VERITAS Highlights 2022

Conor McGrath [1] (for the VERITAS Collaboration [2])

Abstract. The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is an array of four 12 m Imaging Atmospheric Cherenkov Telescopes (IACTs), located at the Fred Lawrence Whipple Observatory in Arizona, USA, that has been in full array operation since 2007. VERITAS conducts research in a variety of areas including galactic science such as supernova remnants, pulsar wind nebulae, binary systems; extra-galactic science including jetted AGN, gamma-ray burst and fast radio burst searches; multimessenger follow-ups and astroparticle physics, including dark matter searches. This paper will cover recent VERITAS highlights and results.

1. Introduction

VERITAS is one of the leading gamma-ray observatories currently in operation. The VERITAS Collaboration currently consists of $\sim$ 100 members from institutes in 4 different countries (Canada, Germany, Ireland, United States of America). VERITAS is funded by the National Science Foundation, Smithsonian Astrophysical Observatory, Natural Sciences and Engineering Research Council, Helmholtz Association and has recently been awarded operations funding through 2025 by the National Science Foundation.

VERITAS detects very high energy (VHE) gamma rays (E $\gtrsim$ 100 GeV) via the fast (ns) flashes of Cherenkov radiation that are produced in the atmosphere by extensive air showers (EAS) when gamma rays and charged cosmic-ray particles collide with air molecules. Signal identification and background rejection are achieved through stereoscopic analysis of the images recorded ($\sim$400 per second) by the telescopes.

1.1. Instruments and Performance

Each of the four VERITAS telescopes utilise a Davies-Cotton design containing 350 hexagonal mirrors which gives each telescope a total collection of $\sim$100 m^2. In each telescope, individual mirrors focus the Cherenkov light onto a camera at the focal plane. The camera of each telescope are made up of 499 photo-multiplier tubes (PMTs) each of which with a field of view of $\sim 0.1^\circ$ which gives a total field of view of 3.5°.

VERITAS can indirectly detect gamma rays in the energy range of 85 GeV to 30 TeV and has an energy resolution of 17% for a 1 TeV photon. VERITAS can detect (5 standard deviations above the background) a source with a 1% of the flux of the Crab Nebula with $\sim$ 25 hours of observations. The VERITAS effective collection area for a 1 TeV photon is on the order of 10^5 m^2. The response of the instrument is known to change over time as a result of PMT and mirrors degradation. Frequent measurements of gain and mirror reflectivity are taken. Corrections are then incorporated into Monte Carlo simulations which are used to derive multi-epoch IRFs. Figure 2 shows the corrected flux after the implementation of the correct IRFs.

2. VERITAS Science Program

The VERITAS observing season runs annually from September to July with the shutdown and startup dates determined by Arizona's wet weather season. During a year of observations VERITAS typically collects $\sim$ 950 hours of dark time observations and $\sim$ 250 hours of bright Moon (30-65% illumination)

[1] conor.mcgrath2@ucdconnect.ie
[2] http://veritas.sao.arizona.edu

Figure 1. A view of the Fred Lawrence Whipple Observatory basecamp and the VERITAS array. CTA-US's prototype Schwarzschild-Couder telescope (pSCT) can be seen near the back left.

