PROCEEDINGS OF SCIENCE

Sustainability and Environmental Impact of IceCube-Gen2

The IceCube-Gen2 Collaboration

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

E-mail: manish.khanal@utah.edu, rott@physics.utah.edu

IceCube-Gen2 is a proposed next-generation neutrino facility at the South Pole, designed to expand upon the achievements of the pioneering IceCube observatory. This contribution provides a comprehensive review of efforts to ensure the sustainability of IceCube-Gen2 and minimize its environmental impact in Antarctica. Scenarios for overcoming logistical challenges in detector construction and operations are explored, including the potential use of renewable energy sources such as wind and solar. A cost-benefit analysis of energy sources for drilling will be presented. Efforts to optimize the IceCube-Gen2 drilling operations will be discussed, along with studies aimed at minimizing the power consumption of detector modules, and evaluating efficient power distribution scenarios and computing resource usage.

Corresponding authors: Manish Khanal[1], Carsten Rott[1*]

[1] *University of Utah*

[*] Presenter

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

https://pos.sissa.it/

PoS(ICRC2025)1159

1. Introduction

The IceCube Neutrino Observatory, located at the geographical South Pole, is the world's largest neutrino detector, consisting of a cubic kilometer of ultra-pure Antarctic ice instrumented with 5,160 digital optical modules (DOMs) [1], distributed over 86 vertical strings. Since its completion in 2010, IceCube has made ground-breaking discoveries, including the first detection of high-energy astrophysical neutrinos [2] and the association of a neutrino event with a known blazar (TXS 0506 + 056), a milestone in multi-messenger astronomy [3].

Based on IceCube's success, an extension to the observatory, IceCube-Gen2, has been proposed. IceCube-Gen2 combines optical, radio, and surface cosmic-ray detector components to increase the discovery potential for high-energy cosmic neutrinos by an order of magnitude and expand the energy range accessible to IceCube [4]. The construction of IceCube-Gen2 foresees the deployment of 120 additional strings of new optical modules into Antarctic ice, and deploying a surface array and a 500 km^2 radio array. The logistics of transporting 10,000 optical sensors to the South Pole, drilling more than hundred holes to 2600 m depth into the ice, deploying and operating the surface and radio array poses significant challenges [5]. Deep drilling operation for IceCube-Gen2 are expected to consume approximately 920,000 gallons of fuel over the construction period. The direct fuel usage per hole is estimated to be 6,000 gallons,which includes both deep and firn drilling activities [5], and indirect fuel consumption is around 20,000 gallons per season.

The construction and operation of the IceCube-Gen2 observatory pose significant challenges due to the extreme polar environment and temperatures, isolation, and limited seasonal access [5]. Generators have proven to be reliable for IceCube construction and their efficiency has improved significantly, for example, by using heat recovery [5]. However, accessibility to the South Pole and the associated logistical challenges for a construction project have worsened in recent years [6]. Supplementing power generation during construction with renewable energy sources could reduce the logistical footprint and offer potential cost savings. To be viable, such renewable systems must be low-maintenance, field-proven for use in extreme conditions, and highly reliable. If successfully deployed during construction, these energy systems could also help offset operational power demands in the future. Renewable energy systems could also reduce the environmental risk associated with power production, for example, by not requiring fuel storage [5, 7].

The South Pole offers favorable conditions for solar photovoltaic (PV) generation during the summer months, including high insolation (the amount of total solar radiation incident on a horizontal surface over a period of time), low cloud cover, and increased PV efficiency due to low temperatures (with silicon cells gaining 0.4% efficiency per $^\circ C$ drop). Additionally, the high surface albedo (the reflectivity of a surface) ($\sim 0.7 - \sim 0.9$) enhances incident radiation through reflected light. PV has been utilized reliably in several Antarctic research stations, however the geographic South Pole certainly represents the most extreme environment.

One obvious option for the application of PV could be to supplement water heating for the hot water drilling infrastructure. Water heating only requires DC power, and due to limited flow rates, variations in the solar power output have minimal effects and could be compensated by ramping up generator power.

A combination of solar and wind might also be used to supplement power to the vast radio array with its proposed 500 km^2 footprint to reduce the power distribution and cabling challenges. Wind

PoS(ICRC2025)1159

energy is year-round available, however the extreme temperatures (−12°C to −83°C), fine drifting snow have presented challenges for mechanical systems, and wind speeds (average 12 km/h) are typically below those at the Antarctic coastal areas (typical 20-40 km/h), where wind power has been extensively used.

