: A Multi-messenger Blazar?

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

► AMON / GCN neutrino alert on Sept. 22

 $E > 100 \text{ TeV}, p_{astro} \sim 0.5$

VERITAS: No detection in 1 h on Sept. 22

▶ LAT ATel on Sept 28: 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



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 Gammaray 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.



TXS 0506+056: A Multi-messenger VHE 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 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 highenergy 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).



Nevertheless, VERITAS persisted...



- 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
- If LAT flare & VHE detections associated with neutrino => Cosmic-ray implications
 VERITAS gives high priority to astrophysical neutrino follow-up: more campaigns in the future!

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Astrophysical Neutrinos from IceCube*





 $\begin{array}{c}
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 y + p/\gamma \rightarrow X + \pi^{0} \rightarrow \gamma\gamma \\
 \rightarrow X + \pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \\
 \mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}
\end{array}$



- Astrophysical neutrino flux detected in the 20
 TeV 8 PeV energy range (various channels and analysis methods)
- **Event rate is low:** ~O(10) events / year
- Point-source upper limits at the level of 1%-10% of the all-sky flux hint at *large number of sources* (N > 10-100)

*See Prof. Shigeru YOSHIDA, "Multi-messenger astronomy driven by the High-energy cosmic neutrinos" B. Humensky, Particle Accelerators in Space: Recent News from VERITAS, CRIS 2018

IceCube Follow-up Programs

Goal: Searching for hadronic VHE emission at the locations of single (or clusters of) high-energy muon neutrinos (~1° ang. resolution)

Variety of follow-up approaches:

Months

days

econds

nutes

Follow-up latency

- Searches for VHE emission at "archival" muon neutrino positions that are likely astrophysical ($E_v \gtrsim 100 \text{ TeV}$)
 - Correlation studies of neutrino and γ -ray emission from VHE sources
- Observation of neutrino "flares" from known VHE sources
 - Observation of neutrino multiplets
- Observation of prompt online HESE alerts
 - Observation of prompt EHE alerts Observation latency: 112 s

http://gcn.gsfc.nasa.gov/gcn3/19377.gcn3





IceCube event 04/27/2016





"Archival" IceCube Neutrino Events





- > Selection of high-energy neutrino events from IceCube publications + shared through MoU that are potentially astrophysical ($p_{astro} > 50\%$) and have good localizations (~1°)
- ~40 hours of VERITAS exposure so far; publication in the works with other IACTs
 No VHE gamma-ray excess found in the region of interest of the neutrino events

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Gamma-ray Flux Upper Limits





- Upper limits on γ -ray emission associated with the archival events
- For reference, the ULs are compared to the IceCube all-sky flux scaled by 10^{-3}

VERITAS GRB (& MM) observations

- GRB alerts processed by the telescope control software in realtime telescopes repoint once observers acknowledge the alert
- ▶ 3 hours of observation above 20° elevation (1 hr for GBM bursts)



• 13 with Fermi-LAT, several prompt. Two several hours later.



Most Recently... GRB 150323A

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

VERITAS

ApJ (2018, in press) arXiv/1803.01266



- 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 lowdensity ISM (inefficient radiative cooling).
 - Can constrain emission models even with no detections.
- Provide a strong test of EBL models in the case of detection.



LIGO detections: 3 high-confidence events associated with BH-BH mergers (not expected to be EM bright)

NS-NS merger within the LIGO horizon (~100 Mpc) may be detected by TeV instruments (Bartos *et al.* 2014, 2017)*

► VERITAS 10 deg² FoV: scan the O(100 deg²) GW localization region

*See T. Di Girolamo, "Strategies for the Follow-up of Gravitational Wave Transients at Very High-Energy Gamma Rays with the Cherenkov Telescope Array" B. Humensky, Particle Accelerators in Space: Recent News from VERITAS, CRIS 2018 29

VERITAS Follow-up strategy

▶Define list of pointings to cover some containment level
 ▶Define ordering (westward pointings first)
 ▶5 min per pointing → sensitivity ~50% Crab Nebula flux

VERIT/

GW170104: 1st Systematic IACT Follow-up of GW Alert

- GW170104: 50-Msun BBH merger at z = 0.2 detected by LIGO
- No EM emission expected. Alert was 6.5 hours old when received. Covered region (39 pointings) includes 27% of containment probability

- ► Analysis in progress. Observations affected by bad weather
- Preliminary results circulated as GCN circular #21153
- Preparing for O3, the next LIGO run to start end of 2018 / beginning of 2019

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GW170817?*

- ► First detection of GWs from binary neutron star merger
- Kilonova + sGRB counterparts
- Extensive MWL campaign to follow-up the evolution of the alert

 VERITAS was not operational at the time (annual monsoon shutdown)
 *See S. Marka, "Introduction to Gravitational Wave detection: GW170817" B. Humensky, Particle Accelerators in Space: Recent News from VERITAS, CRIS 2018

Summary

- ► TeV observations are revealing the processes of cosmic-ray acceleration and transport
- Multi-messenger programs are opening new windows into extreme environments
- Very successful synergy with HAWC, Fermi-LAT and with IceCube, LIGO/Virgo,
- ▶ VERITAS & *Fermi*-LAT follow-up study on 13 out of 16 HAWC unassociated sources
 - SNR G54.1+0.3 & DA 495 detected; others: non-detections still constrain source size/spectrum
- PSR J2032+4127: extreme elliptical orbit enhanced TeV flux during periastron approach. A once-in-an-observatory's-lifetime opportunity
- **BL** Lac: fast TeV γ-ray flare coincident with emergence of a radio knot
 - Multiwavelength observations can help pinpoint the location of TeV emission in jets
- ► A new *TeV-detected radio galaxy*, *3C 264*: No strong activity from the radio knot or core
- Much more not covered: Galactic Center, dark matter, Binaries, AGNe, IGMF, PBHs...
- We welcome proposals from external collaborators for observing time proposals due ~early September for next season; contact Science Working Group Coordinators to get involved https://veritas.sao.arizona.edu/

