The next generation neutrino telescope: IceCube-Gen2

The IceCube-Gen2 Collaboration

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

E-mail: aya@hepburn.s.chiba-u.ac.jp

The IceCube Neutrino Observatory, a cubic-kilometer-scale neutrino detector at the geographic South Pole, has reached a number of milestones in the field of neutrino astrophysics: the discovery of a high-energy astrophysical neutrino flux, the temporal and directional correlation of neutrinos with a flaring blazar, and a steady emission of neutrinos from the direction of an active galaxy of a Seyfert II type and the Milky Way. The next generation neutrino telescope, IceCube-Gen2, currently under development, will consist of three essential components: an array of about 10,000 optical sensors, embedded within approximately 8 cubic kilometers of ice, for detecting neutrinos with energies of TeV and above, with a sensitivity five times greater than that of IceCube; a surface array with scintillation panels and radio antennas targeting air showers; and buried radio antennas distributed over an area of more than 400 square kilometers to significantly enhance the sensitivity of detecting neutrino sources beyond EeV. This contribution describes the design and status of IceCube-Gen2 and discusses the expected sensitivity from the simulations of the optical, surface, and radio components.

Corresponding authors: Aya Ishihara[1]

[1] *International Center for Hadron Astrophysics (ICEHAP), Chiba University, Chiba 263-8522, Japan*

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1. The Extension of IceCube: Motivation

The origins of ultra-high-energy radiation in the universe have long been a significant mystery in the field of astrophysics. To overcome the challenges of observation, the world's first high-energy cosmic neutrino telescope, IceCube, was constructed [1], rewriting our understanding of high-energy cosmic radiation. With the establishment of IceCube, the era of high-energy neutrino astronomy was launched. IceCube's discoveries of a steady flux of high-energy background neutrinos, which are further investigated [2–4], suggest a connection between the generation of cosmic neutrinos and the origin of ultra-high-energy cosmic rays. The comparable energy flux observed in high-energy cosmic neutrino background radiation and ultra-high-energy cosmic rays provides intriguing indications of this relationship, as depicted in Figure 1. Through follow-up observations of cosmic neutrinos [5], the successful identification of a neutrino-emitting flaring blazar, TXS 0506+056, has been achieved [6]. After more than a decade of continuous observations with the fully operational IceCube detector, the accumulated ten years' worth of high-statistics observational data is now revealing sources that consistently emit high-energy neutrinos. Notably, NGC 1068, a Seyfert galaxy, and our own galaxy, have been identified as two of these sources [7–9]. Additionally, IceCube has made a unique contribution to our understanding of the origin of extragalactic ultra-high-energy neutrinos. By searching for neutrinos above PeV energies, IceCube has placed stringent constraints on cosmogenic neutrino models [10]. Furthermore, IceCube's surface detector, IceTop, plays a crucial role in the measurement of secondary particles from cosmic ray air showers. IceTop specifically captures the electromagnetic component of incoming air showers, allowing for the reconstruction of primary energy and shower geometry. Together with the optical array of IceCube, which measures the high-energy muon component, the signals from IceTop enable the identification of the primary mass of cosmic rays [11–14].