A combination of multiple power sources, along with energy storage systems, could provide reliable year-round power. Recent techno-economic studies have shown that significant cost savings and nearly continuous, operations are achievable in the challenging South Pole environment. The feasibility study [7] indicates that a hybrid system combining solar, wind, and battery storage could substantially reduce fuel consumption, lower operational costs, and mitigate the environmental impact of a polar research station. However, the system proposed would have to be field tested to ensure it is a viable option.

The primary goal of this contribution is to review the environmental footprint of construction for IceCube-Gen2 and evaluate options for augmenting the well established diesel-based power production with alternative energy options with the potential to reduce logistics needs.

2. Model for solar power output estimation

We develop a system to predict the power output of a PV array at the South Pole and utilize historic weather data to explore the instantaneous and average power output of different configurations. We first describe the relevant meteorological data and how it is utilized to predict the power output of a single PV panel. We compare different orientations of a single PV panel and discuss their benefits and drawbacks. We then describe building a PV array and how combinations of different orientations can result in a relatively stable power output throughout the day. Subsequently we explore how many panels are necessary to use photovoltaics effectively for drilling and discuss practical mounting options to minimize logistic and maintenance needs. To predict the power output of a PV panel at the geographic South Pole location, we utilize historical solar irradiance data from NOAA [1]. Solar irradiance is the measure of solar power received per unit area at Earth's surface and is influenced by factors such as solar elevation angle, atmospheric aerosols, and ground reflectivity [8]. This irradiance is divided into multiple components depending on the source of the emission at the surface. For our simulation we specifically utilize direct, diffuse, and upwelling irradiance. Direct irradiance refers to the shortwave irradiance directly incident from the solid angle of the Sun disc [9]. Diffuse irradiance is the radiation received on Earth from sunlight isotropically scattered by the atmosphere, excluding the solar disk [9]. Lastly, upwelling irradiance represents the light reflected upward from Earth's surface. Note that the upwelling irradiance is measured as a diffuse component and does not include directional information, which is relevant for a highly reflective environment such as the South Pole, and for vertically mounted panels. To address the directional information, a field test is merited.

Figure 3 shows different practical solar panel configurations under consideration. Natural mounting orientations for PV panels at the South Pole are vertical or horizontal, as these options

[1] https://gml.noaa.gov/aftp/data/radiation/baseline/spo/

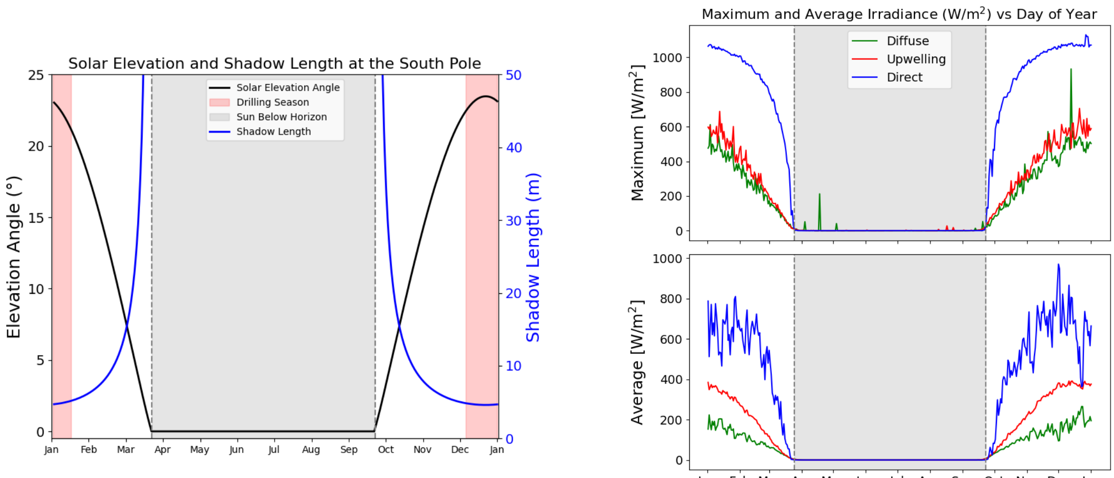
PoS(ICRC2025)1159

minimize maintenance needs and/or could be easily integrated with existing structures. Potential scenarios for PV panels are: (1) Attaching panels to the walls of the drilling infrastructure such as the shipping containers has been considered, however the risk of damage to the panels during operations makes this less practical; (2) Panels mounted vertically on sleds placed near the drill camp have the advantage of not interfering with drilling operations and bifacial panels could generate power more evenly during the entire day; (3) horizontally mounted panels pointing upwards could be attached to existing structures such as the scintillator panels or come with their own structure ; (4) Panels pointing downward could generate power based on the upwelling and reflected radiation in the high albedo polar environment and could be mounted below the scintillator panels; (5) Bifacial panels could be mounted horizontally using their own mounting structure, collecting light from both sides.

