

Multimessenger NuEM Alerts with AMON

Hugo Ayala^{a,*} on behalf of the AMON Group, the HAWC, the IceCube and the Antares Collaboration

(a complete list of authors can be found at the end of the proceedings)

^a*Pennsylvania State University,
State College, US
E-mail: hgayala@psu.edu*

The Astrophysical Multimessenger Observatory Network (AMON), has developed a real-time multi-messenger alert system. The system performs coincidence analyses of datasets from gamma-ray and neutrino detectors, making the Neutrino-Electromagnetic (NuEM) alert channel. For these analyses, AMON takes advantage of sub-threshold events, i.e., events that by themselves are not significant in the individual detectors. The main purpose of this channel is to search for gamma-ray counterparts of neutrino events. We will describe the different analyses that make-up this channel and present a selection of recent results.

*37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany*

*Presenter

1. Multi-messenger Astrophysics

The study of the Universe has been benefited by the improvement of our technology and analysis techniques. Recently, this has allowed us to combine the information available from different observations that focus on individual components of the physical phenomena. The most important results in the past lustrum are the detection of gravitational waves and electromagnetic radiation from the merger of a binary neutron star [1], together with the detection of high-energy neutrinos and gamma-rays from the blazar TXS 0506-056 [2].

The information given by each individual messenger — cosmic rays, electromagnetic radiation, neutrinos, and gravitational waves — help us get a general picture about the acceleration mechanisms and identification of sources that produce cosmic-rays, gamma-ray bursts, the nature of dark matter and other unsolved questions in astrophysics [See for example 3, 4].

In these contribution we present an overview of the Neutrino-Electromagnetic (NuEM) channel of the Astrophysical Multimessenger Observatory Network. This effort is based on the new paradigm of multi-messenger astrophysics, which aims at coordination between different observatories and combining independent datasets into a coincidence analysis.

2. AMON

The Astrophysical Multimessenger Observatory Network (AMON) is a program developed at the Pennsylvania State University. Its primary objective is to perform real-time coincidence searches of sub-threshold events of different observatories. Any statistically significant coincidence is then reported to the astrophysical community through Gamma-ray Coordinates Network (GCN, also known as the Transient Astronomy Network). AMON also stores events into its database to perform archival coincidence searches. It broadcasts individual events to GCN if the observatories providing the events consider them to be of interest to the astrophysical community. And finally, it aims to be a framework that facilitates the interaction between observatories trying to combine their datasets [5]. A list of participants can be found in the AMON webpage¹.

The AMON alert system started sending alerts in 2016. Currently, AMON provides the following public alerts:

- IceCube Gold, Bronze and Cascade alerts,
- HAWC Burst-like alerts,
- NuEM channel alerts.

The notices of these alerts can be found in the GCN webpage². The webpage also includes the now decommissioned IceCube HESE and EHE alerts.

¹<https://www.amon.psu.edu/amon-participants/>

²<https://gcn.gsfc.nasa.gov/amon.html>

3. The NuEM Channel

The AMON NuEM channel focuses on neutrino and high-energy photon coincidences by using sub-threshold data³ from different observatories. The main objective of this channel is to search for the sources of high-energy neutrinos with the help of high-energy gamma rays.

This search can be performed since there are physical processes where neutrinos and gamma rays are produced together. It is known that accelerated cosmic rays interact with radiation fields or interstellar matter surrounding the region around astrophysical sources. These interactions produce secondary charged and neutral pions. Charged pions mainly decay via $\pi^+ \rightarrow \mu^+ + \nu_\mu$, followed by the decay of the muon as $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ and a similar process with the charge conjugate. Neutral pions decay into two gamma-ray photons, $\pi^0 \rightarrow \gamma + \gamma$. A photohadronic interaction, i.e. a collision between a cosmic ray and a photon, will produce charged and neutral pions with probabilities of one-third and two-thirds. If the interaction is just hadronic, then the probability of producing charged and neutral pions is one-third for each type of pion [6].

The NuEM channel receives data from the IceCube [7], ANTARES [8], HAWC [9], and *Fermi*-LAT [10] observatories. We have performed archival coincidences analysis between: *Fermi*-ANTARES [11], HAWC-IceCube [12], *Fermi*-IceCube [13] and HAWC-ANTARES, which preliminary results are shown in this contribution.

The general algorithm used in AMON to find and rank coincidences is as follows:

1. Set a criteria to select events which conform a coincidence. The criteria can be:
 - A time window where events can arrive.
 - A maximum angular distance between events.
2. Calculate a ranking statistic for the coincidence. This usually includes:
 - A likelihood calculation, $\lambda(\boldsymbol{x})$, quantifying the overlap between events. Maximizing the likelihood, λ_{\max} , gives an estimate of the position of the coincidence \boldsymbol{x}_{\max} .
 - A combination of p-values using Fisher's method [14]. The p-values can be, for example, how likely the individual event is from background, or how likely is the overlap between events just random.
3. Calculate the false-alarm rate of the coincidence as a function of the ranking statistic.

The false-alarm rate (FAR) is built by simulating random coincidences and generating a distribution of the ranking statistic. The analysis *Fermi*-ANTARES [11] and HAWC-IceCube [12] are, at the time of writing, running in real-time. The latency of these analyses are in the order of hours: 1 to 12 hours when data is downlinked from the *Fermi*-LAT instrument, and 3 to 7 hours when the data is collected by the HAWC Observatory (which corresponds to the time a point in the sky transits the detector's field of view). The calculation of the ranking statistic and the alert sending time is less than a minute. For the public real-time system we have set, with an agreement between the observatories, a threshold of $\text{FAR} < 4$ per year to send alerts. Alerts are sent as notices and circulars through GCN⁴.

³The numerical definition of a sub-threshold event is set by each individual observatory.

⁴The NuEM notices are found in https://gcn.gsfc.nasa.gov/gcn/amon_nu_em_coinc_events.html

4. Results

Table 1 shows the public alerts that appear in GCN, as well as the results of the archival coincidence searches performed so far. For the archival coincidences we show the ones that have a FAR < 1 per year.