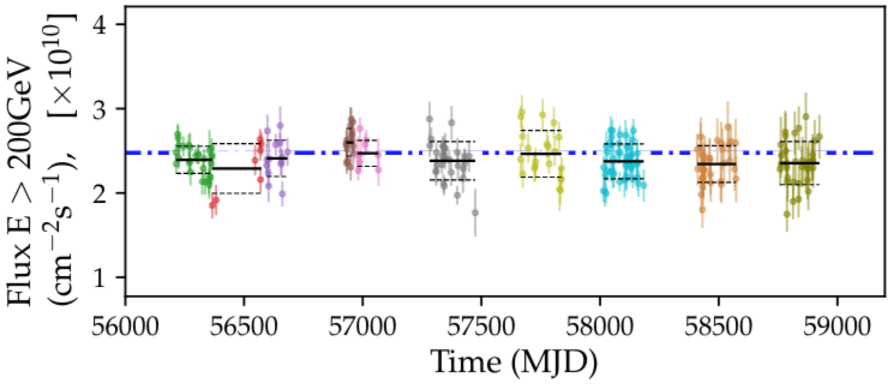

Figure 2. Reconstructed flux of the Crab Nebula above 200 GeV using the updated instrument response functions (IRFs) for each observing season [1]. Each colour denotes a different IRF epoch and the blue dashes represent a reference Crab Nebula flux.

observations. During full Moon (>65%) VERITAS performs optical stellar interferometry observations [2]. The VERITAS science program is outlined in Figure 3, here the 2021-2022 breakdown of VERITAS observing time is shown. Time is given to the three science working groups: Blazar, Galactic and ATOMM (Astroparticle, Transient, Optical, Multi-Messenger), the VERITAS Moonshot program (high-risk, high-reward targets) and targets of opportunities (ToOs). The majority of the remainder is distributed by the Time Allocation Committee (TAC): an elected group who review observation proposals from within the Collaboration and awards observation time accordingly.

3. Galactic Science Highlights

3.1. PeVatrons

Supernova remnants (SNR) are believed to be one of the most likely accelerators of cosmic rays up to PeV energies. In particular, young SNRs are among the best targets in which to find evidence of these ultra-high-energy cosmic rays (UHECR). For this reason VERITAS has performed multiple studies on such objects: Tycho's SNR, a young Type Ia SNR which has been studied in a wide range of energies and detected at 6.9σ by VERITAS in $\sim$ 147 hours [3] and Cassiopeia A SNR , a remnant of a core-collapse Type IIb supernova detected at 13.8σ by VERITAS in $\sim$ 65 hours [4]. The spectra of both Tycho and Cassiopeia A are seen to considerably soften going from Fermi-LAT to VERITAS energies, indicating that they are not significant emitters of PeV particles. VERITAS is currently undergoing a follow-up study on two LHAASO ultra-high-energy (UHE) sources with no VHE counterpart. VERITAS has accumulated 35 hours and 23 hours on LHAASO J2108+5157 [5] and LHAASO J0341+5258 [5] respectively with no detection seen in either point-like (0.09°) or extended (0.25°) analyses.

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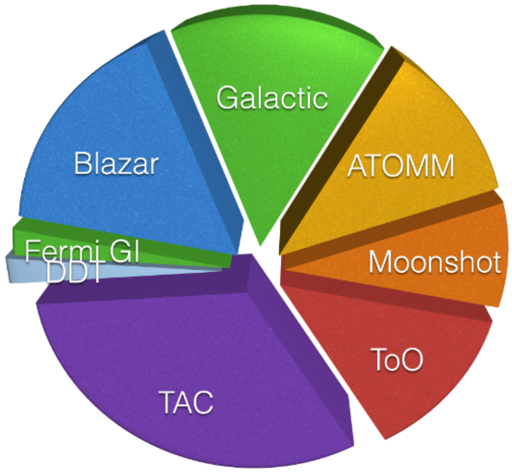

Figure 3. 2021-2022 breakdown of the VERITAS science program.

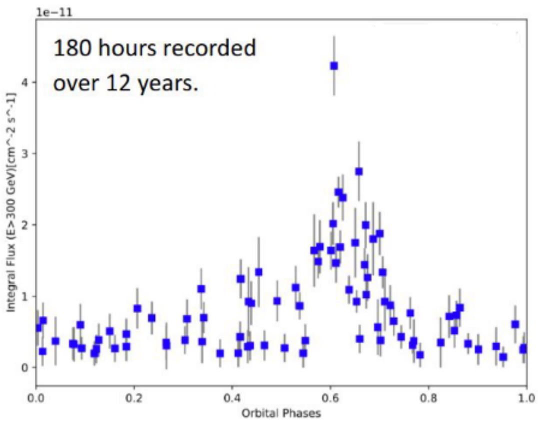

Figure 4. LS I +61 303 orbital phase light curve.