The South Pole is one of the most remote and logistically challenging environments on Earth, where any new system must be carefully evaluated before deployment. To ensure low maintenance of any PV system, snow accumulation on and around the panels must be minimized, and the panels should be mounted in batches.

To predict the power output of a solar panel, we calculate the angle γ between the normal direction of the panel and the position of the Sun, the 'direct' power output scaling as $\cos(\gamma)$, and add the upwelling and diffuse components, respectively. This method does not account for the directional component of the upwelling radiation. To better understand the impact of this, we performed a field test in July 2022 at the Bonneville Salt Flats in Utah, where the terrain has an albedo of ~ 0.4 [10] (see figure 3).

During the austral summer, from mid-September to mid-March, the Sun is always above the horizon, providing continuous daylight. This, combined with the exceptionally high reflective surface of the Pole [10] and low atmospheric moisture, creates ideal conditions for the use of solar energy. Previous field studies have shown reliable operation and structural integrity of solar panels in the extreme conditions over extended periods [11, 12].



(a) Elevation angle of the Sun at the South Pole with drilling season (red block) and shadow length

(b) Solar irradiance at the South Pole

Figure 1: Solar elevation angle and solar irradiance at the South Pole

Figure 1 (a) shows the solar elevation angle at the South Pole alongside the corresponding

PoS(ICRC2025)1159

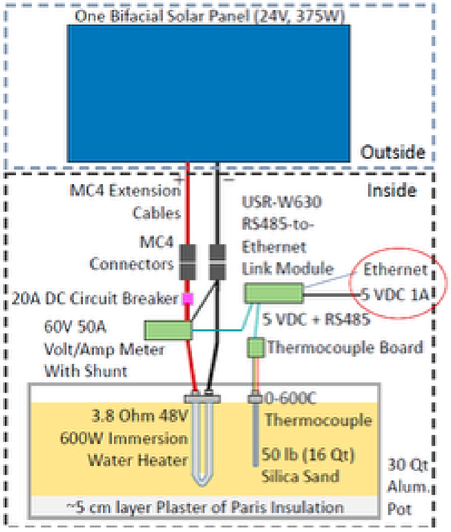


Figure 2: Schematic of the proposed field test at the South Pole

shadow length, calculated for a 2-meter height (solar panel and mount). The red-shaded regions show a typical drilling season at the Pole which runs from early-December to mid-January. During this period, the length of shadow cast by the panel is low which is crucial for optimizing solar array design. Figure 1 (b) shows the maximum and average irradiance components - direct, diffuse, and upwelling - at the South Pole. As the Sun approaches the horizon, the irradiance decreases rapidly due to the large air mass [8].

To better understand the impact on solar panel output, we have proposed a field test setup at the South Pole. This setup features two bifacial solar panels (CanadianSolar BiKu Module, 375W range), a resistor (4Ω-500W braking resistor) and 48V-600W cartridge heaters integrated to provide a small thermal contribution to the drill camp. A PZEM-17 RS485 volt/amp meter will be used for continuous monitoring of system output. We will conduct a continuous measurement of the power output from these solar panels throughout the austral summer. A simplified system schematic is shown in Figure 2. It illustrates the key components, including power routing, heating elements, and data logging setup used for the field test.

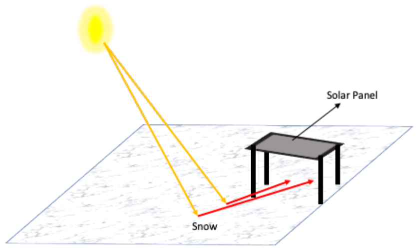
Wind energy is also being explored for autonomous power generation at the South Pole. The collaboration has started field tests with commercial vertical axis wind turbines (LE-V150 12V Extreme Turbine), including one installed on the roof of the IceCube Laboratory (ICL). This turbine is continuously logging data on voltage, current, rotation speed, and wind speed to evaluate its performance. Additional tests are being conducted with other turbines at RNO-G stations in Greenland.