Name	R.A. [°]	Decl. [°]	$\delta\theta$ [°]	FAR [yr^{-1}]	Time UTC
Real-time alerts					
NuEM-210515A	93.64	14.66	0.15	3.93	2021-05-15 00:20:43
NuEM-210515B	93.93	12.51	0.20	1.90	2021-05-15 00:19:27
NuEM-210111A	162.34	19.46	0.37	3.85	2021-01-11 13:06:41
NuEM-201124A	134.99	7.74	0.23	2.96	2020-11-24 14:13:37
NuEM-201107A	140.20	29.76	0.15	3.49	2020-11-07 15:55:31
ANTARES-Fermi 200704A	255.42	-34.48	0.43	0.98	2020-07-04 15:53:48
NuEM-200202A	200.30	12.71	0.17	1.39	2020-02-02 14:07:52
ANTARES-Fermi 191011A	49.96	18.80	0.40	1.21	2019-10-11 15:54:32
Archival Coincidences					
ANTARES-Fermi	248.00	-7.7	0.07	0.09	2012-11-21 20:19:52
ANTARES-Fermi	279.68	-5.05	0.10	0.09	2014-08-05 11:13:33
HAWC-IceCube	4.93	2.96	0.16	0.99	2016-12-12 04:38:41
HAWC-IceCube	173.99	2.27	0.53	0.026	2018-04-12 07:54:51
HAWC-ANTARES	25.6	25.0	0.2	0.7	2016-01-08 04:39:38
HAWC-ANTARES	222.8	-0.8	0.2	0.87	2017-09-07 01:21:22
HAWC-ANTARES	85.4	3.4	0.2	0.41	2019-03-29 03:01:18

Table 1: Real-time and Archival coincidences in the AMON NuEM channel. Real-time alerts are sent when the FAR is less than 4 per year. Archival coincidences have a FAR of less than 1 per year. Although the ANTARES-Fermi alerts are part of the AMON NuEM channel, the alerts are currently sent via GCN circulars instead of notices.

Follow-up observations of the real-time alerts have been made by a couple of observatories. Table 2 shows some of the instruments that submitted GCN circulars of their follow-up observations.

We have also looked at the Fermi All-sky Variability Analysis (FAVA)⁵ as well as the SIMBAD⁶ and NED⁷ catalogs, but no counterpart has been found so far for any of the coincidence alerts.

5. Summary

The multi-messenger approach has become a new paradigm to study astrophysical objects. Its advantages are that we can have a better understanding of different phenomena in the universe, such as sources of high-energy cosmic rays and neutrinos, the processes leading to gamma-ray bursts and the nature of dark matter. However, the tasks are challenging and require development of new

⁵<https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/>

⁶<http://simbad.u-strasbg.fr/simbad/>

⁷<http://ned.ipac.caltech.edu/>

Name	Followed by
NuEM-210515A/B	ANTARES
NuEM-210111A	ANTARES, INTEGRAL, MAXI
NuEM-201124A	ANTARES
NuEM-201107A	<i>Fermi-LAT</i>
NuEM-200202A	MASTER, ANTARES
FERMI-ANTARES-191011A	MASTER

Table 2: Follow-up observations of the NuEM alerts published as GCN Circulars. No counterpart was found in these observations. If seen online, each alert has a link to their respective circular.

techniques as well as the cooperation between different collaborations. AMON is a framework that aims to help with these issues. As an example, we have shown here the NuEM channel, a channel that performs coincidence analyses between neutrino data and gamma-ray data. The datasets used are diverse since they come from observatories such as IceCube, ANTARES, HAWC and Fermi-LAT. The AMON-NuEM channel has been sending alerts to the astrophysical community since 2019. The channel is still growing, with new coincidences planned to be added to it such as the HAWC-ANTARES analysis.

References

- [1] B.P. Abbott, R. Abbott, T.D. Abbott et al., *Multi-messenger Observations of a Binary Neutron Star Merger*, *ApJ* **848** (2017) L12.
- [2] M.G. Aartsen, M. Ackermann, J. Adams et al., *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A*, *Science* **361** (2018) 8.
- [3] F. Halzen, *Multi-messenger astronomy: cosmic rays, gamma-rays, and neutrinos*, in *21st Texas Symposium on Relativistic Astrophysics (Texas in Tuscany)*, 2, 2003, DOI.
- [4] A. Neronov, *Introduction to multi-messenger astronomy*, *J. Phys. Conf. Ser.* **1263** (2019) 012001 [1907.07392].
- [5] H.A. Ayala Solares, S. Coutu, D.F. Cowen et al., *The Astrophysical Multimessenger Observatory Network (AMON): Performance and science program*, *Astroparticle Physics* **114** (2020) 68.
- [6] D. Biehl, D. Boncioli, A. Fedynitch et al., *Astrophysical neutrino production and impact of associated uncertainties in photo-hadronic interactions of UHECRs*, in *European Physical Journal Web of Conferences*, vol. 208 of *European Physical Journal Web of Conferences*, p. 04002, May, 2019, DOI.
- [7] M.G. Aartsen, M. Ackermann, J. Adams et al., *The IceCube Neutrino Observatory: Instrumentation and Online Systems*, *JINST* **P03012** (2017) 12.

