



Tidal Disruption: An Unforgettable Encounter with a Black Hole

Downloaded from: <https://research.chalmers.se>, 2025-09-25 16:02 UTC

Citation for the original published paper (version of record):

Abbasi, R., Ackermann, M., Adams, J. et al (2024). Tidal Disruption: An Unforgettable Encounter with a Black Hole. *Proceedings of Science*, 444. <http://dx.doi.org/10.22323/1.444.1613>

N.B. When citing this work, cite the original published paper.

Tidal Disruption: An Unforgettable Encounter with a Black Hole

The IceCube Collaboration

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

E-mail: mdhosale@yorku.ca, madsen@icecube.wisc.edu, vbasu@wisc.edu

The annual GLEAM outdoor art exhibition features curated, large-scale light installations in the Olbrich Botanical Gardens in Madison, Wisconsin. With submissions from local, regional, and international artists, the annual two-month long event draws tens of thousands of visitors each fall. “Tidal Disruption,” an art-science light sculpture representative of the form and behavior of a tidal disruption event, debuted at GLEAM 2022. The installation was a collaboration between artists Hosale and Abdu’Allah, and astrophysicist Madsen. The immersive light and sound exhibit stylistically depicted the death of a star as it spirals into a black hole in a roughly 4 minute sequence. Designed primarily by Hosale, the components were custom fabricated using clear PVC pipe at the Physical Sciences Laboratory at UW-Madison. In this poster, we will describe the process of developing, fabricating, and installing “Tidal Disruption” and the response from the viewers.

Corresponding authors: Mark-David Hosale¹, Jim Madsen², Vedant Basu^{2*}

¹ *Computational Arts, School of Art, Media, Performance and Design York University, Toronto*

² *WIPAC, UW-Madison, USA*

* Presenter

The 38th International Cosmic Ray Conference (ICRC2023)
26 July – 3 August, 2023
Nagoya, Japan



1. Introduction

The IceCube Collaboration continues to seek new ways to engage with diverse audiences. One path to success in this regard is to partner with artists whose works convey science from a different perspective, providing access to communities that are less likely to attend a more traditional IceCube outreach event. A few examples of prior work with artists have been described in previous ICRC meetings, [1, 2]. Here we describe an ambitious effort to convey the catastrophic process of a star being destroyed by a black hole, referred to as Tidal Disruption Event (TDE).

For many years, Olbrich Botanical Gardens in Madison, Wisconsin has hosted an annual exhibition featuring artistic light installations, **GLEAM**. Preliminary proposals are due about a year in advance of the show, of which a few are selected to submit full proposals. From these, approximately ten projects are selected with a budget up to \$10,000.00 including in-kind contributions. Installation takes place in early August, and the shows are open to the public Wednesday-Saturday evenings in September and October. An admission fee helps fund the projects and support operation of Olbrich Gardens. The total attendance of approximately 30,000 people is much higher than typically drawn for science installations on the UW-Madison campus.

2. Concept Development

A preliminary discussion led to a commitment to put together a proposal, and an initial design idea was developed by Hosale, see Figure (1a). The preliminary proposal was crafted in parallel.

Installation Synopsis: Massive black holes lurk at the center of galaxies, gobbling wayward stars that wander too close. What once was a beautiful ball of fusing matter is torn apart by the phenomenal gravitational strength of the unimaginably dense black hole. Viewers would set off a light and sound “explosion,” representative of the explosive jet of high-energy particles produced when the tidal forces become so strong that not even a star can survive.

An architectonic light sculpture representative of the form and behavior of a tidal disruption event as described above was designed, executed, and installed. Viewers experienced the cosmic fireworks produced by the encounter as they walked around an interactive model of the black hole. The overall experience aimed to express the sublime nature of black holes, exposing the mysterious