3. Results

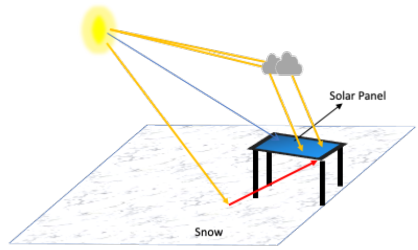
We have explored one of many possible renewable energy solutions for the South Pole. In this section, we will focus primarily on the solar panel system. We investigated different panel orientations, and one of the primary designs explored was vertically oriented bifacial solar panels, allowing capture of sunlight from both sides. This design is particularly well suited for the South

PoS(ICRC2025)1159

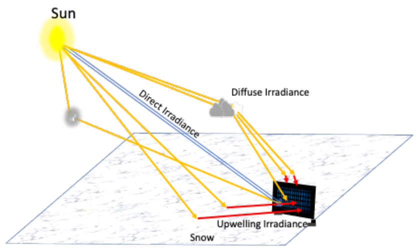
Pole, which has a high surface albedo. Analysis of power output from this configuration showed promising results, indicating that these vertically oriented panels can effectively harness energy even when the Sun remains low on the horizon.



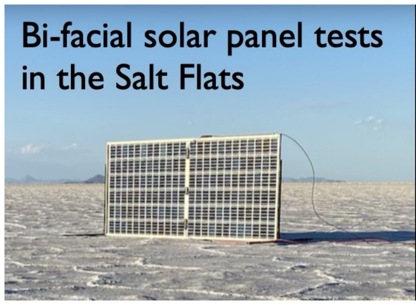
(a) Horizontally mounted panels pointing downward



(b) Horizontally mounted panels pointing upward



(c) Vertically oriented Solar Panel



(d) Salt Flats Test

Figure 3: Conceptual diagrams of various proposed configurations for solar panel deployment: (a) panels positioned at the bottom of a scintillation detector to (b) panels mounted on top of a scintillation detector, and (c) a vertically oriented solar panels setup.

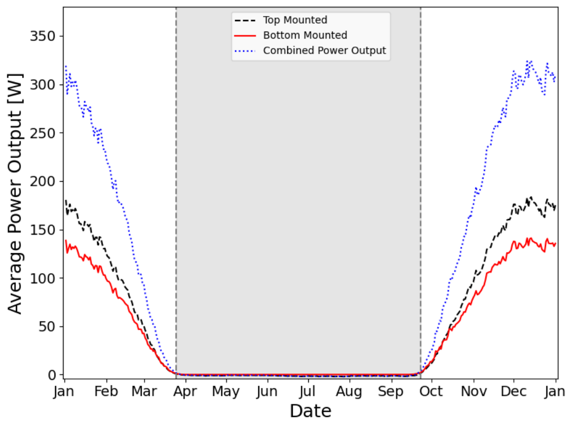


Figure 4: Expected power output from panels mounted on scintillation detector

However, vertical panel installations come with several logistical challenges. They require a supporting structure that can withstand the frequent strong winds and snow accumulation at the pole. Furthermore, the long-term survival of these thousands of panels during the dark and harsh polar winter remains uncertain. Considering this, we explored other possible mounting solutions for the solar panels. As shown in Figure 3, mounting solar panels on top or below a scintillation

PoS(ICRC2025)1159

detector or similar structure units for the surface array could be alternative options. They do not need additional infrastructure, and top-mounted solar panels can take advantage of both incoming solar irradiance and reflected irradiance from the snow surface, while bottom-mounted panels receive plenty of reflected radiation due to high South Pole albedo. As shown in Figure 4, the average power output from a single solar panel remains above 100 W from mid-November to mid-February, for both configurations. Although a configuration with horizontal panels is not as efficient as one with vertically oriented bi-facial panels, lack of additional requirements makes it logistically simpler and a compelling option for power support.

Table 1: Comparison of Fuel-Based vs. Solar-Based Energy Generation (Per Season)

Metric	Fuel-Based System	Solar Panel System
Fuel/Panel units used	92,000 gallons	1,000 panels
Total energy generated	1,288,000 kWh (14 kWh/gallon) [7]	492,000 kWh
Emissions	High (fossil fuel)	None (renewable)
Energy availability	All-weather, 24/7	Seasonal (summer only)
Maintenance complexity	Moderate to high	Low to moderate

4. Conclusions

The integration of renewable energy for the IceCube-Gen2 operation offers a compelling opportunity to reduce both environmental impact and long-term logistic costs. One promising approach we have explored is augmenting hot water drilling with solar power, which has the potential to significantly reduce cargo needs and offer a favorable long-term cost advantage compared to traditional fuel use. The system is designed to be scalable, allowing for increased power generation by expanding the number of solar panels as needed. Vertically mounted 1,000 bifacial solar panels could provide up to 492,000 kWh of clean energy per season during the austral summer, which could reduce the reliance on diesel fuel for drilling operations. In addition to solar energy, wind energy could also be a good candidate at the South Pole and is being actively explored for the South Pole application. These renewable systems could eventually be integrated into the main IceCube computing and detector infrastructure, supporting autonomous operation, and reducing fuel logistics.

