Snowmass2021 - Letter of Interest

Synergies in Very-High-Energy Astroparticle Physics for SWGO over the Coming Decade[*]

Thematic Areas: (check all that apply ☐/■)
☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

Contact Information: (authors listed after the text)
Submitter Name/Institution: Kristi L. Engel / University of Maryland, College Park
Collaboration (optional): HAWC, SWGO
Contact Email: klengel@umd.edu

Abstract: Gamma-ray astrophysics in the very-high-energy range (VHE, E>100 GeV) is mainly conducted from the ground using imaging atmospheric Cherenkov telescopes (IACTs) and ground-level air-shower arrays of water Cherenkov detectors (WCDs). These detectors can also deliver measurements of cosmic-ray composition, spectrum, and anisotropy. The IACT and WCD techniques have intrinsic complementary advantages that can be exploited to improve our coverage of the VHE gamma-ray sky. The continued discoveries enabled by current WCD and IACT arrays will be boosted by the construction of next-generation facilities of both classes, such as the Cherenkov Telescope Array (CTA) and the proposed Southern Wide-field Gamma-ray Observatory (SWGO). Both instrument classes stand poised, ready to revolutionize the field with their supporting science goals. We present herein the highlights of these interrelated studies and how the interplay of both techniques serves the furthering of astroparticle physics research.

[*]This Letter contains excerpts and material from White Papers submitted for the Astro2020 Decadal Survey [1;2]

The Current Generation of VHE Gamma-Ray Instruments

Ground-based instruments dedicated to observations in the very-high-energy (VHE) gamma-ray band include the imaging atmospheric Cherenkov telescope (IACT) arrays H.E.S.S.[3] (located in Namibia), MAGIC[4] (La Palma, Spain), and VERITAS[5] (Arizona, USA), and the High-Altitude Water Cherenkov (HAWC) Observatory[6], a WCD array located in Mexico. Their distinct geographic locations enable observations of the entire VHE gamma-ray sky with complementary capabilities as detailed in Table 1. This complementarity has been demonstrated in recent years by the joint study of new sources and new source classes discovered by HAWC, which surveys the northern gamma-ray sky with nearly 100% duty cycle and an instantaneous field-of-view of ~ 2 sr [7–23]. Detailed follow-up studies of these new sources have been performed with VERITAS[24;25] and MAGIC[26], combining the HAWC sensitivity to extended and hard-spectrum sources with the superior angular and energy resolution of IACTs.

The large field-of-view of HAWC also enables multi-messenger searches for electromagnetic counterparts to gravitational wave and neutrino events, which can then be used to trigger deep target-of-opportunity observations of promising candidates with IACTs. The high duty cycle of the instrument provides a unique opportunity to build long-term light curves for known active VHE emitters, such as Markarian 421 and 501[8], and to alert IACTs if bright TeV flares are detected[14]. Beyond their unique capabilities, WCD arrays such as HAWC can therefore act as surveying and high-cadence monitoring instruments for IACTs. This monitoring capability extends that provided by GeV space telescopes, like *Fermi*-LAT[27], to the TeV range.

Table 1: Comparison of typical performance of current and planned IACT arrays and ground particle arrays for gamma-ray astronomy. See Ref. 1 for details.

	IACT Arrays	Ground-particle Arrays
Field-of-view	3°–10°	90°
Duty cycle	10%–30%	>95%
Energy range	30 GeV – >100 TeV	∼500 GeV – >100 TeV
Angular resolution	0.05°–0.02°	0.4°–0.1°
Energy resolution	∼7%	60%–20%
Background rejection	>95%	90%–99.8%

The success of the water-Cherenkov technology, (also implemented by HAWC) has inspired an ambitious Chinese-lead effort, LHAASO, in the Northern Hemisphere, which uses a similar approach[28]. HAWC, and soon LHAASO, will provide wide-field coverage of the Northern VHE gamma-ray sky in the coming years, but no wide-field detector yet exists to cover the Southern sky. We propose the Southern Wide-field Gamma-ray Observatory[1] (SWGO) as a next-generation, WCD instrument that will provide this observational coverage of the Southern sky at energies from $\gtrsim$ 100 GeV to hundreds of TeV from a site in the Andes mountains of South America. The excellent sensitivity expected from LHAASO at the highest energies[29], and the lessons learned from both HAWC and LHAASO, will inform the SWGO design, opening new opportunities for searches of gamma-ray sources in the southern sky up to the PeV energy range.