- [8] M. Ageron, J. Aguilar, I.A. Samarai et al., *ANTARES: The first undersea neutrino telescope*, *Nucl. Instrum. Methods Phys. Res. A* **656** (2011) 11.
- [9] A.U. Abeysekara, A. Albert, R. Alfaro et al., *Observation of the Crab Nebula with the HAWC Gamma-Ray Observatory*, *ApJ* **843** (2017) 39.
- [10] M. Ackermann, M. Ajello, A. Albert et al., *The Fermi Large Area Telescope on Orbit: Event Classification, Instrument Response Functions, and Calibration*, *ApJS* **203** (2012) 4.
- [11] H.A. Ayala Solares, S. Coutu, J.J. DeLaunay et al., *A Search for Cosmic Neutrino and Gamma-Ray Emitting Transients in 7.3 Years of ANTARES and Fermi LAT Data*, *Astrophys. J.* **886** (2019) 98 [[1904.06420](#)].
- [12] H.A. Ayala Solares, S. Coutu, J.J. DeLaunay et al., *Multimessenger Gamma-Ray and Neutrino Coincidence Alerts Using HAWC and IceCube Subthreshold Data*, *ApJ* **906** (2021) 63 [[2008.10616](#)].
- [13] C.F. Turley, D.B. Fox, A. Keivani, J.J. DeLaunay, D.F. Cowen, M. Mostafa et al., *A Coincidence Search for Cosmic Neutrino and Gamma-Ray Emitting Sources Using IceCube and Fermi LAT Public Data*, *Astrophys. J.* **863** (2018) 64 [[1802.08165](#)].
- [14] R.A. Fisher, *Statistical methods for research workers*, Edinburgh, Oliver and Boyd (1938).

Full Authors List: ANTARES Collaboration

A. Albert^{1,2}, S. Alves³, M. André⁴, M. Anghinolfi⁵, G. Anton⁶, M. Ardid⁷, S. Ardid⁷, J.-J. Aubert⁸, J. Aublin⁹, B. Baret⁹, S. Basa¹⁰, B. Belhorma¹¹, M. Bendahman^{9,12}, V. Bertin⁸, S. Biagi¹³, M. Bissinger⁶, J. Boumaaza¹², M. Bouta¹⁴, M.C. Bouwhuis¹⁵, H. Brânzaş¹⁶, R. Bruijn^{15,17}, J. Brunner⁸, J. Busto⁸, B. Caiffi⁵, A. Capone^{18,19}, L. Caramete¹⁶, J. Carr⁸, V. Carretero³, S. Celli^{18,19}, M. Chabab²⁰, T.N. Chau⁹, R. Cherkaoui El Moursli¹², T. Chiarusi²¹, M. Circella²², A. Coleiro⁹, M. Colomer-Molla^{9,3}, R. Coniglione¹³, P. Coyle⁸, A. Creusot⁹, A. F. Díaz²³, G. de Wasseige⁹, A. Deschamps²⁴, C. Distefano¹³, I. Di Palma^{18,19}, A. Domi^{15,17}, C. Donzaud^{9,25}, D. Dornic⁸, D. Drouhin^{1,2}, T. Eberl⁶, T. van Eeden¹⁵, D. van Eijk¹⁵, N. El Khayati¹², A. Enzenhöfer⁸, P. Fermani^{18,19}, G. Ferrara¹³, F. Filippini^{21,26}, L.A. Fusco⁸, Y. Gatelet⁹, P. Gay^{27,9}, H. Glotin²⁸, R. Gozzini³, R. Gracia Ruiz¹⁵, K. Graf⁶, C. Guidi^{5,29}, S. Hallmann⁶, H. van Haren³⁰, A.J. Heijboer¹⁵, Y. Hello²⁴, J.J. Hernández-Rey³, J. Höbl⁶, J. Hofestädt⁶, F. Huang⁸, G. Illuminati^{9,21,26}, C.W. James³¹, B. Jisse-Jung¹⁵, M. de Jong^{15,32}, P. de Jong¹⁵, M. Kadler³³, O. Kalekin⁶, U. Katz⁶, N.R. Khan-Chowdhury³, A. Kouchner⁹, I. Kreykenbohm³⁴, V. Kulikovskiy^{5,36}, R. Lahmann⁶, R. Le Breton⁹, D. Lefèvre³⁵, E. Leonora³⁶, G. Levi^{21,26}, M. Lincetto⁸, D. Lopez-Coto³⁷, S. Loucatos^{38,9}, L. Maderer⁹, J. Manczak³, M. Marcelin¹⁰, A. Margiotta^{21,26}, A. Marinelli³⁹, J.A. Martínez-Mora⁷, K. Melis^{15,17}, P. Migliozzi³⁹, A. Moussa¹⁴, R. Muller¹⁵, S. Nauts¹⁵, S. Navas³⁷, E. Nezri¹⁰, B. O’Fearraigh¹⁵, A. Păun¹⁶, G.E. Păvălaş¹⁶, C. Pellegrino^{21,40,41}, M. Perrin-Terrin⁸, V. Pestel¹⁵, P. Piattelli¹³, C. Pieterse³, C. Poirè⁷, V. Popa¹⁶, T. Pradier¹, N. Randazzo³⁶, S. Reck⁶, G. Riccobene¹³, A. Romanov^{5,29}, A. Sánchez-Losa^{3,22}, D. F. E. Samtleben^{15,32}, M. Sanguineti^{5,29}, P. Sapienza¹³, J. Schnabel⁶, J. Schumann⁶, F. Schüssler³⁸, M. Spurio^{21,26}, Th. Stolarczyk³⁸, M. Taituti^{5,29}, Y. Tayalati¹², S.J. Tingay³¹, B. Vallage^{38,9}, V. Van Elewyck^{9,41}, F. Versari^{21,26,9}, S. Viola¹³, D. Vivolo^{39,43}, J. Wilms³⁴, S. Zavatarelli⁵, A. Zegarelli^{18,19}, J.D. Zornoza³, and J. Zúñiga³