Future work will focus on optimizing the design of the array and the orientation of the panels to best utilize solar conditions and the minimum logistic requirement for the deployment of these renewable energy sources. In addition, a more comprehensive cost-benefit analysis will be performed with various hybrid renewable configurations including a solar PV system, wind turbines, and a battery storage solution.

References

[1] **IceCube** Collaboration, M. G. Aartsen *et al. Journal of Instrumentation* **12** no. 03, (2017) P03012.

PoS(ICRC2025)1159

[2] **IceCube** Collaboration, M. G. Aartsen *et al. Science* **342** no. 6161, (2013) 1242856.

[3] **IceCube, MAGIC, and others** Collaboration *Science* **361** no. 6398, (2018) eaat1378.

[4] **IceCube** Collaboration, M. G. Aartsen *et al. Journal of Physics G: Nuclear and Particle Physics* **48** no. 6, (2021) 060501.

[5] **IceCube-Gen2** Collaboration, "Part III: Detector Construction and Logistical Support Requirements," tech. rep., University of Wisconsin-Madison (WIPAC), 2023. Version 2023.01.

[6] J. J. Lucci, M. Alegre, and L. Vigna *Antarctic Science* **34** no. 5, (2022) 374–388.

[7] S. Babinec *et al. Renewable and Sustainable Energy Reviews* **193** (2024) 114274.

[8] M. Iqbal, *An introduction to solar radiation*. Elsevier, 2012.

[9] L. Wald, "Basics in solar radiation at earth surface." 2018.

[10] W. J. Wiscombe and S. G. Warren *Journal of Atmospheric Sciences* **37** no. 12, (1980) 2712–2733.

[11] C. R. Williams, J. H. Rand, *et al.*, "Evaluation of photovoltaic panels at the south pole station," tech. rep., 2000.

[12] D. Besson *et al. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **763** (2014) 521–532.

PoS(ICRC2025)1159

Full Author List: IceCube-Gen2 Collaboration (May 17, 2025)