SWGO and Future VHE Gamma-Ray Instruments

We expect SWGO to be in simultaneous operation with the Cherenkov Telescope Array (CTA)[30], the next-generation IACT gamma-ray observatory with sensitivity in the 20 GeV to 300 TeV energy range. CTA will consist of two IACT arrays: one in the Northern Hemisphere (La Palma, Spain), and the other in the Southern Hemisphere (Atacama desert, Chile). SWGO will be complementary to the southern CTA site, therefore enabling full-sky coverage in VHE gamma rays with both IACTs and WCDs. The expected

point-source sensitivity of SWGO is shown in Fig. 1 in comparison with other instruments in the Southern Hemisphere and HAWC.

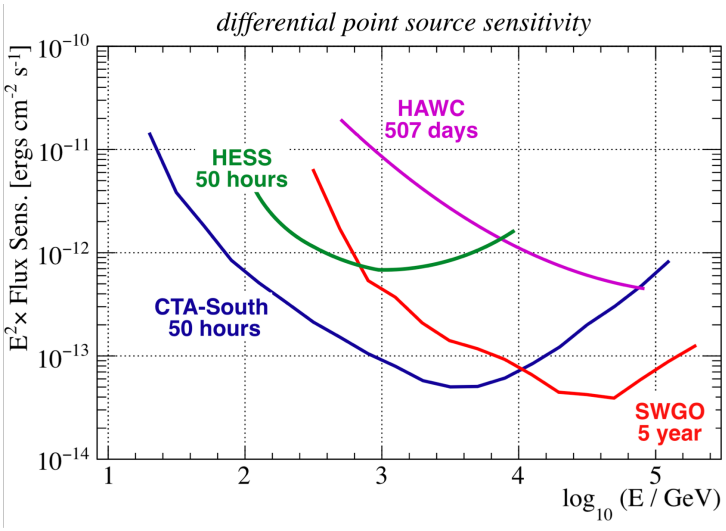

Figure 1: Differential point-source sensitivity as a function of energy for the proposed SWGO detector compared to other existing or proposed instruments. The SWGO and HAWC sensitivities apply to all points in their sky coverage, whereas the curves for H.E.S.S. and CTA-South apply to a 50-hour observation of a single source. SWGO will therefore provide important complementary observations with CTA.

SWGO and CTA share a wide variety of key science goals, such as the search for Galactic objects capable of acceleration particles to PeV energies (i.e. PeVatrons), the study of Pulsar Wind Nebulae (PWNe) and supernova remnants, the observation of active galaxies, and the follow-up of multi-wavelength and multi-messenger transients (such as gamma-ray bursts, gravitational waves, and neutrino events), among other topics. This is complemented by a wide program of searches for physics beyond the Standard Model such as dark-matter annihilation signatures in the Galactic Center, Lorentz Invariance Violation tests, and searches for Axion-Like Particles and primordial black holes.

SWGO will provide sensitive observations of very extended objects ($> 8°$) and diffuse emission features that will still be challenging to cover with CTA-South, such as TeV halos around nearby PWNe[16] or the Fermi bubbles[10]. TeV halos, in particular, are of critical importance to dark-matter interpretations of cosmic-ray data as they can provide a nearby source of positrons. With a lower energy threshold and higher sensitivity when compared to HAWC, SWGO will provide continuous, long-term monitoring of variable extragalactic sources in the Southern sky such as PKS 2155-304[31]. CTA observations could be triggered by the observation of a new fast flare from this object which will enable sensitive searches for Lorentz Invariance Violation effects that manifest themselves as an energy-dependent dispersion in the arrival time of photons at Earth[32]. This approach has the added advantage that it reduces the pressure on CTA to provide constant monitoring for some of the brighter extragalactic sources that will be observable by SWGO. The follow up of transient events with poor angular localization, such as gravitational waves, neutrino cascade events, and some gamma-ray bursts, will also benefit from the wide field-of-view of SWGO— providing CTA with potential VHE gamma-ray candidate localizations for nearby or bright counterparts.