The current phase of the astrophysical neutrino observation is critical as it aims to elucidate the
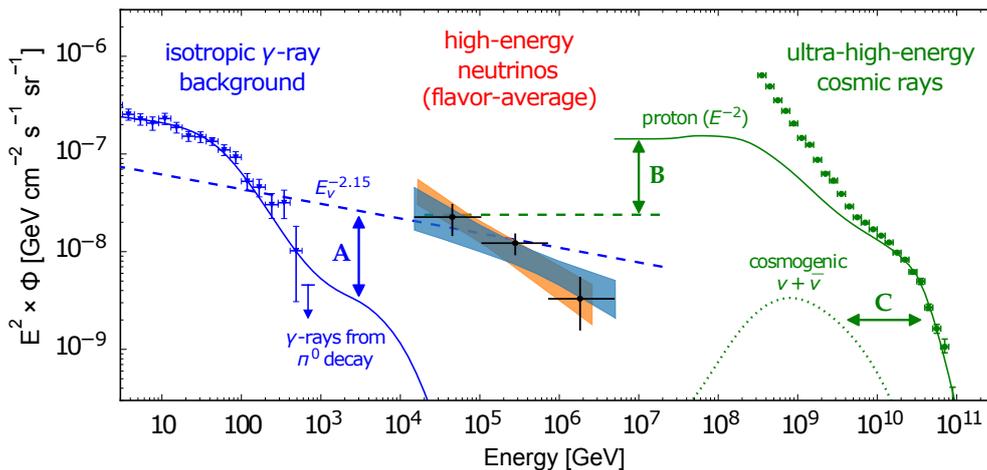
Figure 1: Energy spectrum of cosmic neutrinos measured in several detection channels, corresponds to the per-flavor flux assuming an equal flavor ratio. The orange and blue shaded regions from fitting the observed events with a power-law spectrum, compared to the flux of unresolved extragalactic gamma-ray emission (blue data points) and UHE cosmic-rays (green data points).

mechanisms behind ultra-high-energy radiation through multi-messenger observations, including neutrinos. While several promising indications have been surfaced, there is eager anticipation for higher-significance observations facilitated by improved detector sensitivity. The facility of the future, IceCube-Gen2, will enable the observation of a greater number of sources with higher significance while maintaining the core concept of the successful and established multi-purpose IceCube detector.

Note that the references provided in this proceedings are not arranged in the order of first publication. Instead, we have primarily cited proceedings from this conference, highlighting the recent updates on the subject. Furthermore, the details of the IceCube-Gen2 designs are described in the Technical Design Report (TDR) [15]. All figures in these proceedings are from the TDR.

2. IceCube-Gen2

The primary objective of the IceCube-Gen2 extension is to identify astrophysical sources of neutrinos and gain insights into the energy distribution of the Universe at the highest neutrino energy range, including cosmic rays and associated gamma-rays. Figure 2 provides an overview of the next-generation South Pole neutrino telescope, IceCube-Gen2. Notably, the optical array volume of IceCube-Gen2 will be expanded from 1 km^3 to 8 km^3. Surface stations will be strategically placed across the optical array's surface footprint, while the radio array will be installed in the ice near the surface, extending more than 400 square kilometers beyond the optical array.

Optical Array

Twenty years ago, when the specifications for the IceCube experiment were established, the existence of high-energy astrophysical neutrinos in the universe was still uncertain. As a result, the detector design incorporated a certain level of R&D aspect to accommodate various potential scenarios. Since then, significant progress has been made in understanding astrophysical neutrinos through established detection methods. This improved understanding enables the optimization of the IceCube-Gen2 detector based on more solid scenarios, specifically designed for observing the nature of neutrino-emitting sources.