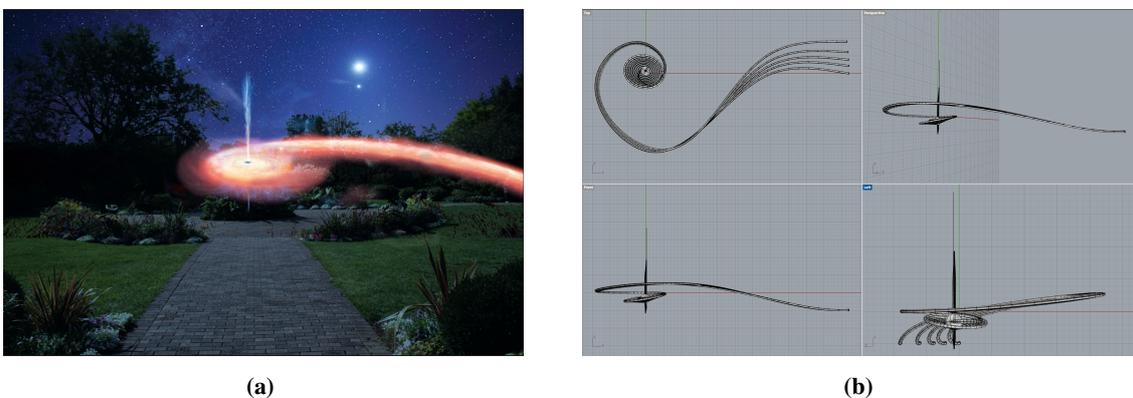


Figure 1: (a) A first artistic vision of the TDE light sculpture. (b) Preliminary wire frame rendering.

beauty and power of cataclysmic cosmic events in a thought-provoking installation where art and science collide.

The next step was to move from conceptual design to a wire frame model (Fig. 1b).

This model progressed to a buildable design (Fig. 2), that needed to satisfy design goals and constraints described below.

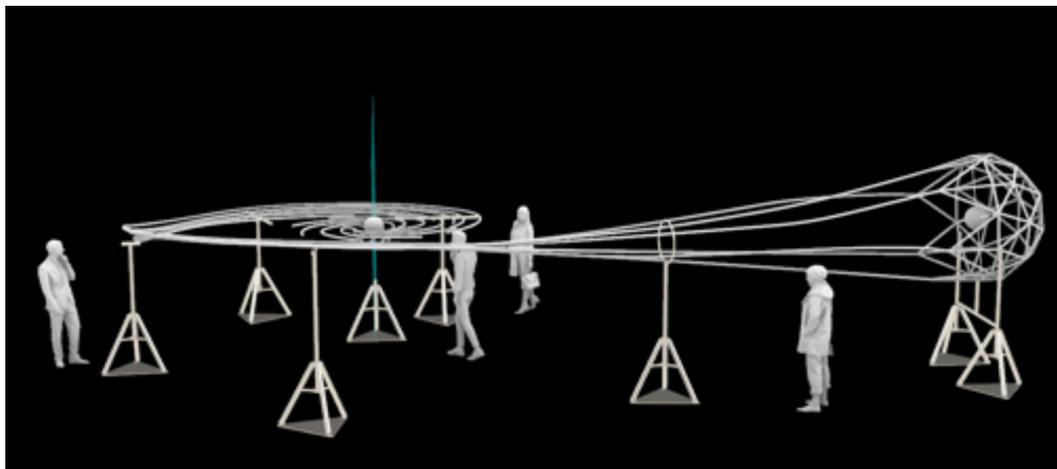


Figure 2: The final rendering of the TDE light sculpture.

Dimensions: Approximately 60’ in length and 20’ at its widest point.

Materials: The main body of the sculpture was constructed of clear PVC tubing illuminated with internal LEDs. The black hole was represented by a black sphere with acrylic rods from the top and bottom that could be “energized” by pulsing a bright light inside the sphere to represent particle jets. The PVC tubing was supported by a structure painted black to minimize visibility at night. Earth anchors screwed into the ground secured the work.

Lighting Fixture Description : The entire installation was lit using three strategies:

1. Side emitting clear PVC pipes illuminated internally form the main bodu of the work.
2. Commercially available [computer-controllable strings of LED discs](#), Fig. 3a, show the progression of matter from the star being pulled into the black hole.
3. Higher power computer-controllable LEDs, Fig. 3b, illuminated the globe at the center of the star, Fig. 6b and the vertical acrylic sculptural rods that represented the jets of particles emanating from the axis of the black hole, Fig. 6a.

In a steady state, the installation cycled from white light to reddish and orange light funneling from the outer end of the sculpture, spiraling and accelerating into the black hole, Figs. 5a-5b.