In summary, we expect that the operation of SWGO will not only deliver unique observations of the gamma-ray sky, but also provide opportunities for sensitive joint studies with other instruments coming online in the next decade— in particular with the Southern CTA array. SWGO will monitor the sky at energies above $\gtrsim$ 100 GeV, complementing and extending the GeV monitoring currently provided by the *Fermi*-LAT to higher energies and into the coming decade.

References

[1] A. Albert et al. Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere. 2 2019.

[2] P. Abreu et al. The Southern Wide-Field Gamma-Ray Observatory (SWGO): A Next-Generation Ground-Based Survey Instrument for VHE Gamma-Ray Astronomy. 7 2019.

[3] F. Aharonian et al. Observations of the Crab Nebula with H.E.S.S. *Astron. Astrophys.*, 457:899–915, 2006.

[4] J. Aleksić, S. Ansoldi, L. A. Antonelli, P. Antoranz, A. Babic, P. Bangale, M. Barceló, J. A. Barrio, J. Becerra González, W. Bednarek, E. Bernardini, B. Biasuzzi, A. Biland, M. Bitossi, O. Blanch, S. Bonnefoy, G. Bonnoli, F. Borracci, T. Bretz, E. Carmona, A. Carosi, R. Cecchi, P. Colin, E. Colombo, J. L. Contreras, D. Corti, J. Cortina, S. Covino, P. Da Vela, F. Dazzi, A. DeAngelis, G. De Caneva, B. De Lotto, E. de Oña Wilhelmi, C. Delgado Mendez, A. Dettlaff, D. Dominis Prester, D. Dorner, M. Doro, S. Einecke, D. Eisenacher, D. Elsaesser, D. Fidalgo, D. Fink, M. V. Fonseca, L. Font, K. Frantzen, C. Fruck, D. Galindo, R. J. García López, M. Garczarczyk, D. Garrido Terrats, M. Gaug, G. Giavitto, N. Godinović, A. González Muñoz, S. R. Gozzini, W. Haberer, D. Hadasch, Y. Hanabata, M. Hayashida, J. Herrera, D. Hildebrand , J. Hose, D. Hrupec, W. Idec, J. M. Illa, V. Kadenius, H. Kellermann, M. L. Knoetig, K. Kodani, Y. Konno, J. Krause, H. Kubo, J. Kushida, A. La Barbera, D. Lelas, J. L. Lemus, N. Lewandowska, E. Lindfors, S. Lombardi, F. Longo, M. López, R. López-Coto, A. López-Oramas, A. Lorca, E. Lorenz, I. Lozano, M. Makariev, K. Mallot, G. Maneva, N. Mankuzhiyil, K. Mannheim, L. Maraschi, B. Marcote, M. Mariotti, M. Martínez, D. Mazin, U. Menzel, J. M. Miranda, R. Mirzoyan, A. Moralejo, P. Munar-Adrover, D. Nakajima, M. Negrello, V. Neustroev, A. Niedzwiecki, K. Nilsson, K. Nishijima, K. Noda, R. Orito, A. Overkemping, S. Paiano, M. Palatiello, D. Paneque, R. Paoletti, J. M. Paredes, X. Paredes-Fortuny, M. Persic, J. Poutanen, P. G. Prada Moroni, E. Prandini, I. Puljak, R. Reinthal, W. Rhode, M. Ribó, J. Rico, J. Rodriguez Garcia, S. Rügamer, T. Saito, K. Saito, K. Satalecka, V. Scalzotto, V. Scapin, C. Schultz, J. Schlammer, S. Schmidl, T. Schweizer, A. Sillanpää, J. Sitarek, I. Snidaric, D. Sobczynska, F. Spanier, A. Stamerra, T. Steinbring, J. Storz, M. Strzys, L. Takalo, H. Takami, F. Tavecchio, L. A. Tejedor, P. Temnikov, T. Terzić, D. Tescaro, M. Teshima, J. Thaele, O. Tibolla, D. F. Torres, T. Toyama, A. Treves, P. Vogler, H. Wetteskind, M. Will, and R. Zanin. The major upgrade of the MAGIC telescopes, Part I: The hardware improvements and the commissioning of the system. *Astroparticle Physics*, 72:61–75, January 2016.