By increasing the horizontal spacing between the drill holes for embedding the approximately 10,000 optical sensors from 125 m in IceCube to 240 m in IceCube-Gen2, while preserving the vertical separation of the optical modules and extending the vertical embedding distance by approximately 40%, the volume of IceCube-Gen2 can be expanded by eight times with only a marginal increase in cost compared to IceCube. This array design of IceCube-Gen2 improves the detection sensitivity required for identifying neutrino sources. The increased size of the instrumentation simply increases event statistics, particularly for events in the vertical direction with a larger detector cross-sectional area. Additionally, the larger detector area enhances angular resolution. The longer trajectories of neutrino-induced muons in IceCube-Gen2 contribute to improved angular resolution. The track length of horizontally passing events in IceCube-Gen2 will be more than doubled, resulting in approximately a three-fold improvement in angular resolution. The challenges persist in the reconstruction of cascade events using sparse optical modules, however. While maintaining the high reliability of the IceCube Digital Optical Module (DOM), the IceCube-Gen2 DOM incorporates advancements in multi-PMT installation within an elongated glass vessel,
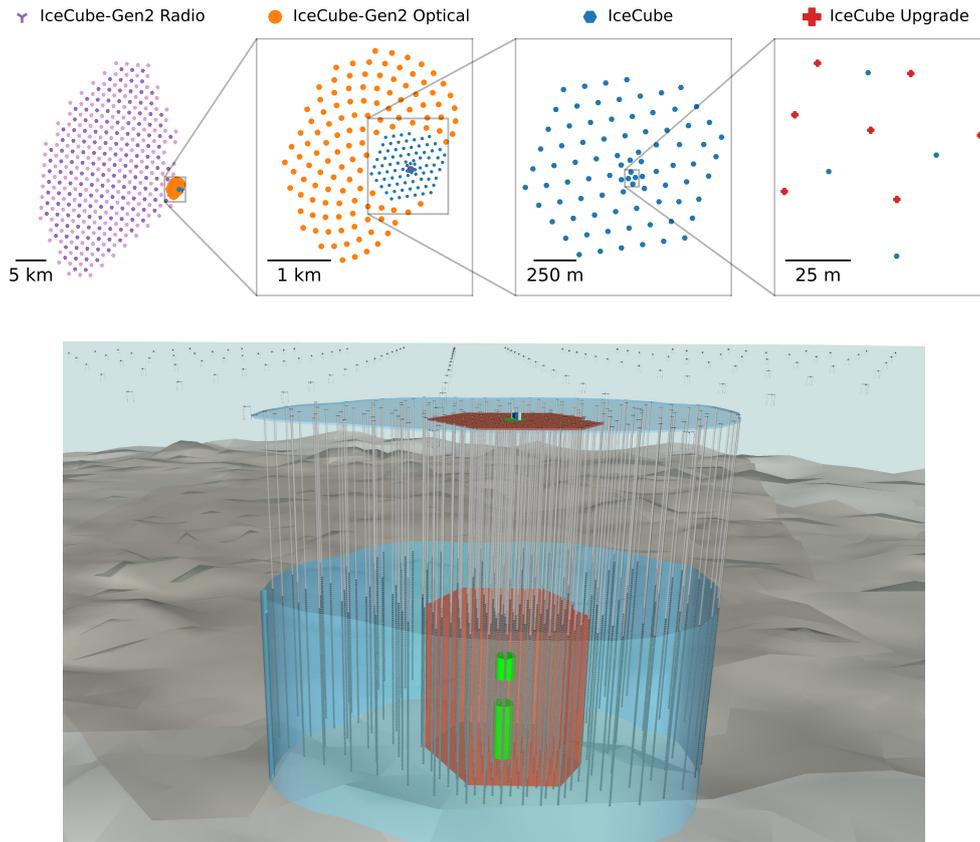
Figure 2: Upper panel: top view of the IceCube-Gen2 Neutrino Observatory at the South Pole Station. The second from the right is the existing IceCube array with upcoming 7 strings of IceCube-Upgrade on the right panel. The second from left is the horizontal layout of the optical array and surface array. The most left panel shows the map of the radio array. Lower panel: artistic image of the IceCube-Gen2 observatory. The optical array, where each of the black dots below the surface represents an optical module in the blue shaded region, and the red shaded IceCube array. A surface array covers the footprint of the optical array and the radio array (black dots) occupy the shallow and near the surface ice for several kilometers beyond the optical array.

resulting in an improved photon detection efficiency of close to a factor of 4 [16–18]. Simulation studies have demonstrated that the angular resolution of cascades is enhanced with the increased photon detection efficiency of the optical modules [19], coupled with precise calibration of the optical modules, as well as improved modeling of photon arrival time distributions [20].