3.2. Gamma Ray Binaries
VERITAS has detected 3 gamma ray binaries systems: HESS J0632+057, LS I +61 303 and PSR J2032+4127, with large data sets amassed particularly on HESS J0632+057 and LS I +61 303.

In an ongoing joint analysis of HESS J0632+057 with VERITAS, MAGIC and HESS, VERITAS has contributed $\sim$ 260 hours of the 450 hours of data. The gamma-ray and X-ray fluxes of HESS J0632+057 have been seen to be highly correlated, with a consistent deduced orbital period in gamma ray (316.7 $\pm$ 4.4 days) and X-ray (317.3 $\pm$ 0.7 days) [6]. Modelling of HESS J0632+057 is still challenged by unknowns such as its orbital geometry and the identity of the compact object. These unknowns could be addressed by a multiyear optical campaign or simultaneous multiwavelength observations with current or future instruments.

Over 12 years of observations, VERITAS has collected $\sim$180 hours of data on LS I +61 303 where the orbital phase light curve comprised of nightly binned flux points can be seen in figure 4 with the highest state seen at an orbital phase of $\sim$0.6 reaching a flux of $\sim$30% Crab flux (E $>$ 300GeV). This long data set also allows VERITAS to perform a a search for super-orbital modulation. As no evidence for super-orbital modulation has been found in the VERITAS data alone, a joint study with MAGIC is in progress.

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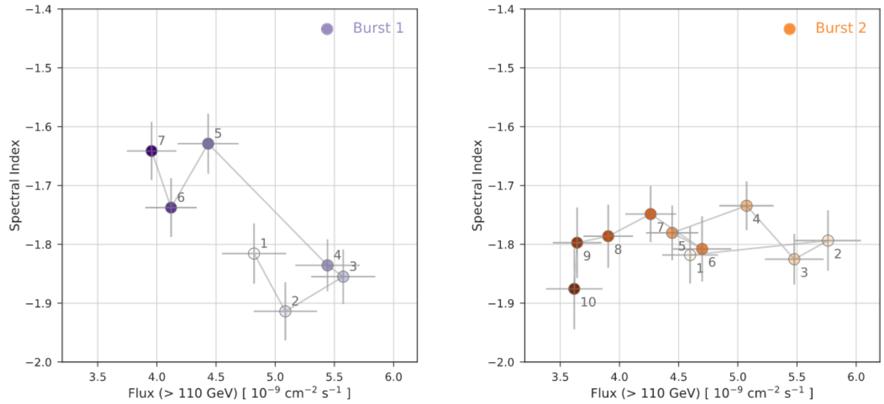

Figure 5. The photon index vs. flux of VERITAS's detections of Mrk 421 during the great flare of 2010. The indices are obtained from fitting an exponential cutoff power law, where the cut off is fixed at 4 TeV [7].

4. Extra-galactic Science Highlights

VERITAS's extra-galactic science program is driven by topics such as active galactic nuclei's jet physics, the extra-galactic background light, the intergalactic magnetic field and the probe for gamma-ray counterparts of neutrinos and cosmic rays. VERITAS achieves ∼590 hours per year of data on extra-galactic targets such as blazars and radio galaxies. This is from both monitoring programs and self-triggering ToOs. To date these observations have been used by VERITAS to detect 37 blazars and 4 radio galaxies as well as in multi-year science projects such as an ongoing project to derive an unbiased high-frequency peaked BL Lac (HBL) luminosity function and a multi-year daily monitoring program on Mrk 421. VERITAS has also performed studies on flaring galaxies such as OJ 287 (2017 flare), Mrk 421 (2010 flare) [7] - see Figure 5 and FSRQs such as 3C 279, PKS 1222+216, and Ton 599 [8].