Safety structures: The goal was to produce a light structure appearing suspended in space. We achieved this by have main supports at the star and black hole, with the light tubes representing matter streaming into the black hole held up by tripods as needed. The earth anchors provided added stability. The design also needed to:

- discourage but survive leaning on, shaking, and limited climbing;



Figure 3: (a) The 3-element LED disks used to illuminate the clear PVC pipes and (b) the off-road headlights used to light the star and black hole jet.

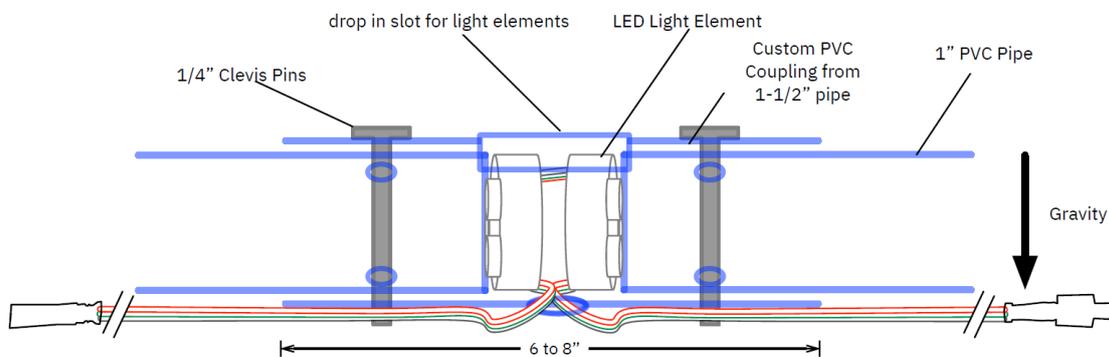


Figure 4: The the LED placement and mechanical connection between PVC pipes.

- withstand harsh conditions like high winds and freeze-thaw cycles; and
- minimize site impact by making everything self-supporting.

Power connection points and total power: A power drop of 1000 watts was required. Power and all light controls were located under the black hole ball in the cantilever portion of the structure and intermediate support structures.

3. Design, Application, and Physical Layers

The form of the installation was developed by Hosale using McNeel’s Rhinoceros [3], a 3D modelling software that integrates well with digital fabrication workflows and is commonly used in architectural scale design. As alluded to above, the flexibility of the software allowed the creation process to move from line drawing sketches to full 3D rendering of every component and fastener in a single environment.

Puck-like LEDs that were specifically designed for outdoor applications were used in the installation, Figure 3a. The wire lengths and wiring of the LED’s were custom fabricated by a

company in China [4] with exact lengths calculated based on the 3D rendering provided. Lights were then strung along the PVC pipe with LEDs dropped in at regular intervals of approximately two feet along the length of the installation. At each connection point two LEDs were placed back to back to illuminate the pipe from both ends. Power was injected into each line of LEDs from power supplies in the tripod supports.

The color of the LEDs were controlled using the same protocol that is used to control the widely used Neopixel built around the WS2812 chip and its variants [5]. This allowed the installation to be controlled using readily available libraries found in the Arduino IDE microcontroller programming environment [6]. The physical layer of the LED control consisted of a Teensy 4.0 [7] with a OctoWS2811 Adaptor [8] that allowed the installation to be addressed in a similar manner as a video wall.

The LED control application was developed in C++ using OpenFrameworks [9], a multi-platform C++ framework for computational based artworks. This application functioned as a simulator of the project as well as a control application for the final installation. The simulation mapped colors on a 3D model of the installation, facilitating the composing of light and sound behaviors before the installation was even built. The control application was deployed on a Raspberry Pi 3 Model B+ [10] a single board low power computer that was connected to the Teensy with OctoWS2811 Adaptor and housed in a tripod at supporting the star portion of the installation.

The behavior of the work was controlled by a manager application running on another Raspberry Pi in the other tripod support of the star. The manager application was developed in a computer music software called SuperCollider [11], and took advantage of its musical timing features to control the sound of lights of the installation via network messages sent to RaspberryPis housed in each tripod of the installation.

Each of the eight tripods , including the one used for light control, had a Raspberry Pi and a sound system. Each Raspberry Pi ran a SuperCollider application that played real-time generated soundscapes that were controlled via messages from the manager application, as described above. This allowed sound to spatially propagate through the work as a sonic expression of the process of the black hole eating the star.