Exploring More Neutrino Sources

IceCube has successfully identified sources that emit neutrinos, but its limited sensitivity restricts observations to sources with high luminosity yet low local number density. Figure 3 illustrates the anticipated discovery potential for different source classes based on their luminosity density and luminosity. Furthermore, IceCube has placed stringent constraints on the contribution of high luminosity source classes like blazars and gamma-ray bursts. This suggests that the primary contributors to the diffuse neutrino flux are more commonly found among source classes
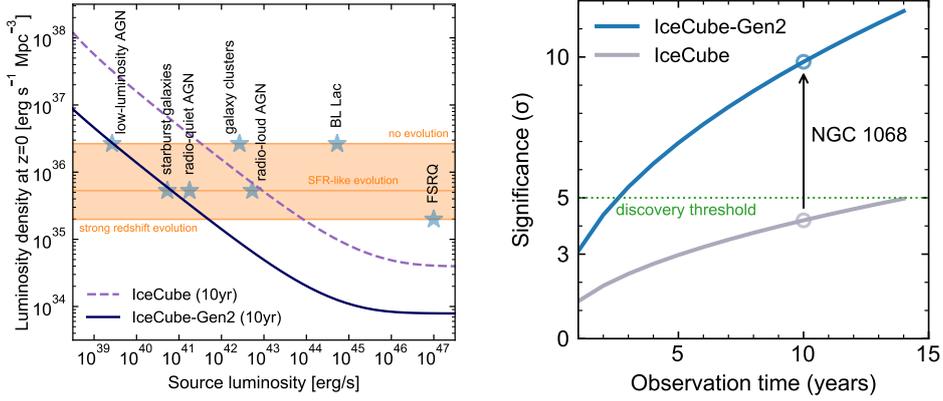
Figure 3: Left: The source discovery potential of IceCube-Gen2 as the line above which one or more sources can be discovered on the plane of Luminosity density and luminosity of neutrino source candidate classes, compared to that of IceCube. The orange band indicates the luminosity density that account for the total diffuse neutrino flux as presented in Figure 1 for different redshift evolution hypothesis. Right: Significance of observations of NGC 1068 as a function of observation time for IceCube and IceCube-Gen2 [21].

characterized by relatively low luminosity and high number density. Examples of such objects include low-luminosity AGN, galaxy clusters, and starburst galaxies. The same rationale applies to transient sources. Identifying these source classes conclusively requires a detector with sensitivity at least five times greater than IceCube, such as IceCube-Gen2. With IceCube-Gen2, it is possible to further study known classes of neutrino-emitting sources, such as AGN. The right panel of Figure 3 indicates the significant developments assumed for the observed source NGC 1068 [21]. A detection at 10σ enables a precise measurement of the spectral shape of the neutrino emission, which is crucial for understanding the acceleration process in the source. Similarly, the sensitivity of measurements of the time variance of neutrino emission can be significantly enhanced. This means that IceCube-Gen2 can detect much smaller neutrino flares than the ones observed from TXS 0506+056 [22].

Radio Array

The radio array of IceCube-Gen2 aims to explore the frontier of ultra-high-energy neutrinos above 10 PeV, marking a significant advancement in this field led by IceCube as demonstrated in Figure 4. It is designed to have an effective detection volume of approximately $O(200\text{km}^3\text{sr})$ at 0.1 EeV and $O(1600\text{km}^3\text{sr})$ at 1 EeV, sensitive to cosmogenic neutrinos resulting from a mixed composition of ultra-high-energy cosmic rays, including around 10% protons. The presence of a mixed composition in ultra-high-energy cosmic rays, particularly if the proton composition is non-zero, can provide an efficient beam that interacts with the target cosmic microwave background (CMB) to produce cosmogenic neutrinos. By observing beyond the GZK sphere, we have the potential to reveal an unseen universe with novel insights.