[5] Jamie Holder et al. The first VERITAS telescope. *Astropart. Phys.*, 25:391–401, 2006.

[6] A. U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J. D. Álvarez, J. R. Angeles Camacho, R. Arceo, J. C. Arteaga-Velázquez, K. P. Arunbabu, D. Avila Rojas, and et al. Measurement of the crab nebula spectrum past 100 tev with hawc. *The Astrophysical Journal*, 881(2):134, Aug 2019.

[7] A. U. Abeysekara, R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, H. A. Ayala Solares, A. S. Barber, B. M. Baughman, and N. Bautista-Elivar. Search for Gamma-Rays from the Unusually Bright GRB 130427A with the HAWC Gamma-Ray Observatory. , 800(2):78, Feb 2015.

[8] A. U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, D. Avila Rojas, H. A. Ayala Solares, and A. S. Barber. Daily Monitoring of TeV Gamma-Ray Emission from Mrk 421, Mrk 501, and the Crab Nebula with HAWC. , 841(2):100, Jun 2017.

[9] Icecube Collaboration, M. G. Aartsen, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, I. Al Samarai, D. Altmann, and K. Andeen. Multiwavelength follow-up of a rare IceCube neutrino multiplet. *Astronomy & Astrophysics*, 607:A115, Nov 2017.

[10] A. U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, H. A. Ayala Solares, A. S. Barber, and N. Bautista-Elivar. Search for Very High-energy Gamma Rays from the Northern Fermi Bubble Region with HAWC. , 842(2):85, Jun 2017.

[11] A. U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, H. A. Ayala Solares, A. S. Barber, N. Bautista-Elivar, A. Becerril, E. Belmont-Moreno, S. Y. BenZvi, D. Berley, J. Braun, C. Brisbois, K. S. Caballero-Mora, T. Capistrán, A. Carramiñana, S. Casanova, M. Castillo, U. Cotti, J. Cotzomi, S. Coutiño de León, E. de la Fuente, C. De León, T. DeYoung, B. L. Dingus, M. A. DuVernois, J. C. Díaz-Vélez, R. W. Ellsworth, D. W. Fiorino, N. Fraija, J. A. García-González, M. Gerhardt, A. González Munöz, M. M. González, J. A. Goodman, Z. Hampel-Arias, J. P. Harding, S. Hernandez, A. Hernandez-Almada, J. Hinton, C. M. Hui, P. Hüntemeyer, A. Iriarte, A. Jardin-Blicq, V. Joshi, S. Kaufmann, D. Kieda, A. Lara, R. J. Lauer, W. H. Lee, D. Lennarz, H. León Vargas, J. T. Linnemann, A. L. Longinotti, G. L. Raya, R. Luna-García, R. López-Coto, K. Malone, S. S. Marinelli, O. Martinez, I. Martinez-Castellanos, J. Martínez-Castro, H. Martínez-Huerta, J. A. Matthews, P. Miranda-Romagnoli, E. Moreno, M. Mostafá, L. Nellen, M. Newbold, M. U. Nisa, R. Noriega-Papaqui, R. Pelayo, J. Pretz, E. G. Pérez-Pérez, Z. Ren, C. D. Rho, C. Rivière, D. Rosa-González, M. Rosenberg, E. Ruiz-Velasco, H. Salazar, F. Salesa Greus, A. Sandoval, M. Schneider, H. Schoorlemmer, G. Sinnis, A. J. Smith, R. W. Springer, P. Surajbali, I. Taboada, O. Tibolla, K. Tollefson, I. Torres, T. N. Ukwatta, L. Villaseñor, T. Weisgarber, S. Westerhoff, I. G. Wisher, J. Wood, T. Yapici, G. B. Yodh, P. W. Younk, A. Zepeda, and H. Zhou. Observation of the Crab Nebula with the HAWC Gamma-Ray Observatory. , 843:39, July 2017.

[12] A. U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, H. A. Ayala Solares, A. S. Barber, and B. Baughman. The 2HWC HAWC Observatory Gamma-Ray Catalog. , 843(1):40, Jul 2017.