4. Fabrication

The bulk of the fabrication work took about three weeks and involved cutting a total 284 pieces of clear 1.5" diameter PVC pipe in lengths that ranged from 9" to 34.5". Most of these pieces had to subsequently be heated and bent to a predetermined arc. Finally, their surfaces were roughened with coarse sand paper to ensure diffusive light scattering along the length of the pipe. Larger diameter pipes were cut into 6" long sections that were used as connectors. Cutting, bending, drilling and sanding took about 120 people-hours.

At each juncture of the star stream, LED "pucks" (Figure 3a) were placed back-to-back held in place by the clear PVC fittings and then fastened with clevis pins (which allow for quick installation and deinstallation), Figure 4. For the star, 3, 4, or 5 armed connectors were fabricated that provided both mechanical support and held a single LED "puck" in place.

Tripods were configured from readily available antenna supports. These were bolted to plywood bases painted black. A shelf was added to hold the electronics which were contained in molded



Figure 5: The sculpture at twilight showing the start of the light sequence, (a), and at full color, (b).

plastic boxes. Uprights and cross pieces were cut from 2" PVC pipe painted black. Electrical conduit tape was used to reinforce the PVC as necessary.

5. Installation

Installation of the work took six days. All the pieces were fabricated at the UW-Madison Physical Sciences Lab, and then loaded into a van and brought to Olbrich Gardens. Multiple people pitched in to ensure the project would be completed by opening night. There was a great deal of "custom" wiring to get power and data to the LEDs in addition to physically joining the high quality waterproof connections on the LEDs.

Once the mechanical and electrical components were installed, the software to control the sound and light was fine-tuned. The final program was a sequence that lasted about 4 minutes that started by illuminating the star in white light that traveled down the "streams" to the swirl and be consumed by the black hole. This was indicated by a change in color and sound. The beginning and middle of the color sequence is shown in Figure 5a and Figure 5b.

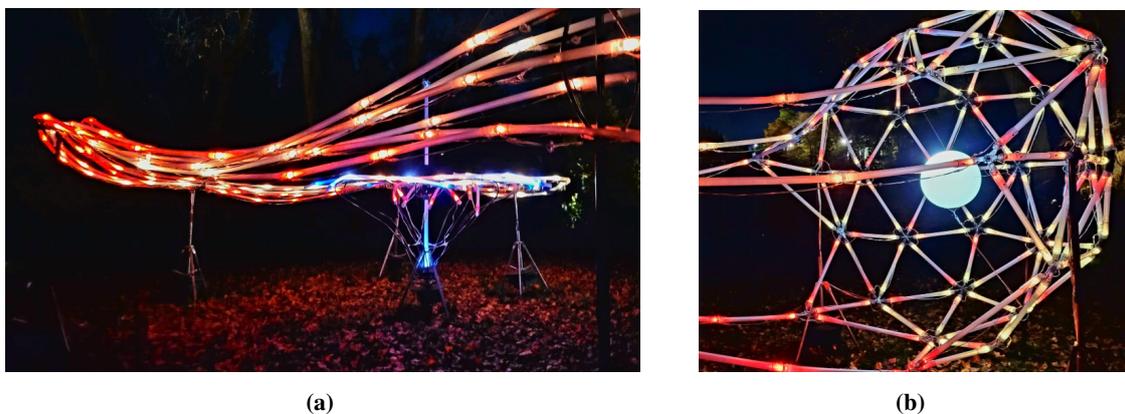


Figure 6: Close ups of the black hole, (a), and star, (b).

6. Response

The TDE light sculpture was a tremendous hit, Figs, 7a, 7b. People were intrigued by the sculpture with several interesting guesses of what it represented. After reading the accompanying description or talking to volunteer docents assigned to the TDE sculpture, they were generally awed by the thought that a star could be pulled apart. As the pictures show, many people chose to view the sculpture from different vantage points, resulting in dramatic images and experiences, Figure 7a, Figure 7b.