The antennas in the IceCube-Gen2 Radio Array detect radio emissions resulting from the Askaryan effect, which is generated by particle showers originating from neutrino interactions within the ice [23]. The Askaryan signals typically contribute to the frequency range between 100 MHz and 1 GHz, corresponding to nanosecond-scale fast radio pulses in the time domain. The
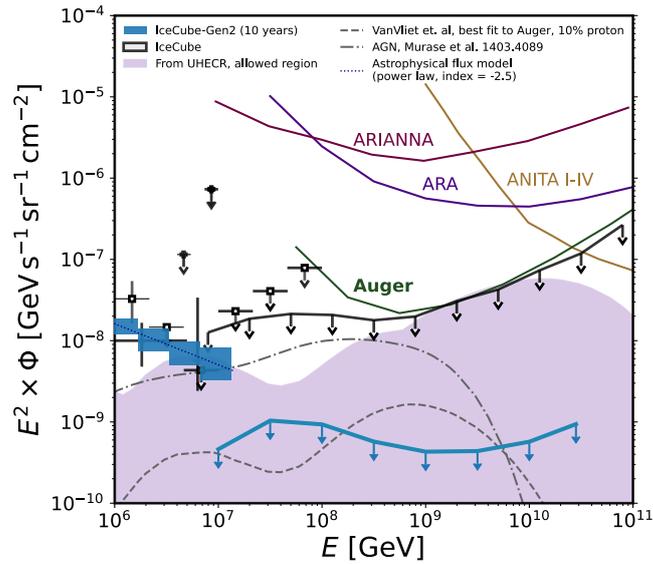
Figure 4: The dark blue line with arrows indicates the sensitivity of IceCube-Gen2 at the highest neutrino energies. The uncertainties on the IceCube-Gen2 radio array sensitivity are ±20%, representing uncertainties in the estimated sensitivity of the array, such as those arising from remaining design decisions. The sensitivity for IceCube-Gen2 incorporates best estimates for backgrounds and analysis efficiency. All fluxes are shown as the all-flavor sum, assuming equal flux in each flavor. This figure is slightly simplified from the Technical Design Report (TDR) [15].

antennas in the radio array operate in the frequency range of 100 MHz to 600 MHz, where the Askaryan signal is most prominent. Unlike an optical array that measures UV to visible light and has an absorption length of approximately $O(100\text{m})$, the attenuation of the radio signal in the cold ice, such as that at the South Pole, is roughly on the order of one kilometer. Therefore, only sparse distributions of antennas are needed to cover the large blocks of ice media in which the neutrino interactions are being searched.

To trigger and reconstruct events, a few antennas are clustered to achieve multiple antenna detection. Each cluster of antennas is referred to as a station and acts as an independent Askaryan signal detector, capable of reconstructing events within its effective detection volume. There are two types of stations in IceCube-Gen2. The first type is a shallow station, which consists of seven log-periodic dipole antennas positioned 3 meters below the surface, along with one fat dipole antenna situated 15 meters below. Shallow stations are designed to detect radio waves from deep neutrino-induced particle showers, whose trajectories bend toward the surface as they propagate through the ice. The reduction in ice density towards the surface allows the radio waves to reach the shallow antennas. The second type of station is called a hybrid station, which incorporates an additional 16 antennas positioned in the deeper region, reaching down to 150 meters below the surface. These antennas detect radio signals both in the upward-moving direction and the downward-bent direction. These antennas are installed within a borehole. The timing information of the radio pulse enables the reconstruction of the vertex position, which is crucial for energy and directional reconstruction [24, 25].

Surface Array

The surface array of IceCube-Gen2 with ehnanced physics target to IceCube's IceTop surface air shower array, significantly improves the detector's capabilities in various aspects of cosmic-ray physics. This includes studying the anisotropy in the arrival direction of cosmic rays [26], performing combined measurements of muon bundles with the optical array, which can also serve as an atmospheric muon background veto for astrophysical neutrino searches, and independently measuring cosmic rays in the energy range from a few 100 TeV to a few EeV. The extended energy range allows for the investigation of the predicted transition region from galactic to extragalactic cosmic rays [27]. Surface stations are installed on top of each IceCube-Gen2 string and on the surface of each string of IceCube to address the performance degradation of IceTop due to accumulated snow over time. Each surface station includes 8 elevated scintillation panels and 3 elevated radio antennas. Additionally, there will be four IceAct stations located at the center of the IceCube surface. IceAct is an air-Cherenkov telescope equipped with a Fresnel lens and a silicone photomultiplier camera [28]. Further information regarding the physics, design specifics, and current status can be found in [26–29].