R. Abbasi[16], M. Ackermann[77], J. Adams[21], S. K. Agarwalla[46,78], J. A. Aguilar[10], M. Ahlers[25], J.M. Alameddine[26], N. M. Amin[52], K. Andeen[49], G. Anton[29], C. Argüelles[13], Y. Ashida[63], S. Athanasiadou[77], J. Audehm[1], S. N. Axani[52], R. Babu[27], X. Bai[60], A. Balagopal V.[46], M. Baricevic[46], S. W. Barwick[33], V. Basu[63], R. Bay[6], J. Becker Tjus[9,79], P. Behrens[1], J. Beise[75], C. Bellenghi[30], B. Benkel[77], S. BenZvi[62], D. Berley[22], E. Bernardini[58,80], D. Z. Besson[39], A. Bishop[46], E. Blaufuss[22], L. Bloom[71], S. Blot[77], M. Bohmer[30], F. Bontempo[34], J. Y. Book Motzkin[13], J. Borowka[1], C. Boscolo Meneguolo[58,80], S. Böser[47], O. Botner[75], J. Böttcher[1], S. Bouma[29], J. Braun[46], B. Brinson[4], Z. Brisson-Tsavoussis[36], R. T. Burley[2], M. Bustamante[25], D. Butterfield[46], M. A. Campana[59], K. Carloni[13], M. Cataldo[29], S. Chattopadhyay[46,78], N. Chau[10], Z. Chen[66], D. Chirkin[46], B. A. Clark[22], R. Clark[41], A. Coleman[75], P. Coleman[1], G. H. Collin[14], J. M. Conrad[14], R. Corley[63], D. F. Cowen[72,73], B. Dasgupta[50], C. Deaconu[17,20], C. De Clercq[11], S. De Kockere[11], J. J. DeLaunay[72], D. Delgado[13], S. Deng[1], A. Desai[46], P. Desiati[46], K. D. de Vries[11], G. de Wasseige[43], J. C. Díaz-Vélez[46], S. DiKerby[27], M. Dittmer[51], G. Do[1], A. Domi[29], L. Draper[63], L. Dueser[1], H. Dujmovic[46], D. Durnford[28], K. Dutta[47], M. A. DuVernois[46], T. Egby[5], T. Ehrhardt[47], L. Eidenschink[30], A. Eimer[29], P. Eller[30], E. Ellinger[76], D. Elsässer[26], R. Engel[34,35], H. Erpenbeck[46], W. Esmail[51], J. Evans[22], J. J. Evans[48], P. A. Evenson[52], K. L. Fan[22], K. Fang[46], K. Farrag[15], A. R. Fazely[5], A. Fedynitch[69], N. Feigl[8], C. Finley[65], L. Fischer[77], B. Flaggs[52], D. Fox[72], A. Franckowiak[9], T. Fujii[56], S. Fukami[77], P. Fürst[1], J. Gallagher[45], E. Ganster[1], A. Garcia[13], G. Garg[46,78], E. Genton[13], L. Gerhardt[7], A. Ghadimi[71], P. Giri[40], C. Glaser[75], T. Glüsenkamp[75], S. Goswami[37,38], A. Granados[27], D. Grant[12], S. J. Gray[22], S. Griffin[46], S. Griswold[62], D. Guevel[46], C. Günther[1], P. Gutjahr[26], C. Ha[64], C. Haack[29], A. Hallgren[75], S. Hallmann[77], L. Halve[1], F. Halzen[46], L. Hamacher[1], M. Ha Minh[30], M. Handt[1], K. Hanson[46], J. Hardin[14], A. A. Harnisch[27], P. Hatch[36], A. Haungs[34], J. Häußler[1], D. Heinen[1], K. Helbing[76], J. Hellrung[9], B. Hendricks[73,74], L. Hennig[29], J. Henrichs[77], L. Heuermann[1], N. Heyer[75], S. Hickford[76], A. Hidvegi[65], C. Hill[15], G. C. Hill[2], K. D. Hoffman[22], B. Hoffmann[34], S. Hori[46], K. Hoshina[46,81], M. Hostert[13], W. Hou[34], T. Huber[34], T. Huege[34], K. Hultqvist[65], R. Hussain[46], K. Hymon[26,69], A. Ishihara[15], T. Ishii[56], W. Iwakiri[15], M. Jacquart[46], S. Jain[46], O. Janik[29], M. Jansson[67], M. Jeong[63], M. Jin[13], O. Kalekin[29], N. Kamp[13], D. Kang[34], W. Kang[67], X. Kang[59], A. Kappes[51], L. Kardum[26], T. Karg[77], M. Karl[30], A. Karle[46], A. Katil[28], T. Katori[41], U. Katz[29], M. Kauer[46], J. L. Kelley[46], M. Khanal[63], A. Khatee Zathul[46], A. Kheirandish[37,38], J. Kiryluk[66], M. Kleifges[34], C. Klein[29], S. R. Klein[6,7], T. Kobayashi[56], Y. Kobayashi[15], A. Kochocki[27], H. Kolanoski[8], T. Kontrimas[30], L. Köpke[47], C. Kopper[29], D. J. Koskinen[25], P. Koundal[52], M. Kowalski[8,77], T. Kozynets[25], I. Kravchenko[40], N. Krieger[9], J. Krishnamoorthi[46,78], T. Krishnan[13], E. Krupczak[27], A. Kumar[77], E. Kun[9], N. Kurahashi[59], N. Lad[77], M. J. Larson[22], F. Lauber[76], K. Leonard