¹Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France. ² Université de Haute Alsace, F-68100 Mulhouse, France. ³IFIC - Instituto de Física Corpuscular (CSIC - Universitat de València) c/ Catedrático José Beltrán, 2 E-46980 Paterna, Valencia, Spain. ⁴Technical University of Catalonia, Laboratory of Applied Bioacoustics, Rambla Exposició, 08800 Vilanova i la Geltrú, Barcelona, Spain. ⁵INFN - Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy. ⁶Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany. ⁷Institut d’Investigació per a la Gestió Integrada de les Zones Costaneres (IGIC) - Universitat Politècnica de València. C/ Paraninf 1, 46730 Gandia, Spain. ⁸Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France. ⁹Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France. ¹⁰Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France. ¹¹National Center for Energy Sciences and Nuclear Techniques, B.P.1382, R. P.10001 Rabat, Morocco. ¹²University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco. ¹³INFN - Laboratori Nazionali del Sud (LNS), Via S. Sofia 62, 95123 Catania, Italy. ¹⁴University Mohammed I, Laboratory of Physics of Matter and Radiations, B.P.717, Oujda 6000, Morocco. ¹⁵Nikhef, Science Park, Amsterdam, The Netherlands. ¹⁶Institute of Space Science, RO-077125 Bucharest, Măgurele, Romania. ¹⁷Universiteit van Amsterdam, Instituut voor Hoge-Energie Fysica, Science Park 105, 1098 XG Amsterdam, The Netherlands. ¹⁸INFN - Sezione di Roma, P.le Aldo Moro 2, 00185 Roma, Italy. ¹⁹Dipartimento di Fisica dell’Università La Sapienza, P.le Aldo Moro 2, 00185 Roma, Italy. ²⁰LPHEA, Faculty of Science - Semlali, Cadi Ayyad University, P.O.B. 2390, Marrakech, Morocco. ²¹INFN - Sezione di Bologna, Viale Bertini-Pichat 6/2, 40127 Bologna, Italy. ²²INFN - Sezione di Bari, Via E. Orabona 4, 70126 Bari, Italy. ²³Department of Computer Architecture and Technology/CITIC, University of Granada, 18071 Granada, Spain. ²⁴Géoazur, UCA, CNRS, IRD, Observatoire de la Côte d’Azur, Sophia Antipolis, France. ²⁵Université Paris-Sud, 91405 Orsay Cedex, France. ²⁶Dipartimento di Fisica e Astronomia dell’Università, Viale Bertini Pichat 6/2, 40127 Bologna, Italy. ²⁷Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, BP 10448, F-63000 Clermont-Ferrand, France. ²⁸LIS, UMR Université de Toulon, Aix Marseille Université, CNRS, 83041 Toulon, France. ²⁹Dipartimento di Fisica dell’Università, Via Dodecaneso 33, 16146 Genova, Italy. ³⁰Royal Netherlands Institute for Sea Research (NIOZ), Landsdiep 4, 1797 SZ ’t Horntje (Texel), the Netherlands. ³¹International Centre for Radio Astronomy Research - Curtin University, Bentley, WA 6102, Australia. ³²Huygens-Kamerlingh Onnes Laboratorium, Universiteit Leiden, The Netherlands. ³³Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Emil-Fischer Str. 31, 97074 Würzburg, Germany. ³⁴Dr. Reimis-Sternwarte and ECAP, Friedrich-Alexander-Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany. ³⁵Mediterranean Institute of Oceanography (MIO), Aix-Marseille University, 13288, Marseille, Cedex 9, France; Université du Sud Toulon-Var, CNRS-INSU/IRD UM 110, 83957, La Garde Cedex, France. ³⁶INFN - Sezione di Catania, Via S. Sofia 64, 95123 Catania, Italy. ³⁷Dpto. de Física Teórica y del Cosmos & C.A.F.P.E., University of Granada, 18071 Granada, Spain. ³⁸IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France. ³⁹INFN - Sezione di Napoli, Via Cintia 80126 Napoli, Italy. ⁴⁰Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Piazza del Viminale 1, 00184, Roma. ⁴¹INFN - CNAF, Viale C. Bertini Pichat 6/2, 40127, Bologna. ⁴²Institut Universitaire de France, 75005 Paris, France. ⁴³Dipartimento di Fisica dell’Università Federico II di Napoli, Via Cintia 80126, Napoli, Italy.

Full Authors List: HAWC Collaboration

A.U. Abeyssekara⁴⁸, A. Albert²¹, R. Alfaro¹⁴, C. Alvarez⁴¹, J.D. Álvarez⁴⁰, J.R. Angeles Camacho¹⁴, J.C. Arteaga-Velázquez⁴⁰, K. P. Arunbabu¹⁷, D. Avila Rojas¹⁴, H.A. Ayala Solares²⁸, R. Babu²⁵, V. Baghmanyan¹⁵, A.S. Barber⁴⁸, J. Becerra Gonzalez¹¹, E. Belmont-Moreno¹⁴, D. Berley³⁹, C. Brisbois³⁹, K.S. Caballero-Mora⁴¹, T. Capistrán¹², A. Carramiñana¹⁸, S. Casanova¹⁵, O. Chaparro-Amaro³, U. Cotti⁴⁰, J. Cotzomi⁸, S. Coutiño de León¹⁸, E. De la Fuente⁴⁶, C. de León⁴⁰, L. Diaz-Cruz⁸, R. Diaz Hernandez¹⁸, J.C. Díaz-Vélez⁴⁶, B.L. Dingus²¹, M. Durocher²¹, M.A. DuVernois⁴⁵, R.W. Ellsworth³⁹, K. Engel³⁹, C. Espinoza¹⁴,