3. Outlook

In summary, the field of neutrino astronomy has witnessed significant advancements with the detection of neutrinos from various astrophysical sources, including flaring blazars, steady Syfert II galaxies, and our own galaxy. To further explore the high-energy Universe and gain new scientific insights, the development of a next-generation neutrino telescope is crucial. IceCube-Gen2 is envisioned as the next step in this endeavor, with plans to instrument approximately 8 km^3 of ice with around 10,000 optical sensors. In addition, the inclusion of a large-scale radio array and a surface array will provide unique scientific opportunities. The IceCube Upgrade [30], involving seven densely instrumented new strings of optical modules, is currently scheduled to be installed at the South Pole during the 2025-26 Austral summer season. This project is specifically designed to enhance the capabilities of the current IceCube detector and includes the production of a new ice drill at the South Pole. These advancements play a crucial role in paving the way for the promising realization of IceCube-Gen2 as the next-generation neutrino telescope.

Furthermore, the Technical Design Report (TDR) of IceCube-Gen2 has been released [15], serving as the foundation of the design. We are committed to realizing this design. Moreover, these proceedings feature many contributions that enhance our understanding of the potential of IceCube-Gen2 as the next-generation neutrino telescope.

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Full Author List: IceCube-Gen2 Collaboration

R. Abbasi[17], M. Ackermann[76], J. Adams[22], S. K. Agarwalla[47, 77], J. A. Aguilar[12], M. Ahlers[26], J.M. Alameddine[27], N. M. Amin[53], K. Andeen[50], G. Anton[30], C. Argüelles[14], Y. Ashida[64], S. Athanasiadou[76], J. Audehm[1], S. N. Axani[53], X. Bai[61], A. Balagopal V.[47], M. Baricevic[47], S. W. Barwick[34], V. Basu[47], R. Bay[8], J. Becker Tjus[11, 78], J. Beise[74], C. Bellenghi[31], C. Benning[1], S. BenZvi[63], D. Berley[23], E. Bernardini[59], D. Z. Besson[40], A. Bishop[47], S. Blaufuss[23], S. Blot[76], F. Bohmer[31], F. Bontempo[35], J. Y. Book[14], J. Borowka[1], C. Boscolo Meneguolo[59], S. Böser[48], O. Botner[74], J. Böttcher[1], S. Bouma[30], E. Bourbeau[26], J. Braun[47], B. Brinson[6], J. Brostean-Kaiser[76], R. T. Burley[2], R. S. Busse[52], D. Butterfield[47], M. A. Campana[60], K. Carloni[14], E. G. Carnie-Bronca[2], M. Cataldo[30], S. Chattopadhyay[47, 77], N. Chau[12], C. Chen[6], Z. Chen[66], D. Chirkin[47], S. Choi[67], B. A. Clark[23], R. 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Mancina[47, 59], S. Mandalia[43], W. Marie Sainte[47], I. C. Mariş[12], S. Marka[55], Z. Marka[55], M. Marsee[70], I. Martinez-Soler[14], R. Maruyama[54], F. Mayhew[28], T. McElroy[29], F. McNally[45], J. V. Mead[26], K. Meagher[47], S. Mechbal[76], A. Medina[25], M. Meier[16], Y. Merckx[13], L. Merten[11], Z. Meyers[76], J. Micallef[28], M. Mikhailova[40], J. Mitchell[7], T. Montaruli[32], R. W. Moore[29], Y. Morii[16], R. Morse[47], M. Moulai[47], T. Mukherjee[35], R. Naab[76], R. Nagai[16], M. Nakos[47], A. Narayan[51], U. Naumann[75], J. Necker[76], A. Negi[4], A. Nelles[30, 