4.1. Radio Galaxies

VERITAS has to date detected four radio galaxies: M87, NGC 1275, IC 310, and 3C 264 which was discovered by VERITAS in 2020 [9]. VERITAS continues long-term monitoring of each of the four detected radio galaxies, including an eight-year long multi-wavelength (gamma-radio) study of NGC 1275 and long-term M87 studies which include joint observations with the Event Horizon Telescope.

4.2. Unbiased HBL Luminosity Function

VERITAS is currently conducting a study with the aim of deriving an unbiased HBL luminosity function. This study takes the 3HSP catalog [10] that contains 36 high-frequency-peaked BL Lacs (21 of detected in VHE). For each object VERITAS uses least 8 hours of unbiased data to derive a luminosity function. This means removing any data taken as a result of other observations and taking any additional data to achieve the required 8 hours per object.

4.3. RBS 1366 (RGB J1417+257)

In Summer 2022 VERITAS announced the detection of a new VHE Extreme HBL RBS 1366 (RGB J1417+257). RBS 1366 (redshift: z=0.237) is believed to be a TeV-peaked BL Lac [11] with a synchrotron peak frequency $\nu > 10^{17}$ Hz and a possible UHECR accelerator [12]. Using ∼ 60 hours of data including data taken for the unbiased luminosity function study, VERITAS achieved a $> 5\sigma$ detection in two analysis packages.

5. ATOMM Science Highlights

5.1. Gamma-Ray Bursts

Gamma-ray bursts (GRBs) are a high priority topic for VERITAS and will take priority over any other observations. To date VERITAS has conducted observations of 211 GRBs, 127 of which with a position uncertainty inferior to the VERITAS gamma-ray PSF. Although no detection has been yet achieved,

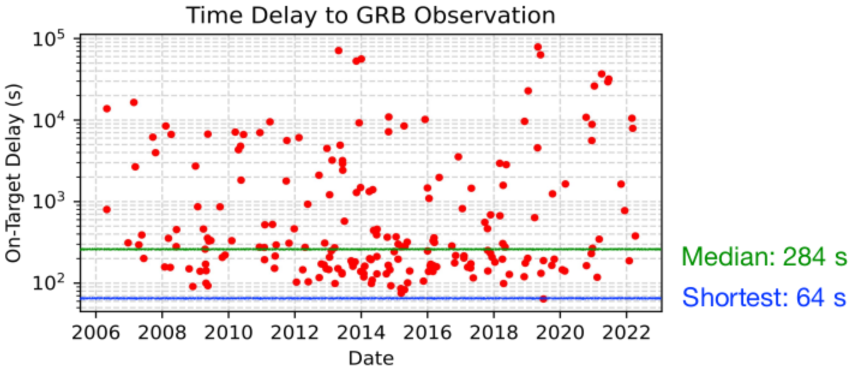

Figure 6. Time delay between GRB alerts and observations by VERITAS. GRBs are shown as red dots, the median time of 284 seconds from alert to observation is shown by the green line and the shortest time of 64 seconds from alert to observation is shown by the blue line.

previous VERITAS observations of GRBs have been published [13, 14, 15] and now a detailed stacked analysis of all VERITAS-observed bursts is underway. A visualisation of the delay between received GRB alerts and actual VERITAS observations can be seen in Figure 6.

5.2. Neutrino Follow-up

Neutrino source candidates are also high priority targets for VERITAS. In the case of a Gold or Bronze alert from IceCube, VERITAS will undergo an automatic repointing. Since the VHE detection of TXS 0506+056, VERITAS has performed real-time follow ups on 9 neutrino alerts leading to $\sim$ 45 hours of observations per year.