The most common comment was an appreciation for the artistic interpretation depicting an almost incomprehensible event. The light display cycled through a 4 minute sequence that began with the sphere representing the star being illuminated with white lights. The star being pulled apart and consumed by the black hole was shown by illuminating the "arms" that streamed toward and eventually spiraled around the black sphere representing the black hole. As the event progressed, the lights in the star sphere would fade until the last matter from the star was consumed. This sequence was summarized on a plaque near the light sculpture. A docent stationed at the light sculpture was available to answer questions as well.



(a)



(b)

Figure 7: Viewers enraptured by the light sculpture, (a) and (b).

7. Conclusion

There are multiple ways to communicate science that go beyond expressing a technically challenging topic in an accessible language. We have developed strong partnerships with artists who bring different techniques, perspectives and often novel venues to connect with new audiences and communities. This light sculpture is a prime example.

8. Key Contributions

We thank Faisal Abdu'Allah, for his help securing funding. We thank the WIPAC students and staff who helped with the fabrication, installation and tear down of the light sculpture—Vedant Basu, Delaney Butterfield, Ellen Bechtol, Hannah Haynes, Jean DeMerit, Yuya Makino, and Laura Mercier. Special thanks to Melissa Jeanne, Special Projects Manager at Olbrich Gardens, for her help during all stages of the project.

References

- [1] J. Madsen, F. Abdu'Allah, M.-D. Hosale, and M. Ladoni *PoS ICRC2019* (2019) 951.
- [2] J. Madsen and L. e. Mulot *PoS ICRC2021* (2021) 1381.
- [3] R. McNeel *et al. Robert McNeel & Associates, Seattle, WA* (2010) .
- [4] “Shenzhen Shiji Lighting Co. LTD.” <http://www.shiji-led.com/>.
- [5] “Neopixel Guide.” <https://learn.adafruit.com/adafruit-neopixel-uberguide/the-magic-of-neopixels/>.
- [6] A. IDE, “Arduino IDE.” <https://www.arduino.cc/>.
- [7] “Teensy 4.0.” <https://www.pjrc.com/store/teensy40.html/>.
- [8] “OctoWS2811 Adaptor.” https://www.pjrc.com/store/octo28_adaptor.html/.
- [9] “OpenFrameworks.” <https://openframeworks.cc/>.
- [10] “Raspberry Pi 3 Model B+.” <https://www.raspberrypi.com/products/raspberry-pi-3-model-b/>.
- [11] “SuperCollider.” <https://supercollider.github.io/>.