[13] R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, D. Avila Rojas, H. A. Ayala Solares, A. S. Barber, N. Bautista-Elivar, and A. Becerril. Search for Very-high-energy Emission from Gamma-Ray Bursts Using the First 18 Months of Data from the HAWC Gamma-Ray Observatory. , 843(2):88, Jul 2017.

[14] A. U. Abeysekara, R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, D. Avila Rojas, H. A. Ayala Solares, A. S. Barber, and N. Bautista-Elivar. The HAWC Real-time Flare Monitor for Rapid Detection of Transient Events. , 843(2):116, Jul 2017.

[15] B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, and et al. Multi-messenger Observations of a Binary Neutron Star Merger. , 848:L12, October 2017.

[16] A. U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, D. Avila Rojas, H. A. Ayala Solares, A. S. Barber, N. Bautista-Elivar, A. Becerril, E. Belmont-Moreno, S. Y. BenZvi, D. Berley, A. Bernal, J. Braun, C. Brisbois, K. S. Caballero-Mora, T. Capistrán, A. Carramiñana, S. Casanova, M. Castillo, U. Cotti, J. Cotzomi, S. Coutiño de León, C. De León, E. De la Fuente, B. L. Dingus, M. A. DuVernois, J. C. Díaz-Vélez, R. W. Ellsworth, K. Engel, O. Enríquez-Rivera, D. W. Fiorino, N. Fraija, J. A. García-González, F. Garfias, M. Gerhardt, A. González Muñoz,

M. M. González, J. A. Goodman, Z. Hampel-Arias, J. P. Harding, S. Hernández, A. Hernández-Almada, J. Hinton, B. Hona, C. M. Hui, P. Hüntemeyer, A. Iriarte, A. Jardin-Blicq, V. Joshi, S. Kaufmann, D. Kieda, A. Lara, R. J. Lauer, W. H. Lee, D. Lennarz, H. L. Vargas, J. T. Linnemann, A. L. Longinotti, G. Luis Raya, R. Luna-García, R. López-Coto, K. Malone, S. S. Marinelli, O. Martinez, I. Martinez-Castellanos, J. Martínez-Castro, H. Martínez-Huerta, J. A. Matthews, P. Miranda-Romagnoli, E. Moreno, M. Mostafá, L. Nellen, M. Newbold, M. U. Nisa, R. Noriega-Papaqui, R. Pelayo, J. Pretz, E. G. Pérez-Pérez, Z. Ren, C. D. Rho, C. Rivière, D. Rosa-González, M. Rosenberg, E. Ruiz-Velasco, H. Salazar, F. Salesa Greus, A. Sandoval, M. Schneider, H. Schoorlemmer, G. Sinnis, A. J. Smith, R. W. Springer, P. Surajbali, I. Taboada, O. Tibolla, K. Tollefson, I. Torres, T. N. Ukwatta, G. Vianello, T. Weisgarber, S. Westerhoff, I. G. Wisher, J. Wood, T. Yapici, G. Yodh, P. W. Younk, A. Zepeda, H. Zhou, F. Guo, J. Hahn, H. Li, and H. Zhang. Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth. *Science*, 358:911–914, November 2017.

[17] A. Albert, R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, D. Avila Rojas, H. A. Ayala Solares, N. Bautista-Elivar, and A. Becerril. Dark Matter Limits from Dwarf Spheroidal Galaxies with the HAWC Gamma-Ray Observatory. , 853(2):154, Feb 2018.

[18] A. U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, R. Arceo, J. C. Arteaga-Velázquez, D. Avila Rojas, H. A. Ayala Solares, A. Becerril, and E. Belmont-Moreno. A search for dark matter in the Galactic halo with HAWC. , 2018(2):049, Feb 2018.

[19] A. Albert, R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, D. Avila Rojas, H. A. Ayala Solares, A. Becerril, and E. Belmont-Moreno. Search for dark matter gamma-ray emission from the Andromeda Galaxy with the High-Altitude Water Cherenkov Observatory. , 2018(6):043, Jun 2018.

[20] IceCube Collaboration, M. G. Aartsen, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, I. Al Samarai, D. Altmann, K. Andeen, and et al. Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. *Science*, 361:eaat1378, July 2018.