DeHolton[73], A. Leszczyńska[52], J. Liao[4], M. Liu[40], M. Liubarska[28], M. Lohan[50], J. LoSecco[55], C. Love[59], L. Lu[46], F. Lucarelli[31], Y. Lyu[6,7], J. Madsen[46], E. Magnus[11], K. B. M. Mahn[27], Y. Makino[46], E. Manao[30], S. Mancina[58,82], S. Mandalia[42], W. Marie Sainte[46], I. C. Mariş[10], S. Marka[54], Z. Marka[54], M. Marsee[71], L. Marten[1], I. Martinez-Soler[13], R. Maruyama[53], F. Mayhew[27], F. McNally[44], J. V. Mead[25], K. Meagher[46], S. Mechbal[77], A. Medina[24], M. Meier[15], Y. Merckx[11], L. Merten[9], Z. Meyers[77], M. Mikhailova[39], A. Millsop[41], J. Mitchell[5], T. Montaruli[31], R. W. Moore[28], Y. Morii[15], R. Morse[46], A. Mosbrugger[29], M. Moulai[46], D. Mousadi[77], T. Mukherjee[34], M. Muzio[72,73,74], R. Naab[77], M. Nakos[46], A. Narayan[50], U. Naumann[76], J. Necker[77], A. Nelles[29,77], L. Neste[65], M. Neumann[51], H. Niederhausen[27], M. U. Nisa[27], K. Noda[15], A. Noell[1], A. Novikov[52], E. Oberla[17,20], A. Obertacke Pollmann[15], V. O'Dell[46], A. Olivas[22], R. Orsoe[30], J. Osborn[46], E. O'Sullivan[75], V. Palusova[47], L. Papp[30], A. Parenti[10], N. Park[36], E. N. Paudel[71], L. Paul[60], C. Pérez de los Heros[75], T. Pernice[77], T. C. Petersen[25], J. Peterson[46], A. Pizzuto[46], M. Plum[60], A. Pontén[75], Y. Popovych[47], M. Prado Rodriguez[46], B. Pries[27], R. Procter-Murphy[22], G. T. Przybylski[7], L. Pyras[63], J. Rack-Helleis[47], N. Rad[77], M. Rameez[50], M. Ravn[75], K. Rawlins[3], Z. Rechav[46], A. Rehman[52], E. Resconi[30], S. Reusch[77], C. D. Rho[67], W. Rhode[26], B. Riedel[46], M. Riegel[34], A. Rifaie[76], E. J. Roberts[2], S. Robertson[6,7], S. Rodan[67,68], M. Rongen[29], C. Rott[63], T. Ruhe[26], L. Ruohan[30], D. Ryckbosch[32], I. Safa[46], J. Saffer[35], D. Salazar-Gallegos[27], P. Sampathkumar[34], A. Sandrock[76], P. Sandstrom[46], G. Sanger-Johnson[27], M. Santander[71], S. Sarkar[57], J. Savelberg[1], P. Savina[46], P. Schaile[30], M. Schaufel[1], H. Schieler[34], S. Schindler[29], L. Schlickmann[47], B. Schlüter[51], F. Schlüter[10], N. Schmeisser[76], T. Schmidt[22], F. G. Schröder[34,52], L. Schumacher[29], S. Schwirn[1], S. Sclafani[22], D. Seckel[52], M. Seikh[39], S. Seunarine[61], M. H. Shaevitz[54], R. Shah[59], S. Shefali[35], N. Shimizu[15], M. Silva[46], B. Skrzypek[6], R. Snihur[46], J. Soedingrekso[26], A. Søgaard[25], D. Soldin[63], P. Soldin[1], G. Sommani[9], C. Spannfellner[30], G. M. Spiczak[61], C. Spiering[77], J. Stachurska[32], M. Stamatikos[24], T. Stanev[52], T. Stezelberger[7], J. Stoffels[11], T. Stürwald[76], T. Stuttard[25], G. W. Sullivan[22], I. Taboada[4], A. Taketa[70], H. K. M. Tanaka[70], S. Ter-Antonyan[5], A. Terliuk[30], W. G. Thompson[13], J. Thwaites[46], S. Tilav[52], K. Tollefson[27], C. Tönnis[67], J. Torres[23,24], S. Toscano[10], D. Tosi[46], A. Trettin[77], Y. Tsunesada[56], J. P. Twagirayezu[27], M. A. Unland Elorrieta[51], A. K. Upadhyay[46,78], K. Upshaw[5], A. Vaidyanathan[49], N. Valtonen-Mattila[9,75], J. Vandenbroucke[46], T. Van Eeden[77], N. van Eijndhoven[11], J. van Santen[77], J. Vara[51], F. Varsi[35], D. Veberic[34], J. Veitch-Michaelis[46], M. Venugopal[34], S. Vergara Carrasco[21], S. Verpoest[52], A. Vieregg[17,18,19,20], A. Vijai[22], J. Villarreal[14], C. Walck[65], A. Wang[4], D. Washington[73], C. Weaver[27], P. Weigel[14], A. Weindl[34], A. Y. Wen[13], C. Wendt[46], J. Werthebach[26], M. Weyrauch[34], N. Whitehorn[27], C. H. Wiebusch[1], D. R. Williams[71], S. Wissel[72,73,74], L. Witthaus[26], M. Wolf[30], G. Wörner[34], G. Wrede[29], S. Wren[48], X. W. Xu[5], J. P. Ya\~nez[28], E. Yildizci[46], S. Yoshida[15], R. Young[39], F. Yu[13], S. Yu[63], T. Yuan[46], A. Zegarelli[9], S. Zhang[27], Z. Zhang[66], P. Zhelnin[13], S. Zierke[1], P. Zilberman[46], M. Zimmerman[46]