5.2.1. TXS 0506+056 In September 2017, the IceCube neutrino observatory detected a neutrino event of an origin bidirectionally consistent with the blazar TXS 0506+056. Within 12 hours of the IceCube event, VERITAS performed one hour of observations achieving no detection. Following Fermi-LAT detecting the increased gamma-ray activity of TXS 0506+056 [16] and the first VHE detection by MAGIC [17], VERITAS took an additional 5 hours of observations, again not resulting in a detection. In 2018, following an additional 35 hrs of observations spread over five months, VERITAS also achieved a detection at 5.8σ. Since detection, as part of an ongoing monitoring program, VERITAS has collected more than 100 hours of data on TXS 0506+056 and a multi-wavelength study with NuSTAR and Swift is currently underway.

5.3. Gravitational Wave Follow-up

VERITAS has conducted a follow-up search for electromagnetic radiation from 12 gravitational wave sources seen in the LIGO/Virgo O3 run (2019-2020), no detection has been seen in these observations. VERITAS has also used data taken during O3 to develop a tiling algorithm to scan gravitational wave error regions. In the upcoming O4 run, VERITAS plans to perform synergised observations of gravitational wave events with CTA-US's pSCT, an example of which is shown in Figure 7 where the tiling of single gravitational wave event by both VERITAS and an SCT telescope is shown. CTA-US's pSCT is a pathfinder medium-sized telescope (MST) for CTA. The future SCTs, expected to be included within the CTA-South array, will have a smaller point spread function (PSF) and as a result will have improved angular resolution, they will also have field of view of 7.6 deg - the largest of any IACT. The pSCT is located alongside the VERITAS telescopes in Fred Lawrence Whipple Observatory and can be seen in Figure 1 and is planned to begin operations in normal conditions in roughly one year's time. VERITAS has also performed an archival search for binary neutron star merger candidates identified in LIGO's O1 run. This study used 8 hours of data on 7 candidate events, but achieved no detection [18].

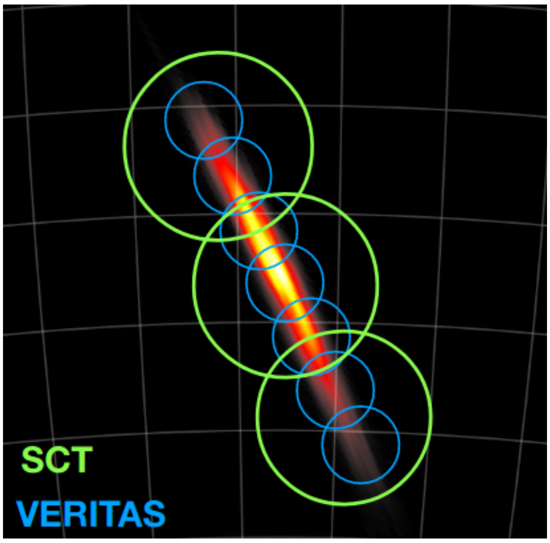

Figure 7. An example of how VERITAS and SCT could be used together to tile a gravitational wave event.

5.4. Fast Radio Bursts

Fast radio bursts (FRBs) are radio pulses on the order of millisecond to second timescales. The origin of FRBs is yet unknown but theories surrounding magnetars have become the most prominent models. There is believed to be two populations of FRBs, namely: repeaters and non-repeaters. As the names imply, repeaters are seen to repeat with an average interval between bursts on the order of days, whereas non-repeaters are not believed to repeat.

The goals for VERITAS's upcoming FRB observations will be to achieve simultaneous VHE and optical observations of both a repeating and non-repeating FRBs. Due to VERITAS's location, simultaneous observations can be performed with the Canadian Hydrogen Intensity Mapping Experiment (CHIME): a radio telescope with over 500 FRB detections. FRBs are an ideal target for VERITAS due to the instrument's unique capability to search for coincident VHE and rapid optical transients [19]. VERITAS currently has VHE observations of 12 FRBs (objects) and VHE data overlapping 21 FRB (bursts) detected in radio. VERITAS has found no significant emissions in any of the gamma-ray FRB data.