76], M. Neumann[52], H. Niederhausen[28], M. U. Nisa[28], A. Noell[1], A. Novikov[53], S. C. Nowicki[28], A. Nozdrina[40], E. Oberla[20, 21], A. Obertacke Pollmann[16], V. O'Dell[47], M. Oehler[35], B. Oeyen[33], A. Olivas[23], R. Ørsøe[31], J. Osborn[47], E. O'Sullivan[74], L. Papp[31], N. Park[37], G. K. Parker[4], E. N. Paudel[53], L. Paul[50, 61], C. Pérez de los Heros[74], T. C. Petersen[26], J. Peterson[47], S. Philippen[1], S. Pieper[75], J. L. Pinfold[29], A. Pizzuto[47], I. Plaisier[76], M. Plum[61], A. Pontén[74], Y. Popovych[48], M. Prado Rodriguez[47], B. Pries[28], R. Procter-Murphy[23], G. T. Przybylski[9], L. Pyras[76], J. Rack-Helleis[48], M. Rameez[51], K. Rawlins[3], Z. Rechav[47], A. Rehman[53], P. Reichherzer[11], G. Renzi[12], E. Resconi[31], S. Reusch[76], W. Rhode[27], B. Riedel[47], M. Riegel[35], A. Rifaie[1], E. J. Roberts[2], S. Robertson[8, 9], S. Rodan[67], G. Roellinghoff[67], M. Rongen[30], C. Rott[64, 67], T. Ruhe[27], D. Ryckbosch[33], I. Safa[14, 47], J. Saffer[36], D. Salazar-Gallegos[28], P. Sampathkumar[35], S. E. Sanchez Herrera[28], A. Sandrock[75], P. Sandstrom[47], M. Santander[70], S. Sarkar[29], S. Sarkar[58], J. Savelberg[1], P. Savina[47], M. Schaufel[1], H. Schieler[35], S. Schindler[30], L. Schlickmann[1], B. Schlüter[52], F. Schlüter[12], N. Schmeisser[75], T. Schmidt[23], J. Schneider[30], F. G. Schröder[35, 53], L. Schumacher[30], G. Schwefer[1], S. Sclafani[23], D. Seckel[53], M. Seikh[40], S. Seunarine[62], M. H. Shaevitz[55], R. Shah[60], A. Sharma[74], S. Shefali[36], N. Shimizu[16], M. Silva[47], B. Skrzypek[14], D. Smith[19, 21], B. Smithers[4], R. Snihur[47], J. Soedingrekso[27], A. Søgaard[26], D. Soldin[36], P. Soldin[1], G. Sommani[11], D. Southall[19, 21], C. Spannfellner[31], G. M. Spiczak[62], C. Spiering[76], M. Stamatikos[25], T. Stanev[53], T. Stezelberger[9], J. Stoffels[13], T. Stürwald[75], T. Stuttard[26], G. W. Sullivan[23], I. Taboada[6], A. Taketa[69], H. K. M. Tanaka[69], S. Ter-Antonyan[7], M. Thiesmeyer[1], W. G. Thompson[14], J. Thwaites[47], S. Tilav[53], K. Tollefson[28], C. Tönnis[67], J. Torres[24, 25], S. Toscano[12], D. Tosi[47], A. Trettin[76], Y. Tsunesada[57], C. F. Tung[6], R. Turcotte[35], J. P. Twagirayezu[28], B. Ty[47], M. A. Unland Elorrieta[52], A. K. Upadhyay[47, 77], K. Upshaw[7], N. Valtonen-Mattila[74], J. Vandenbroucke[47], N. van Eijndhoven[13], D. Vannerom[15], J. van Santen[76], J. Vara[52], D. Veberic[35], J. Veitch-Michaelis[47], M. Venugopal[35], S. Verpoest[53], A. Vieregg[18, 19, 20, 21], A. Vijai[23], C. Walck[65], C. Weaver[28], P. Weigel[15], A. Weindl[35], J. Weldert[72], C. Welling[21], C. Wendt[47], J. Werthebach[27], M. Weyrauch[35], N. Whitehorn[28], C. H. Wiebusch[1], N. Willey[28], D. R. Williams[70], S. Wissel[71, 72, 73], L. Witthaus[27], A. Wolf[1], M. Wolf[31], G. Wörner[35], G. Wrede[30], S. Wren[49], X. W. Xu[7], J. P. Yanez[29], E. Yildizci[47], S. Yoshida[16], R. Young[40], F. Yu[14], S. Yu[28], T. Yuan[47], Z. Zhang[66], P. Zhelnin[14], S. Zierke[1], M. Zimmerman[47]