[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] School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA
[5] Dept. of Physics, Southern University, Baton Rouge, LA 70813, USA
[6] Dept. of Physics, University of California, Berkeley, CA 94720, USA
[7] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[8] Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany

PoS(ICRC2025)1159

[9] Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany
[10] Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium
[11] Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium
[12] Dept. of Physics, Simon Fraser University, Burnaby, BC V5A 1S6, Canada
[13] Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA
[14] Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[15] Dept. of Physics and The International Center for Hadron Astrophysics, Chiba University, Chiba 263-8522, Japan
[16] Department of Physics, Loyola University Chicago, Chicago, IL 60660, USA
[17] Dept. of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
[18] Dept. of Physics, University of Chicago, Chicago, IL 60637, USA
[19] Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA
[20] Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
[21] Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
[22] Dept. of Physics, University of Maryland, College Park, MD 20742, USA
[23] Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA
[24] Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA
[25] Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
[26] Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany
[27] Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
[28] Dept. of Physics, University of Alberta, Edmonton, Alberta, T6G 2E1, Canada
[29] Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
[30] Physik-department, Technische Universität München, D-85748 Garching, Germany
[31] Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland
[32] Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium
[33] Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, USA
[34] Karlsruhe Institute of Technology, Institute for Astroparticle Physics, D-76021 Karlsruhe, Germany
[35] Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany
[36] Dept. of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada
[37] Department of Physics & Astronomy, University of Nevada, Las Vegas, NV 89154, USA
[38] Nevada Center for Astrophysics, University of Nevada, Las Vegas, NV 89154, USA
[39] Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
[40] Dept. of Physics and Astronomy, University of Nebraska–Lincoln, Lincoln, Nebraska 68588, USA
[41] Dept. of Physics, King's College London, London WC2R 2LS, United Kingdom
[42] School of Physics and Astronomy, Queen Mary University of London, London E1 4NS, United Kingdom
[43] Centre for Cosmology, Particle Physics and Phenomenology - CP3, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[44] Department of Physics, Mercer University, Macon, GA 31207-0001, USA
[45] Dept. of Astronomy, University of Wisconsin—Madison, Madison, WI 53706, USA
[46] Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin—Madison, Madison, WI 53706, USA
[47] Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany
[48] School of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom
[49] Department of Physics, Marquette University, Milwaukee, WI 53201, USA
[50] Dept. of High Energy Physics, Tata Institute of Fundamental Research, Colaba, Mumbai 400 005, India
[51] Institut für Kernphysik, Universität Münster, D-48149 Münster, Germany
[52] Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
[53] Dept. of Physics, Yale University, New Haven, CT 06520, USA
[54] Columbia Astrophysics and Nevis Laboratories, Columbia University, New York, NY 10027, USA
[55] Dept. of Physics, University of Notre Dame du Lac, 225 Nieuwland Science Hall, Notre Dame, IN 46556-5670, USA
[56] Graduate School of Science and NITEP, Osaka Metropolitan University, Osaka 558-8585, Japan
[57] Dept. of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom
[58] Dipartimento di Fisica e Astronomia Galileo Galilei, Università Degli Studi di Padova, I-35122 Padova PD, Italy
[59] Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA
[60] Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA
[61] Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA
[62] Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
[63] Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
[64] Dept. of Physics, Chung-Ang University, Seoul 06974, Republic of Korea
[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, Republic of Korea
[68] Institute of Basic Science, Sungkyunkwan University, Suwon 16419, Republic of Korea

PoS(ICRC2025)1159

[69] Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan
[70] Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan
[71] Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
[72] Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
[73] Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA
[74] Institute of Gravitation and the Cosmos, Center for Multi-Messenger Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
[75] Dept. of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden
[76] Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
[77] Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, D-15738 Zeuthen, Germany
[78] Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India
[79] Department of Space, Earth and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden
[80] INFN Padova, I-35131 Padova, Italy
[81] Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan
[82] INFN Padova, I-35131 Padova, Italy

Acknowledgments

The authors gratefully acknowledge the support from the following agencies and institutions: USA – U.S. National Science Foundation-Office of Polar Programs, U.S. National Science Foundation-Physics Division, U.S. National Science Foundation-EPSCoR, U.S. National Science Foundation-Office of Advanced Cyberinfrastructure, Wisconsin Alumni Research Foundation, Center for High Throughput Computing (CHTC) at the University of Wisconsin–Madison, Open Science Grid (OSG), Partnership to Advance Throughput Computing (PATh), Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS), Frontera and Ranch 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, Astroparticle physics computational facility at Marquette University, NVIDIA Corporation, and Google Cloud Platform; 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; European Union – EGI Advanced Computing for research; Australia – Australian Research Council; Canada – Natural Sciences and Engineering Research Council of Canada, Calcul Québec, Compute Ontario, Canada Foundation for Innovation, WestGrid, and Digital Research Alliance of Canada; Denmark – Villum Fonden, Carlsberg Foundation, and European Commission; 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).

PoS(ICRC2025)1159