K.L. Fan³⁹, K. Fang⁴⁵, M. Fernández Alonso²⁸, B. Fick²⁵, H. Fleischhack^{51,11,52}, J.L. Flores⁴⁶, N.I. Fraija¹², D. García¹⁴, J.A. García-González²⁰, J. L. García-Luna⁴⁶, G. García-Torales⁴⁶, F. Garfias¹², G. Giacinti²², H. Goksu²², M.M. González¹², J.A. Goodman³⁹, J.P. Harding²¹, S. Hernandez¹⁴, I. Herzog²⁵, J. Hinton²², B. Hona⁴⁸, D. Huang²⁵, F. Hueyotl-Zahuantitla⁴¹, C.M. Hui²³, B. Humensky³⁹, P. Hüntemeyer²⁵, A. Iriarte¹², A. Jardin-Blicq^{22,49,50}, H. Jhee⁴³, V. Joshi⁷, D. Kieda⁴⁸, G.J. Kunde²¹, S. Kunwar²², A. Lara¹⁷, J. Lee⁴³, W.H. Lee¹², D. Lennarz⁹, H. León Vargas¹⁴, J. Linnemann²⁴, A.L. Longinotti¹², R. López-Coto¹⁹, G. Luis-Raya⁴⁴, J. Lundeen²⁴, K. Malone²¹, V. Marandon²², O. Martinez⁸, I. Martinez-Castellanos³⁹, H. Martínez-Huerta³⁸, J. Martínez-Castro³, J.A.J. Matthews⁴², J. McEnery¹¹, P. Miranda-Romagnoli³⁴, J.A. Morales-Soto⁴⁰, E. Moreno⁸, M. Mostafá²⁸, A. Nayerhoda¹⁵, L. Nellen¹³, M. Newbold⁴⁸, M.U. Nisa²⁴, R. Noriega-Papaqui³⁴, L. Olivera-Nieto²², N. Omodei³², A. Peisker²⁴, Y. Pérez Araujo¹², E.G. Pérez-Pérez⁴⁴, C.D. Rho⁴³, C. Rivière³⁹, D. Rosa-Gonzalez¹⁸, E. Ruiz-Velasco²², J. Ryan²⁶, H. Salazar⁸, F. Salesa Greus^{15,53}, A. Sandoval¹⁴, M. Schneider³⁹, H. Schoorlemmer²², J. Serna-Franco¹⁴, G. Sennis²¹, A.J. Smith³⁹, R.W. Springer⁴⁸, P. Surajbali²², I. Taboada⁹, M. Tanner²⁸, K. Tollefson²⁴, I. Torres¹⁸, R. Torres-Escobedo³⁰, R. Turner²⁵, F. Ureña-Mena¹⁸, L. Villaseñor⁸, X. Wang²⁵, I.J. Watson⁴³, T. Weisgarber⁴⁵, F. Werner²², E. Wilcox³⁹, J. Wood²³, G.B. Yodh³⁵, A. Zepeda⁴, H. Zhou³⁰

¹Barnard College, New York, NY, USA, ²Department of Chemistry and Physics, California University of Pennsylvania, California, PA, USA, ³Centro de Investigación en Computación, Instituto Politécnico Nacional, Ciudad de México, México, ⁴Physics Department, Centro de Investigación y de Estudios Avanzados del IPN, Ciudad de México, México, ⁵Colorado State University, Physics Dept., Fort Collins, CO, USA, ⁶DCI-UDG, Leon, Gto, México, ⁷Erlangen Centre for Astroparticle Physics, Friedrich Alexander Universität, Erlangen, BY, Germany, ⁸Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Puebla, México, ⁹School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA, USA, ¹⁰School of Physics Astronomy and Computational Sciences, George Mason University, Fairfax, VA, USA, ¹¹NASA Goddard Space Flight Center, Greenbelt, MD, USA, ¹²Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, México, ¹³Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México, México, ¹⁴Instituto de Física, Universidad Nacional Autónoma de México, Ciudad de México, México, ¹⁵Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland, ¹⁶Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, SP, Brasil, ¹⁷Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad de México, México, ¹⁸Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Puebla, México, ¹⁹INFN Padova, Padova, Italy, ²⁰Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501, Monterrey, N.L., 64849, México, ²¹Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA, ²²Max-Planck Institute for Nuclear Physics, Heidelberg, Germany, ²³NASA Marshall Space Flight Center, Astrophysics Office, Huntsville, AL, USA, ²⁴Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA, ²⁵Department of Physics, Michigan Technological University, Houghton, MI, USA, ²⁶Space Science Center, University of New Hampshire, Durham, NH, USA, ²⁷The Ohio State University at Lima, Lima, OH, USA, ²⁸Department of Physics, Pennsylvania State University, University Park, PA, USA, ²⁹Department of Physics and Astronomy, University of Rochester, Rochester, NY, USA, ³⁰Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China, ³¹Sungkyunkwan University, Gyeonggi, Rep. of Korea, ³²Stanford University, Stanford, CA, USA, ³³Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL, USA, ³⁴Universidad Autónoma del Estado de Hidalgo, Pachuca, Hgo., México, ³⁵Department of Physics and Astronomy, University of California, Irvine, Irvine, CA, USA, ³⁶Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, Santa Cruz, CA, USA, ³⁷Universidad de Costa Rica, San José, Costa Rica, ³⁸Department of Physics and Mathematics, Universidad de Monterrey, San Pedro Garza García, N.L., México, ³⁹Department of Physics, University of Maryland, College Park, MD, USA, ⁴⁰Instituto de Física y Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México, ⁴¹FCFM-MCTP, Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, México, ⁴²Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA, ⁴³University of Seoul, Seoul, Rep. of Korea, ⁴⁴Universidad Politécnica de Pachuca, Pachuca, Hgo, México, ⁴⁵Department of Physics, University of Wisconsin-Madison, Madison, WI, USA, ⁴⁶CUCEI, CUCEA, Universidad de Guadalajara, Guadalajara, Jalisco, México, ⁴⁷Universität Würzburg, Institute for Theoretical Physics and Astrophysics, Würzburg, Germany, ⁴⁸Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA, ⁴⁹Department of Physics, Faculty of Science, Chulalongkorn University, Pathumwan, Bangkok 10330, Thailand, ⁵⁰National Astronomical Research Institute of Thailand (Public Organization), Don Kaeo, MaeRim, Chiang Mai 50180, Thailand, ⁵¹Department of Physics, Catholic University of America, Washington, DC, USA, ⁵²Center for Research and Exploration in Space Science and Technology, NASA/GSFC, Greenbelt, MD, USA, ⁵³Instituto de Física Corpuscular, CSIC, Universitat de València, Paterna, Valencia, Spain