Full Author List: IceCube Collaboration

R. Abbasi¹⁷, M. Ackermann⁶³, J. Adams¹⁸, S. K. Agarwalla^{40, 64}, J. A. Aguilar¹², M. Ahlers²², J.M. Alameddine²³, N. M. Amin⁴⁴, K. Andeen⁴², G. Anton²⁶, C. Argüelles¹⁴, Y. Ashida⁵³, S. Athanasiadou⁶³, S. N. Axani⁴⁴, X. Bai⁵⁰, A. Balagopal V.⁴⁰, M. Baricevic⁴⁰, S. W. Barwick³⁰, V. Basu⁴⁰, R. Bay⁸, J. J. Beatty^{20, 21}, J. Becker Tjus^{11, 65}, J. Beise⁶¹, C. Bellenghi²⁷, C. Benning¹, S. BenZvi⁵², D. Berley¹⁹, E. Bernardini⁴⁸, D. Z. Besson³⁶, E. Blaufuss¹⁹, S. Blot⁶³, F. Bontempo³¹, J. Y. Book¹⁴, C. Boscolo Meneguolo⁴⁸, S. Böser⁴¹, O. Botner⁶¹, J. Böttcher⁷, E. Bourbeau²², J. Braun⁴⁰, B. Brinson⁶, J. Brostean-Kaiser⁶³, R. T. Burley², R. S. Busse⁴³, D. Butterfield⁴⁰, M. A. Campana⁴⁹, K. Carloni¹⁴, E. G. Carnie-Bronca², S. Chattopadhyay^{40, 64}, N. Chau¹², C. Chen⁶, Z. Chen⁵⁵, D. Chirkin⁴⁰, S. Choi⁵⁶, B. A. Clark¹⁹, L. Classen⁴³, A. Coleman⁶¹, G. H. Collin¹⁵, A. Connolly^{20, 21}, J. M. Conrad¹⁵, P. Coppin¹³, P. Correa¹³, D. F. Cowen^{59, 60}, P. Dave⁶, C. De Clercq¹³, J. J. DeLaunay⁵⁸, D. Delgado¹⁴, S. Deng¹, K. Deoskar⁵⁴, A. Desai⁴⁰, P. Desati⁴⁰, K. D. de Vries¹³, G. de Wasseige³⁷, T. DeYoung²⁴, A. Diaz¹⁵, J. C. Díaz-Vélez⁴⁰, M. Dittmer⁴³, A. Domi²⁶, H. Dujmovic⁴⁰, M. A. DuVernois⁴⁰, T. Ehrhardt⁴¹, P. Eller²⁷, E. Ellinger⁶², S. El Mentawi¹, D. Elsässer²³, R. Engel^{31, 32}, H. Erpenbeck⁴⁰, J. Evans¹⁹, P. A. Evenson⁴⁴, K. L. Fan¹⁹, K. Fang⁴⁰, K. Farrag¹⁶, A. R. Fazzari⁷, A. Fedynitch⁵⁷, N. Feigl¹⁰, S. Fiedlschuster²⁶, C. Finley⁵⁴, L. Fischer⁶⁷, D. Fox⁵⁹, A. Frankowiak¹¹, A. Fritz⁴¹, P. Fürst¹, J. Gallagher³⁹, E. Ganster¹, A. Garcia¹⁴, L. Gerhardt⁹, A. Ghadimi⁵⁸, C. Glaser⁶¹, T. Glauch²⁷, T. Glusenkamp^{26, 61}, N. Goehke³², J. G. Gonzalez⁴⁴, S. Goswami⁵⁸, D. Grant²⁴, S. J. Gray¹⁹, O. Gries¹, S. Griffin⁴⁰, S. Griswold⁵², K. M. Groth²², C. Günther¹, P. Gutjahr²³, C. Haack²⁶, A. Hallgren⁶¹, R. Halliday²⁴, L. Halve¹, F. Halzen⁴⁰, H. Hamdaoui⁵⁵, M. Ha Minh²⁷, K. Hanson⁴⁰, J. Hardin¹⁵, A. A. Harnisch²⁴, P. Hatch³³, A. Haungs³¹, K. Helbing⁶², J. Hellrung¹¹, F. Henningsen²⁷, L. Heuermann¹, N. Heyer⁶¹, S. Hickford⁶², A. Hidvegi⁵⁴, C. Hill¹⁶, G. C. Hill², K. D. Hoffman¹⁹, S. Hori⁴⁰, K. Hoshina^{40, 66}, W. Hou³¹, T. Huber³¹, K. Hultqvist⁵⁴, M. Hünnefeld²³, R. Hussain⁴⁰, K. Hymon²³, S. In⁵⁶, A. Ishihara¹⁶, M. Jacquart¹⁶, O. Janik¹, M. Jansson⁵⁴, G. S. Japaridze⁵, M. Jeong⁵⁶, M. Jin¹⁴, B. J. P. Jones⁴, D. Kang³¹, W. Kang⁵⁶, X. Kang⁴⁹, A. Kappes⁴³, D. Kappesser⁴¹, L. Kardum²³, T. Karg⁶³, M. Karle²⁷, A. Karle⁴⁰, U. Katz²⁶, M. Kauer⁴⁰, J. L. Kelley⁴⁰, A. Khatee Zathul⁴⁰, A. Kheirandish^{34, 35}, J. Kiryluk⁵⁵, S. R. Klein^{8, 9}, A. Kochocki²⁴, R. Koirala⁴⁴, H. Kolanoski¹⁰, T. Kontrimas²⁷, L. Köpke⁴¹, C. Kopper²⁶, D. J. Koskinen²², P. Koundal³¹, M. Kovacevich⁴⁹, M. Kowalski^{10, 63}, T. Kozynets²², J. Krishnamoorthi^{40, 64}, K. Kruijswijk³⁷, E. Krupczak²⁴, A. Kumar⁶³, E. Kun¹¹, N. Kurahashi⁴⁹, N. Lad⁶³, C. Lagunas Gualda⁶³, M. Lamoureux³⁷, M. J. Larson¹⁹, S. Latseva¹, F. Lauber⁶², J. P. Lazar^{14, 40}, J. W. Lee⁵⁶, K. Leonard