5.5. Dark Matter

The VERITAS indirect dark matter search is performed on 3 different target populations: dwarf spheroidal galaxies (dSphs), the galactic center and galactic sub-halos. In a search using $\sim$ 230 hours of data across 4 dSphs no DM signal has been detected, and as a result a upper limits on weakly interacting massive particles (WIMP) DM cross-section has been derived [20]. These upper limits are shown alongside the published limits of other gamma-ray telescopes in Figure 8. There is currently ongoing research on a dSph data set containing $\sim$ 960 hours of data, as well as a combined analysis of published data with Fermi-LAT, HAWC, H.E.S.S. and MAGIC.

6. Summary

VERITAS has a varied science program in galactic, extra-galactic and cosmic-ray astrophysics and amassed a large data set over 15 years of operation. The VERITAS Collaboration has recently published works on AGN, gamma-ray binary systems, gravitational waves and more. Within VERITAS there is continued work on long-term programs such as the GRB and neutrino follow-ups, monitoring of both galactic and extra-galactic objects as well as on-going work on topics such as dark matter, fast radio bursts and axion-like particles. VERITAS will soon begin joint observations with CTA-US's pSCT as well as simultaneous observations with the Imaging X-ray Polarimetry Explorer (IXPE) from 2022-2025. VERITAS is funded for operations through the year 2025 and will continue all of its science programs through this time.

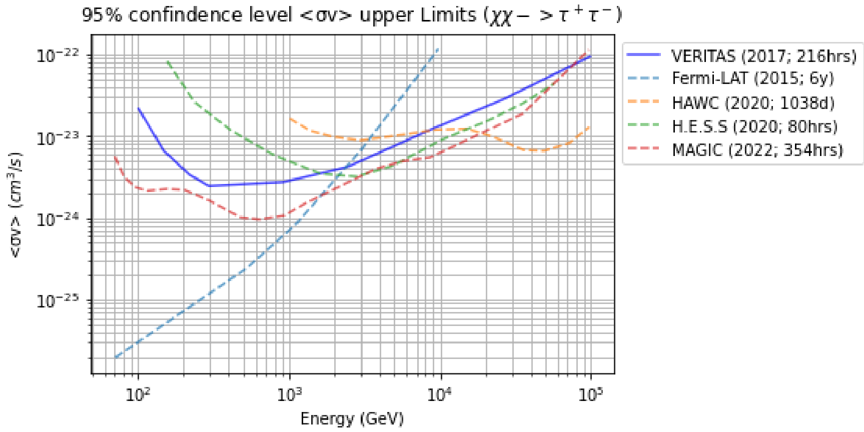

Figure 8. Published WIMP dark matter limits from gamma-ray telescopes. Shown is the WIMP dark matter velocity average cross section upper limits for a particle in the $\tau^+\tau^-$ channel.

7. Acknowledgements

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References

[1] Mireia Nievas Rosillo et al. The throughput calibration of the VERITAS telescopes. *PoS*, ICRC2021:721, 2021. doi: 10.22323/1.395.0721.

[2] A. U. Abeysekara et al. Demonstration of stellar intensity interferometry with the four VERITAS telescopes. *Nature Astronomy*, **4**(12):1164–1169, jul 2020. doi: 10.1038/s41550-020-1143-y.

[3] S. Archambault et al. Gamma-Ray Observations of Tycho's Supernova Remnant with VERITAS and Fermi. , **836**(1):23, February 2017. doi: 10.3847/1538-4357/836/1/23.

[4] A. U. Abeysekara et al. Evidence for Proton Acceleration up to TeV Energies Based on VERITAS and Fermi-LAT Observations of the Cas A SNR. , **894**(1):51, May 2020. doi: 10.3847/1538-4357/ab8310.