HAWC Acknowledgments

We acknowledge the support from: the US National Science Foundation (NSF); the US Department of Energy Office of High-Energy Physics; the Laboratory Directed Research and Development (LDRD) program of Los Alamos National Laboratory; Consejo Nacional de Ciencia y Tecnología (CONACyT), México, grants 271051, 232656, 260378, 179588, 254964, 258865, 243290, 132197, A1-S-46288, A1-S-22784, cátedras 873, 1563, 341, 323, Red HAWC, México; DGAPA-UNAM grants IG101320, IN111716-3, IN111419, IA102019, IN110621, IN110521; VIEP-BUAP; PIFI 2012, 2013, PROFOCIE 2014, 2015; the University of Wisconsin Alumni Research Foundation; the Institute of Geophysics, Planetary Physics, and Signatures at Los Alamos National Laboratory; Polish Science Centre grant, DEC-2017/27/B/ST9/02272; Coordinación de la Investigación Científica de la Universidad Michoacana; Royal Society - Newton Advanced Fellowship 180385; Generalitat Valenciana, grant CIDEGENT/2018/034; Chulalongkorn University's Universe (CUAASC) grant; Coordinación General Académica e Innovación (CGAI-UdeG), PRODEP-SEP UDG-CA-499; Institute of Cosmic Ray Research (ICRR), University of Tokyo, H.F. acknowledges support by NASA under award number 80GSFC21M0002. We also acknowledge the

significant contributions over many years of Stefan Westerhoff, Gaurang Yodh and Arnulfo Zepeda Dominguez, all deceased members of the HAWC collaboration. Thanks to Scott Delay, Luciano Díaz and Eduardo Murrieta for technical support.