DeHolton⁶⁰, A. Leszczyńska⁴⁴, M. Lincetto¹¹, Q. R. Liu⁴⁰, M. Liubarska²⁵, E. Lohfink⁴¹, C. Love⁴⁹, C. J. Lozano Mariscal⁴³, L. Lu⁴⁰, F. Lucarelli²⁸, W. Luszczyk^{20, 21}, Y. Lyu^{8, 9}, J. Madsen⁴⁰, K. B. M. Mahn²⁴, Y. Makino⁴⁰, E. Manao²⁷, S. Mancina^{40, 48}, W. Marie Sainte⁴⁰, I. C. Mariş¹², S. Marka⁴⁶, Z. Marka⁴⁶, M. Marsee⁵⁸, I. Martinez-Soler¹⁴, R. Maruyama⁴⁵, F. Mayhew²⁴, T. McElroy²⁵, F. McNally³⁸, J. V. Mead²², K. Meagher⁴⁰, S. Mechbal⁶³, A. Medina²¹, M. Meier¹⁶, Y. Merckx¹³, L. Merten¹¹, J. Micallef²⁴, J. Mitchell⁷, T. Montaruli²⁸, R. W. Moore²⁵, Y. Morii¹⁶, R. Morse⁴⁰, M. Moulai⁴⁰, T. Mukherjee³¹, R. Naab⁶³, R. Nagai¹⁶, M. Nakos⁴⁰, U. Naumann⁶², J. Necker⁶³, A. Negi⁴, M. Neumann⁴³, H. Niederhausen²⁴, M. U. Nisa²⁴, A. Noell¹, A. Novikov⁴⁴, S. C. Nowicki²⁴, A. Obertacke Pollmann¹⁶, V. O'Dell⁴⁰, M. Oehler³¹, B. Oeyen²⁹, A. Olivas¹⁹, R. Ørsøe²⁷, J. Osborn⁴⁰, E. O'Sullivan⁶¹, H. Pandya⁴⁴, N. Park³³, G. K. Parker⁴, E. N. Paudel⁴⁴, L. Paul^{42, 50}, C. Pérez de los Heros⁶¹, J. Peterson⁴⁰, S. Philippen¹, A. Pizzuto⁴⁰, M. Plum⁵⁰, A. Pontén⁶¹, Y. Popovych⁴¹, M. Prado Rodriguez⁴⁰, B. Pries²⁴, R. Procter-Murphy¹⁹, G. T. Przybylski⁹, C. Raab³⁷, J. Riedel⁴⁰, K. Rawlins³, Z. Rechac⁴⁰, A. Rehman⁴⁴, P. Reichherzer¹¹, G. Renzi¹², E. Resconi²⁷, S. Reusch⁶³, W. Rhode²³, B. Riedel⁴⁰, A. Rifaie¹, E. J. Roberts², S. Robertson^{8, 9}, S. Rodan⁵⁶, G. Roellinghoff⁵⁶, M. Rongen²⁶, C. Rott^{53, 56}, T. Ruhe²³, L. Ruohan²⁷, D. Ryckbosch²⁹, I. Safa^{14, 40}, J. Saffer³², D. Salazar-Gallegos²⁴, P. Sampathkumar³¹, S. E. Sanchez Herrera²⁴, A. Sandrock⁶², M. Santander⁵⁸, S. Sarkar²⁵, S. Sarkar⁴⁷, J. Savelberg¹, P. Savina⁴⁰, M. Schaufel¹, H. Schieler³¹, S. Schindler²⁶, L. Schlickmann¹, B. Schlüter⁴³, F. Schlüter¹², N. Schmeisser⁶², T. Schmidt¹⁹, J. Schneider²⁶, F. G. Schröder^{31, 44}, L. Schumacher²⁶, G. Schwefer¹, S. Sclafani¹⁹, D. Seckel⁴⁴, M. Seikh³⁶, S. Seunarine⁵¹, R. Shah⁴⁹, A. Sharma⁶¹, S. Shefali³², N. Shimizu¹⁶, M. Silva⁴⁰, B. Skrzypek¹⁴, B. Smithers⁴, R. Snihur⁴⁰, J. Soedingrekso²³, A. Sogaard²², D. Soldin³², P. Soldin¹, G. Sommani¹¹, C. Spannfellner²⁷, G. M. Spiczak⁵¹, C. Spiering⁶³, M. Stamatikos²¹, T. Stanev⁴⁴, T. Stetzelberger⁹, T. Stürwald⁶², T. Stuttard²², G. W. Sullivan¹⁹, I. Taboada⁶, S. Ter-Antonyan⁷, M. Thiesmeyer¹, W. G. Thompson¹⁴, J. Thwaites⁴⁰, S. Tilav⁴⁴, K. Tollefson²⁴, C. Tönnis⁵⁶, S. Toscano¹², D. Tosi⁴⁰, A. Trettin⁶³, C. F. Tung⁶, R. Turcotte³¹, J. P. Twagirayezu²⁴, B. Ty⁴⁰, M. A. Unland Elorrieta⁴³, A. K. Upadhyay^{40, 64}, K. Uphaw⁷, N. Valtonen-Mattila⁶¹, J. Vandenbroucke⁴⁰, N. van Eijndhoven¹³, D. Vannerom¹⁵, J. van Santen⁶³, J. Vara⁴³, J. Veitch-Michaelis⁴⁰, M. Venugopal³¹, M. Vereecken³⁷, S. Verpoest⁴⁴, D. Veske⁴⁶, A. Vijai¹⁹, C. Walck⁵⁴, C. Weaver²⁴, P. Weigel¹⁵, A. Weindl³¹, J. Weldert⁶⁰, C. Wendt⁴⁰, J. Werthebach²³, M. Weyrauch³¹, N. Whitehorn²⁴, C. H. Wiebusch¹, N. Willey²⁴, D. R. Williams⁵⁸, L. Witthaus²³, A. Wolf¹, M. Wolf²⁷, G. Wrede²⁶, X. W. Xu⁷, J. P. Yanez²⁵, E. Yildizci⁴⁰, S. Yoshida¹⁶, R. Young³⁶, F. Yu¹⁴, S. Yu²⁴, T. Yuan⁴⁰, Z. Zhang⁵⁵, P. Zhelnin¹⁴, M. Zimmerman⁴⁰