[21] A. Albert, R. Alfaro, C. Alvarez, R. Arceo, J. C. Arteaga-Velázquez, D. Avila Rojas, H. A. Ayala Solares, E. Belmont-Moreno, S. Y. BenZvi, and C. Brisbois. Constraints on spin-dependent dark matter scattering with long-lived mediators from TeV observations of the Sun with HAWC. , 98(12):123012, Dec 2018.

[22] A. U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J. D. Álvarez, R. Arceo, J. C. Arteaga-Velázquez, D. Avila Rojas, H. A. Ayala Solares, E. Belmont-Moreno, S. Y. BenZvi, C. Brisbois, K. S. Caballero-Mora, T. Capistrán, A. Carramiñana, S. Casanova, M. Castillo, U. Cotti, J. Cotzomi, S. Coutiño de León, C. De León, E. De la Fuente, J. C. Díaz-Vélez, S. Dichiara, B. L. Dingus, M. A. DuVernois, R. W. Ellsworth, K. Engel, C. Espinoza, K. Fang, H. Fleischhack, N. Fraija, A. Galván-Gámez, J. A. García-González, F. Garfias, A. González-Muñoz, M. M. González, J. A. Goodman, Z. Hampel-Arias, J. P. Harding, S. Hernandez, J. Hinton, B. Hona, F. Hueyotl-Zahuantitla, C. M. Hui, P. Hüntemeyer, A. Iriarte, A. Jardin-Blicq, V. Joshi, S. Kaufmann, P. Kar, G. J. Kunde, R. J. Lauer, W. H. Lee, H. León Vargas, H. Li, J. T. Linnemann, A. L. Longinotti, G. Luis-Raya, R. López-Coto, K. Malone, S. S. Marinelli, O. Martinez, I. Martinez-Castellanos, J. Martínez-Castro, J. A. Matthews, P. Miranda-Romagnoli, E. Moreno, M. Mostafá, A. Nayerhoda, L. Nellen, M. Newbold, M. U. Nisa, R. Noriega-Papaqui, J. Pretz, E. G. Pérez-Pérez, Z. Ren, C. D. Rho, C. Rivière, D. Rosa-González, M. Rosenberg, E. Ruiz-Velasco, F. Salesa Greus, A. Sandoval, M. Schneider, H. Schoorlemmer, M. Seglar Arroyo, G. Sinnis, A. J. Smith, R. W. Springer, P. Surajbali, I. Taboada, O. Tibolla, K. Tollefson, I. Torres, G. Vianello, L. Villaseñor, T. Weisgarber, F. Werner, S. Westerhoff, J. Wood, T. Yapici, G. Yodh,

A. Zepeda, H. Zhang, and H. Zhou. Very-high-energy particle acceleration powered by the jets of the microquasar SS 433. , 562:82–85, October 2018.

[23] HAWC Collaboration, A. U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J. D. Álvarez, J. R. Angeles Camacho, R. Acero, J. C. Arteaga-Velázquez, and K. P. Arunbabu. Measurement of the Crab Nebula at the Highest Energies with HAWC. *arXiv e-prints (accepted for pub. in)*, page arXiv:1905.12518, May 2019.

[24] A.U. Abeysekara et al. VERITAS and Fermi-LAT Observations of TeV Gamma-Ray Sources Discovered by HAWC in the 2HWC Catalog. *Astrophys. J.*, 866(1):24, 2018.

[25] A. Coerver et al. Multiwavelength Investigation of Pulsar Wind Nebula DA 495 with HAWC, VERITAS, and NuSTAR. *Astrophys. J.*, 878(2):126, 2019.

[26] M.L. Ahnen et al. MAGIC and Fermi-LAT gamma-ray results on unassociated HAWC sources. 1 2019.