[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

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[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 The International Center for Hadron Astrophysics, Chiba University, Chiba 263-8522, Japan

[17] Department of Physics, Loyola University Chicago, Chicago, IL 60660, USA

[18] Dept. of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA

[19] Dept. of Physics, University of Chicago, Chicago, IL 60637, USA

[20] Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA

[21] Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA

[22] Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

[23] Dept. of Physics, University of Maryland, College Park, MD 20742, USA

[24] Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA

[25] Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA

[26] Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark

[27] Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany

[28] Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

[29] Dept. of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1

[30] Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

[31] Technical University of Munich, TUM School of Natural Sciences, Department of Physics, D-85748 Garching bei München, Germany

[32] Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland

[33] Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium

[34] Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, USA

[35] Karlsruhe Institute of Technology, Institute for Astroparticle Physics, D-76021 Karlsruhe, Germany

[36] Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany

[37] Dept. of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada

[38] Department of Physics & Astronomy, University of Nevada, Las Vegas, NV, 89154, USA

[39] Nevada Center for Astrophysics, University of Nevada, Las Vegas, NV 89154, USA

[40] Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA

[41] Dept. of Physics and Astronomy, University of Nebraska–Lincoln, Lincoln, Nebraska 68588, USA

[42] Dept. of Physics, King's College London, London WC2R 2LS, United Kingdom

[43] School of Physics and Astronomy, Queen Mary University of London, London E1 4NS, United Kingdom

[44] Centre for Cosmology, Particle Physics and Phenomenology - CP3, Université catholique de Louvain, Louvain-la-Neuve, Belgium

[45] Department of Physics, Mercer University, Macon, GA 31207-0001, USA

[46] Dept. of Astronomy, University of Wisconsin–Madison, Madison, WI 53706, USA

[47] Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin–Madison, Madison, WI 53706, USA

[48] Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany

[49] School of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom

[50] Department of Physics, Marquette University, Milwaukee, WI, 53201, USA

[51] Dept. of High Energy Physics, Tata Institute of Fundamental Research, Colaba, Mumbai 400 005, India

[52] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany

[53] Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

[54] Dept. of Physics, Yale University, New Haven, CT 06520, USA

[55] Columbia Astrophysics and Nevis Laboratories, Columbia University, New York, NY 10027, USA

[56] Dept. of Physics, University of Notre Dame du Lac, 225 Nieuwland Science Hall, Notre Dame, IN 46556-5670, USA

[57] Graduate School of Science and NITEP, Osaka Metropolitan University, Osaka 558-8585, Japan

[58] Dept. of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

[59] Dipartimento di Fisica e Astronomia Galileo Galilei, Università Degli Studi di Padova, 35122 Padova PD, Italy

[60] Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA

[61] Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA

[62] Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA

[63] Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA

[64] Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA

[65] Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden

[66] Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA

[67] Dept. of Physics, Sungkyunkwan University, Suwon 16419, Korea

[68] Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan

[69] Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan

[70] Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA

[71] Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA

[72] Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA

[73] Institute of Gravitation and the Cosmos, Center for Multi-Messenger Astrophysics, Pennsylvania State University, University Park, PA 16802, USA

[74] Dept. of Physics and Astronomy, Uppsala University, Box 516, S-75120 Uppsala, Sweden

[75] Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany

[76] Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany

[77] Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India

[78] Department of Space, Earth and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden

[79] Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan

Acknowledgements