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 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 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 Technical University of Munich, TUM School of Natural Sciences, Department of Physics, D-85748 Garching bei München, 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 Department of Physics & Astronomy, University of Nevada, Las Vegas, NV, 89154, USA
³⁵ Nevada Center for Astrophysics, University of Nevada, Las Vegas, NV 89154, USA
³⁶ Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
³⁷ Centre for Cosmology, Particle Physics and Phenomenology - CP3, Université catholique de Louvain, Louvain-la-Neuve, Belgium
³⁸ Department of Physics, Mercer University, Macon, GA 31207-0001, USA
³⁹ Dept. of Astronomy, University of Wisconsin–Madison, Madison, WI 53706, USA
⁴⁰ Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin–Madison, Madison, WI 53706, USA
⁴¹ Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany
⁴² Department of Physics, Marquette University, Milwaukee, WI, 53201, USA
⁴³ Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany
⁴⁴ Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
⁴⁵ Dept. of Physics, Yale University, New Haven, CT 06520, USA
⁴⁶ Columbia Astrophysics and Nevis Laboratories, Columbia University, New York, NY 10027, USA
⁴⁷ Dept. of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom
⁴⁸ Dipartimento di Fisica e Astronomia Galileo Galilei, Università Degli Studi di Padova, 35122 Padova PD, Italy
⁴⁹ Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA
⁵⁰ Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA
⁵¹ Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA
⁵² Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
⁵³ Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
⁵⁴ Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden
⁵⁵ Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
⁵⁶ Dept. of Physics, Sungkyunkwan University, Suwon 16419, Korea
⁵⁷ Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan
⁵⁸ Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
⁵⁹ Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
⁶⁰ Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA
⁶¹ Dept. of Physics and Astronomy, Uppsala University, Box 516, S-75120 Uppsala, Sweden
⁶² Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
⁶³ Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany
⁶⁴ Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India
⁶⁵ Department of Space, Earth and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden
⁶⁶ Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan

Acknowledgements

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, Wisconsin Alumni Research Foundation, Center for High Throughput Computing (CHTC) at the University of Wisconsin–Madison, Open Science

Grid (OSG), Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS), 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; 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 Compute 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); United Kingdom – Department of Physics, University of Oxford.