[27] W. B. Atwood, A. A. Abdo, M. Ackermann, W. Althouse, B. Anderson, M. Axelsson, L. Baldini, J. Ballet, D. L. Band, G. Barbiellini, J. Bartelt, D. Bastieri, B. M. Baughman, K. Bechtol, D. Bédérède, F. Bellardi, R. Bellazzini, B. Berenji, G. F. Bignami, D. Bisello, E. Bissaldi, R. D. Blandford, E. D. Bloom, J. R. Bogart, E. Bonamente, J. Bonnell, A. W. Borgland , A. Bouvier, J. Bregeon, A. Brez, M. Brigida, P. Bruel, T. H. Burnett, G. Busetto, G. A. Caliandro, R. A. Cameron, P. A. Caraveo, S. Carius, P. Carlson, J. M. Casandjian, E. Cavazzuti, M. Ceccanti, C. Cecchi, E. Charles, A. Chekhtman, C. C. Cheung, J. Chiang, R. Chipaux, A. N. Cillis, S. Ciprini, R. Claus, J. Cohen-Tanugi, S. Condamoor, J. Conrad, R. Corbet, L. Corucci, L. Costamante, S. Cutini, D. S. Davis, D. Decotigny, M. DeKlotz, C. D. Dermer, A. de Angelis, S. W. Digel, E. do Couto e Silva, P. S. Drell, R. Dubois, D. Dumora, Y. Edmonds, D. Fabiani, C. Farnier, C. Favuzzi, D. L. Flath, P. Fleury, W. B. Focke, S. Funk, P. Fusco, F. Gargano, D. Gasparrini, N. Gehrels, F. X. Gentit, S. Germani, B. Giebels, N. Giglietto, P. Giommi, F. Giordano, T. Glanzman, G. Godfrey, I. A. Grenier, M. H. Grondin, J. E. Grove, L. Guillemot, S. Guiriec, G. Haller, A. K. Harding, P. A. Hart, E. Hays, S. E. Healey, M. Hirayama, L. Hjalmarsdotter, R. Horn, R. E. Hughes, G. Jóhannesson, G. Johansson, A. S. Johnson, R. P. Johnson, T. J. Johnson, W. N. Johnson, T. Kamae, H. Katagiri, J. Kataoka, A. Kavelaars, N. Kawai, H. Kelly, M. Kerr, W. Klamra, J. Knödlseder, M. L. Kocian, N. Komin, F. Kuehn, M. Kuss, D. Landriu, L. Latronico, B. Lee, S. H. Lee, M. Lemoine-Goumard, A. M. Lionetto, F. Longo, F. Loparco, B. Lott, M. N. Lovellette, P. Lubrano, G. M. Madejski, A. Makeev, B. Marangelli, M. M. Massai, M. N. Mazziotta, J. E. McEnery, N. Menon, C. Meurer, P. F. Michelson, M. Minuti, N. Mirizzi, W. Mitthumsiri, T. Mizuno, A. A. Moiseev, C. Monte, M. E. Monzani, E. Moretti, A. Morselli, I. V. Moskalenko, S. Murgia, T. Nakamori, S. Nishino, P. L. Nolan, J. P. Norris, E. Nuss, M. Ohno, T. Ohsugi, N. Omodei, E. Orlando, J. F. Ormes, A. Paccagnella, D. Paneque, J. H. Panetta, D. Parent, M. Pearce, M. Pepe, A. Perazzo, M. Pesce-Rollins, P. Picozza, L. Pieri, M. Pinchera, F. Piron, T. A. Porter, L. Poupard, S. Rainò, R. Rando, E. Rapposelli, M. Razzano, A. Reimer, O. Reimer, T. Reposeur, L. C. Reyes, S. Ritz, L. S. Rochester, A. Y. Rodriguez, R. W. Romani, M. Roth, J. J. Russell, F. Ryde, S. Sabatini, H. F. W. Sadrozinski, D. Sanchez, A. Sand er, L. Sapozhnikov, P. M. Saz Parkinson, J. D. Scargle, T. L. Schalk, G. Scolieri, C. Sgrò, G. H. Share, M. Shaw, T. Shimokawabe, C. Shrader, A. Sierpowska-Bartosik, E. J. Siskind, D. A. Smith, P. D. Smith, G. Spandre, P. Spinelli, J. L. Starck, T. E. Stephens, M. S. Strickman, A. W. Strong, D. J. Suson, H. Tajima, H. Takahashi, T. Takahashi, T. Tanaka, A. Tenze, S. Tether, J. B. Thayer, J. G. Thayer, D. J. Thompson, L. Tibaldo, O. Tibolla, D. F. Torres, G. Tosti, A. Tramacere, M. Turri, T. L. Usher, N. Vilchez, V. Vitale, P. Wang, K. Watters, B. L. Winer, K. S. Wood, T. Ylinen, and M. Ziegler. The Large Area Telescope on the Fermi Gamma-Ray Space Telescope Mission. , 697(2):1071–1102, June 2009.