[5] Zhen Cao et al. Discovery of a new gamma-ray source, LHAASO j03415258, with emission up to 200 TeV. *The Astrophysical Journal Letters*, **917**(1):L4, aug 2021. doi: 10.3847/2041-8213/ac0fd5.

[6] C. B. Adams et al. Observation of the Gamma-Ray Binary HESS J0632+057 with the H.E.S.S., MAGIC, and VERITAS Telescopes. *Astrophys. J.*, **923**(2):241, 2021. doi: 10.3847/1538-4357/ac29b7.

[7] A. U. Abeysekara et al. The Great Markarian 421 Flare of 2010 February: Multiwavelength Variability and Correlation Studies. , **890**(2):97, February 2020. doi: 10.3847/1538-4357/ab6612.

[8] C. B. Adams et al. Variability and Spectral Characteristics of Three Flaring Gamma-Ray Quasars Observed by VERITAS and Fermi-LAT. , **924**(2):95, January 2022. doi: 10.3847/1538-4357/ac32bd.

[9] A. Archer et al. VERITAS Discovery of VHE Emission from the Radio Galaxy 3C 264: A Multiwavelength Study. , **896**(1):41, June 2020. doi: 10.3847/1538-4357/ab910e.

[10] Y. L. Chang, B. Arsioli, P. Giommi, P. Padovani, and C. H. Brandt. The 3HSP catalogue of extreme and high-synchrotron peaked blazars. , **632**:A77, December 2019. doi: 10.1051/0004-6361/201834526.

[11] L. Costamante. TeV-peaked candidate BL Lac objects. , **491**(2):2771–2778, January 2020. doi: 10.1093/mnras/stz3018.

[12] Michael W. Toomey, Foteini Oikonomou, and Kohta Murase. Gamma-ray counterparts of 2WHSP high-synchrotron-peaked BL Lac objects as possible signatures of ultra-high-energy cosmic ray emission. , **497**(2):2455–2468, September 2020. doi: 10.1093/mnras/staa1990.

[13] V. A. Acciari et al. VERITAS OBSERVATIONS OF GAMMA-RAY BURSTS DETECTED BY SWIFT. *The Astrophysical Journal*, **743**(1):62, nov 2011. doi: 10.1088/0004-637x/743/1/62.

[14] E. Aliu et al. CONSTRAINTS ON VERY HIGH ENERGY EMISSION FROM GRB 130427a. *The Astrophysical Journal*, **795**(1):L3, oct 2014. doi: 10.1088/2041-8205/795/1/l3.

[15] A. U. Abeysekara et al. A strong limit on the very-high-energy emission from GRB 150323a. *The Astrophysical Journal*, **857**(1):33, apr 2018. doi: 10.3847/1538-4357/aab371.

[16] Yasuyuki T Tanaka, Sara Buson, and Daniel Kocevski. Fermi-lat detection of increased gamma-ray activity of txs 0506+ 056, located inside the icecube-170922a error region. *The Astronomer's Telegram*, **10791**:1, 2017.

[17] Razmik Mirzoyan. First-time detection of vhe gamma rays by magic from a direction consistent with the recent ehe neutrino event icecube-170922a. *The Astronomer's Telegram*, **10817**:1, 2017.

[18] C. B. Adams et al. An Archival Search for Neutron-star Mergers in Gravitational Waves and Very-high-energy Gamma Rays. , **918**(2):66, September 2021. doi: 10.3847/1538-4357/ac0623.

[19] W. Benbow et al. Direct measurement of stellar angular diameters by the VERITAS cherenkov telescopes. *Nature Astronomy*, **3**(6):511–516, apr 2019. doi: 10.1038/s41550-019-0741-z.

[20] S. Archambault et al. Dark Matter Constraints from a Joint Analysis of Dwarf Spheroidal Galaxy Observations with VERITAS. *Phys. Rev. D*, **95**(8):082001, 2017. doi: 10.1103/PhysRevD.95.082001.