Full Authors List: IceCube Collaboration

R. Abbasi¹⁷, M. Ackermann⁵⁹, J. Adams¹⁸, J. A. Aguilar¹², M. Ahlers²², M. Ahrens⁵⁰, C. Alispach²⁸, A. A. Alves Jr.³¹, N. M. Amin⁴², R. An¹⁴, K. Andeen⁴⁰, T. Anderson⁵⁶, G. Anton²⁶, C. Argüelles¹⁴, Y. Ashida³⁸, S. Axani¹⁵, X. Bai⁴⁶, A. Balagopal V.³⁸, A. Barbano²⁸, S. W. Barwick³⁰, B. Bastian⁵⁹, V. Basu³⁸, S. Baur¹², R. Bay⁸, J. J. Beatty^{20, 21}, K.-H. Becker⁵⁸, J. Becker Tjus¹¹, C. Bellenghi²⁷, S. BenZvi⁴⁸, D. Berley¹⁹, E. Bernardini^{59, 60}, D. Z. Besson^{34, 61}, G. Binder^{8, 9}, D. Bindig⁵⁸, E. Blaufuss¹⁹, S. Blot⁵⁹, M. Boddenberg¹, F. Bontempo³¹, J. Borowka¹, S. Böser³⁹, O. Botner⁵⁷, J. Böttcher¹, E. Bourbeau²², F. Bradascio⁵⁹, J. Braun³⁸, S. Bron²⁸, J. Brostean-Kaiser⁵⁹, S. Browne³², A. Burgman⁵⁷, R. T. Burley², R. S. Busse⁴¹, M. A. Campana⁴⁵, E. G. Carnie-Bronca², C. Chen⁶, D. Chirkin³⁸, K. Choi⁵², B. A. Clark²⁴, K. Clark³³, L. Classen⁴¹, A. Coleman⁴², G. H. Collin¹⁵, J. M. Conrad¹⁵, P. Coppin¹³, P. Correa¹³, D. F. Cowen^{55, 56}, R. Cross⁴⁸, C. Dappen¹, P. Dave⁶, C. De Clercq¹³, J. J. DeLaunay⁵⁶, H. Dembinski⁴², K. Deoskar⁵⁰, S. De Ridder²⁹, A. Desai³⁸, P. Desiati³⁸, K. D. de Vries¹³, G. de Wasseige¹³, M. de With¹⁰, T. DeYoung²⁴, S. Dharani¹, A. Diaz¹⁵, J. C. Díaz-Vélez³⁸, M. Dittmer⁴¹, H. Dujmovic³¹, M. Dunkman⁵⁶, M. A. DuVernois³⁸, E. Dvorak⁴⁶, T. Ehrhardt³⁹, P. Eller²⁷, R. Engel^{31, 32}, H. Erpenbeck¹, J. Evans¹⁹, P. A. Evenson⁴², A. R. Fazely⁷, S. Fiedlschuster²⁶, A. T. Fienberg⁵⁶, K. Filimonov⁸, C. Finley⁵⁰, L. Fischer⁵⁹, D. Fox⁵⁵, A. Franckowiak^{11, 59}, E. Friedman¹⁹, A. Fritz³⁹, P. Fürst¹, T. K. Gaisser⁴², J. Gallagher³⁷, E. Ganster¹, A. Garcia¹⁴, S. Garrappa⁵⁹, L. Gerhardt⁹, A. Ghadimi⁵⁴, C. Glaser⁵⁷, T. Glauch²⁷, T. Glüskenkamp²⁶, A. Goldschmidt⁹, J. G. Gonzalez⁴², S. Goswami⁵⁴, D. Grant²⁴, T. Grégoire⁵⁶, S. Griswold⁴⁸, M. Gündüz¹¹, C. Günther¹, C. Haack²⁷, A. Hallgren⁵⁷, R. Halliday²⁴, L. Halve¹, F. Halzen³⁸, M. Ha Minh²⁷, K. Hanson³⁸, J. Hardin³⁸, A. A. Harnisch²⁴, A. Haungs³¹, S. Hauser¹, D. Hebecker¹⁰, K. Helbing⁵⁸, F. Henningsen²⁷, E. C. Hettlinger²⁴, S. Hickford⁵⁸, J. Hignight²⁵, C. Hill¹⁶, G. C. Hill², K. D. Hoffman¹⁹, R. Hoffmann⁵⁸, T. Hoinka²³, B. Hokanson-Fasig³⁸, K. Hoshina^{38, 62}, F. Huang⁵⁶, M. Huber²⁷, T. Huber³¹, K. Hultqvist⁵⁰, M. Hünnefeld²³, R. Hussain³⁸, S. In⁵², N. Iovine¹², A. Ishihara¹⁶, M. Jansson⁵⁰, G. S. Japaridze⁵, M. Jeong⁵², B. J. P. Jones⁴, D. Kang³¹, W. Kang⁵², X. Kang⁴⁵, A. Kappes⁴¹, D. Kappesser³⁹, T. Karg⁵⁹, M. Karl²⁷, A. Karle³⁸, U. Katz²⁶, M. Kauer³⁸, M. Kellermann¹, J. L. Kelley³⁸, A. Kheirandish⁵⁶, K. Kin¹⁶, T. Kintscher⁵⁹, J. Kiryluk⁵¹, S. R. Klein^{8, 9}, R. Koirala⁴², H. Kolanoski¹⁰, T. Kontrimas²⁷, L. Köpke³⁹, C. Kopper²⁴, S. Kopper⁵⁶, D. J. Koskinen²², P. Koundal³¹, M. Kovacevich⁴⁵, M. Kowalski^{10, 59}, T. Kozynets²², E. Kun¹¹, N. Kurahashi⁴⁵, N. Lad⁵⁹, C. Lagunas Gualda⁵⁹, J. L. Lanfranchi⁵⁶, M. J. Larson¹⁹, F. Lauber⁵⁸, J. P. Lazar^{14, 38}, J. W. Lee⁵², K. Leonard³⁸, A. Leszczyńska³², Y. Li⁵⁶, M. Lincetto¹¹, Q. R. Liu³⁸, M. Liubarska²⁵, E. Lohfink³⁹, C. J. Lozano Mariscal⁴¹, L. Lu³⁸, F. Lucarelli²⁸, A. Ludwig^{24, 35}, W. Luszczak³⁸, Y. Lyu^{8, 9}, W. Y. Ma⁵⁹, J. Madsen³⁸, K. B. M. Mahn²⁴, Y. Makino³⁸, S. Mancina³⁸, I. C. Mariş¹², R. Maruyama⁴³, K. Mase¹⁶, T. McElroy²⁵, F. McNally³⁶, J. V. Mead²², K. Meagher³⁸, A. Medina²¹, M. Meier¹⁶, S. Meighen-Berger²⁷, J. Micallef²⁴, D. Mockler¹², T. Montaruli²⁸, R. W. Moore²⁵, R. Morse³⁸, M. Moulai¹⁵, R. Naab⁵⁹, R. Nagai¹⁶, U. Naumann⁵⁸, J. Necker⁵⁹, L. V. Nguyễn²⁴, H. Niederhausen²⁷, S. C. Nowicki²⁴, D. R. Nygren⁹, A. Obertacke Pollmann⁵⁸, M. Oehler³¹, A. Olivás¹⁹, E. O'Sullivan⁵⁷, H. Pandya⁴², D. V. Pankova⁵⁶, N. Park³³, G. K. Parker⁴, E. N. Paudel⁴², L. Paul⁴⁰, C. Pérez de los Heros⁵⁷, L. Peters¹, J. Peterson³⁸, S. Philippen¹, D. Pieloth²³, S. Pieper⁵⁸, M. Pittermann³², A. Pizzuto³⁸, M. Plum⁴⁰, Y. Popovych³⁹, A. Porcelli²⁹, M. Prado Rodriguez³⁸, P. B. Price⁸, B. Pries²⁴, G. T. Przybylski⁹, C. Raab¹², A. Raissi¹⁸, M. Rameez²², K. Rawlins³, I. C. Rea²⁷, A. Rehman⁴², P. Reichherzer¹¹, R. Reimann¹, G. Renzi¹², E. Resconi²⁷, S. Reusch⁵⁹, W. Rhode²³, M. Richman⁴⁵, B. Riedel³⁸, E. J. Roberts², S. Robertson^{8, 9}, G. Roellinghoff⁵², M. Rongen³⁹, C. Rott^{49, 52}, T. Ruhe²³, D. Ryckbosch²⁹, D. Rysewyk Cantu²⁴, I. Safa^{14, 38}, J. Saffer³², S. E. Sanchez Herrera²⁴, A. Sandrock²³, J. Sandroos³⁹, M. Santander⁵⁴, S. Sarkar⁴⁴, S. Sarkar²⁵, K. Satalecka⁵⁹, M. Scharf¹, M. Schaufel¹, H. Schieler³¹, S. Schindler²⁶, P. Schlunder²³, T. Schmidt¹⁹, A. Schneider³⁸, J. Schneider²⁶, F. G. Schröder^{31, 42}, L. Schumacher²⁷, G. Schwefer¹, S. Scialfani⁴⁵, D. Seckel⁴², S. Seunarine⁴⁷, A. Sharma⁵⁷, S. Shefali³², M. Silva³⁸, B. Skrzypek¹⁴, B. Smithers⁴, R. Snihur³⁸, J. Soedingrekso²³, D. Soldin⁴², C. Spannfellner²⁷, G. M. Spiczak⁴⁷, C. Spiering^{59, 61}, J. Stachurska⁵⁹, M. Stamatikos²¹, T. Stanev⁴², R. Stein⁵⁹, J. Stettner¹, A. Steuer³⁹, T. Stezelberger⁹, T. Stürwald⁵⁸, T. Stuttard²², G. W. Sullivan¹⁹, I. Taboada⁶, F. Tenholt¹¹, S. Ter-Antonyan⁷, S. Tilav⁴², F. Tischbein¹, K. Tollefson²⁴, L. Tomankova¹¹, C. Tönnis⁵³, S. Toscano¹², D. Tosi³⁸, A. Trettin⁵⁹, M. Tselengidou²⁶, C. F. Tung⁶, A. Turcati²⁷, R. Turcotte³¹, C. F. Turley⁵⁶, J. P. Twagirayezu²⁴, B. Ty³⁸, M. A. Unland Elorrieta⁴¹, N. Valtonen-Mattila⁵⁷, J. Vandenbroucke³⁸, N. van Eijndhoven¹³, D. Vannerom¹⁵, J. van Santen⁵⁹, S. Verpoest²⁹, M. Vraeghe²⁹, C. Walck⁵⁰, T. B. Watson⁴, C. Weaver²⁴, P. Weigel¹⁵, A. Weindl³¹, M. J. Weiss⁵⁶, J. Weldert³⁹, C. Wendt³⁸, J. Werthebach²³, M. Weyrauch³², N. Whitehorn^{24, 35}, C. H. Wiebusch¹, D. R. Williams⁵⁴, M. Wolf²⁷, K. Woschnagg⁸, G. Wrede²⁶, J. Wulf¹¹, X. W. Xu⁷, Y. Xu⁵¹, J. P. Yanez²⁵, S. Yoshida¹⁶, S. Yu²⁴, T. Yuan³⁸, Z. Zhang⁵¹