[28] X. Bai, B. Y. Bi, X. J. Bi, Z. Cao, S. Z. Chen, Y. Chen, A. Chiavassa, X. H. Cui, Z. G. Dai, and D. della Volpe. The Large High Altitude Air Shower Observatory (LHAASO) Science White Paper. *arXiv e-prints*, page arXiv:1905.02773, May 2019.

[29] Huihai He. Status and First Results of the LHAASO Experiment. *PoS*, ICRC2019:693, 2019.

[30] B.S. Acharya et al. *Science with the Cherenkov Telescope Array*. WSP, 11 2018.

[31] F. Aharonian et al. An Exceptional Very High Energy Gamma-Ray Flare of PKS 2155-304. *Astrophys. J. Lett.*, 664:L71–L78, 2007.

[32] A. Albert et al. Constraints on Lorentz Invariance Violation from HAWC Observations of Gamma Rays above 100 TeV. *Phys. Rev. Lett.*, 124(13):131101, 2020.

Authors: A.M. Albert (Los Alamos National Laboratory), L.H. Arnaldi (CNEA/IB, Argentina), J.C. Arteaga-Velázquez (Universidad Michoacana, Mexico), H.A. Ayala Solares (Pennsylvania State University, University Park), U. Barres de Almeida (CBPF, Brazil), C.A. Brisbois (University of Maryland, College Park), K.S. Caballero-Mora (UNACH, México), A. Carramiñana (INAOE, México), A. Chiavassa (Torino University, IT), R. Conceição (LIP/IST, Lisbon, Portugal), S. Dasso (IAFE-DCAO, Argentina), C.O. Dib (UTFSM, Chile), J.C. Díaz-Vélez (University of Wisconsin–Madison), B.L. Dingus (University of Maryland), M. Durocher (Los Alamos National Laboratory), M.A. DuVernois (University of Wisconsin–Madison), R.W. Ellsworth (University of Maryland, College Park), K.L. Engel (University of Maryland, College Park), C. Espinoza (UNAM, México), K.L. Fan (University of Maryland, College Park), K. Fang (Stanford University, University of Wisconsin-Madison), N. Fraija (IA-UNAM, México), J.A. García-González (ITESM-EIC), G. Giacinti (MPIK, Germany), J.A. Goodman (University of Maryland, College Park), J.P. Harding (Los Alamos National Laboratory), R.N. Hix (University of Maryland, College Park), D.Z. Huang (Michigan Technological University, Houghton), P. Huentemeyer (Michigan Technological University, Houghton), G. La Mura (LIP, Lisbon, Portugal), F. Longo (University and INFN Trieste), K. Malone (Los Alamos

National Laboratory), I. Martinez-Castellanos (NASA-GSFC/CRESST/UMD), J.A. Morales-Soto (Universidad Michoacana, Mexico), E. Moreno (BUAP, México), L. Nellen (ICN-UNAM, México), M. Newbold (University of Utah, Salt Lake City), M.U. Nisa (Michigan State University, East Lansing), E. Orlando (University of Trieste and Stanford University), A. Pichel (Instituto de Astronomía y Física del Espacio, CONICET-UBA, Argentina), M. Pimenta (LIP/IST, Lisbon, Portugal), C.D. Rho (University of Seoul, Seoul), A.C. Rovero (Instituto de Astronomía y Física del Espacio, CONICET-UBA, Argentina), A. Sandoval (UNAM, México), M. Santander (University of Alabama, USA), M. Schneider (University of Maryland, College Park), H. Schoorlemmer (MPIK, Germany), A.J. Smith (University of Maryland, College Park), K. Tollefson (Michigan State University, East Lansing), B. Tomé (LIP/IST, Lisbon, Portugal), I. Torres (INAOE, México), R. Torres Escobedo (Universidad de Guadalajara, Mexico/Texas Tech University, Lubbock TX), J. Vícha (FZU, Prague, Czech Republic), E.J. Willox (University of Maryland, College Park)