¹ III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany

² Department of Physics, University of Adelaide, Adelaide, 5005, Australia

³ Dept. of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Dr., Anchorage, AK 99508, USA

⁴ Dept. of Physics, University of Texas at Arlington, 502 Yates St., Science Hall Rm 108, Box 19059, Arlington, TX 76019, USA

⁵ CTSPS, Clark-Atlanta University, Atlanta, GA 30314, USA

⁶ School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA

⁷ Dept. of Physics, Southern University, Baton Rouge, LA 70813, USA

⁸ Dept. of Physics, University of California, Berkeley, CA 94720, USA

⁹ Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

¹⁰ Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany

- ¹¹ Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany
- ¹² Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium
- ¹³ Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium
- ¹⁴ Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA
- ¹⁵ Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
- ¹⁶ Dept. of Physics and Institute for Global Prominent Research, Chiba University, Chiba 263-8522, Japan
- ¹⁷ Department of Physics, Loyola University Chicago, Chicago, IL 60660, USA
- ¹⁸ Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
- ¹⁹ Dept. of Physics, University of Maryland, College Park, MD 20742, USA
- ²⁰ Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA
- ²¹ Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA
- ²² Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
- ²³ Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany
- ²⁴ Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
- ²⁵ Dept. of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1
- ²⁶ Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
- ²⁷ Physik-department, Technische Universität München, D-85748 Garching, Germany
- ²⁸ Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland
- ²⁹ Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium
- ³⁰ Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, USA
- ³¹ Karlsruhe Institute of Technology, Institute for Astroparticle Physics, D-76021 Karlsruhe, Germany
- ³² Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany
- ³³ Dept. of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada
- ³⁴ Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
- ³⁵ Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095, USA
- ³⁶ Department of Physics, Mercer University, Macon, GA 31207-0001, USA
- ³⁷ Dept. of Astronomy, University of Wisconsin–Madison, Madison, WI 53706, USA
- ³⁸ Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin–Madison, Madison, WI 53706, USA
- ³⁹ Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany
- ⁴⁰ Department of Physics, Marquette University, Milwaukee, WI, 53201, USA
- ⁴¹ Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany
- ⁴² Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
- ⁴³ Dept. of Physics, Yale University, New Haven, CT 06520, USA
- ⁴⁴ Dept. of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK
- ⁴⁵ Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA
- ⁴⁶ Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA
- ⁴⁷ Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA
- ⁴⁸ Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
- ⁴⁹ Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
- ⁵⁰ Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden
- ⁵¹ Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
- ⁵² Dept. of Physics, Sungkyunkwan University, Suwon 16419, Korea
- ⁵³ Institute of Basic Science, Sungkyunkwan University, Suwon 16419, Korea
- ⁵⁴ Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
- ⁵⁵ Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
- ⁵⁶ Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA
- ⁵⁷ Dept. of Physics and Astronomy, Uppsala University, Box 516, S-75120 Uppsala, Sweden
- ⁵⁸ Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
- ⁵⁹ DESY, D-15738 Zeuthen, Germany
- ⁶⁰ Università di Padova, I-35131 Padova, Italy
- ⁶¹ National Research Nuclear University, Moscow Engineering Physics Institute (MEPhI), Moscow 115409, Russia
- ⁶² Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan

IceCube Acknowledgments

USA – U.S. National Science Foundation–Office of Polar Programs, U.S. National Science Foundation–Physics Division, U.S. National Science Foundation–EPSCoR, Wisconsin Alumni Research Foundation, Center for High Throughput Computing (CHTC) at the University of Wisconsin–Madison, Open Science Grid (OSG), Extreme Science and Engineering Discovery Environment (XSEDE), Frontera computing project at the Texas Advanced Computing Center, U.S. Department of Energy–National Energy Research Scientific Computing Center, Particle astrophysics research computing center at the University of Maryland, Institute for Cyber-Enabled Research at Michigan State University, and Astroparticle physics computational facility at Marquette University; Belgium – Funds for Scientific

Research (FRS-FNRS and FWO), FWO Odysseus and Big Science programmes, and Belgian Federal Science Policy Office (Belspo); Germany – Bundesministerium für Bildung und Forschung (BMBF), Deutsche Forschungsgemeinschaft (DFG), Helmholtz Alliance for Astroparticle Physics (HAP), Initiative and Networking Fund of the Helmholtz Association, Deutsches Elektronen Synchrotron (DESY), and High Performance Computing cluster of the RWTH Aachen; Sweden – Swedish Research Council, Swedish Polar Research Secretariat, Swedish National Infrastructure for Computing (SNIC), and Knut and Alice Wallenberg Foundation; Australia – Australian Research Council; Canada – Natural Sciences and Engineering Research Council of Canada, Calcul Québec, Compute Ontario, Canada Foundation for Innovation, WestGrid, and Compute Canada; Denmark – Villum Fonden and Carlsberg Foundation; New Zealand – Marsden Fund; Japan – Japan Society for Promotion of Science (JSPS) and Institute for Global Prominent Research (IGPR) of Chiba University; Korea – National Research Foundation of Korea (NRF); Switzerland – Swiss National Science Foundation (SNSF); United Kingdom – Department of Physics, University of Oxford.