

# IceCat-2: Updated IceCube Event Catalog of Alert Tracks

## The IceCube Collaboration

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

*E-mail:* [azegarelli@icecube.wisc.edu](mailto:azegarelli@icecube.wisc.edu), [anna.franckowiak@icecube.wisc.edu](mailto:anna.franckowiak@icecube.wisc.edu),  
[sommani.giacomo@icecube.wisc.edu](mailto:sommani.giacomo@icecube.wisc.edu), [nora.valtonen-mattila@icecube.wisc.edu](mailto:nora.valtonen-mattila@icecube.wisc.edu),  
[tianlu.yuan@icecube.wisc.edu](mailto:tianlu.yuan@icecube.wisc.edu)

We present preliminary results for IceCat-2, the second public catalog of IceCat Alert Tracks, which plans to build and improve upon the first release, IceCat-1. The initial catalog, last updated in October 2023, included all real-time alerts issued since 2016, as well as events observed by IceCube since the start of full-detector data collection in 2011 that would have triggered an alert if the program had been in place at that time. IceCat-2 plans to expand on this by incorporating all additional alerts since IceCat-1, and reprocessing all events with significantly improved reconstruction algorithms. A key advancement in IceCat-2 will come from an updated reconstruction technique introduced by the IceCube Collaboration in September 2024. This approach substantially enhances the angular resolution of muon track alerts, while also improving statistical coverage. With respect to IceCat-1, the 50%(90%) angular uncertainty on track alerts is expected to be reduced by a factor of approximately 5(4). These refined reconstructions will allow us to revisit possible correlations between past alerts and sources in gamma-ray and X-ray catalogs. The enhanced precision may uncover new astrophysical associations with known astrophysical sources, offering deeper insight into potential cosmic ray accelerators.

**Corresponding authors:** Angela Zegarelli<sup>1\*</sup>, Anna Franckowiak<sup>1</sup>, Giacomo Sommani<sup>1</sup>, Nora Valtonen-Mattila<sup>1</sup>, Tianlu Yuan<sup>2</sup>

<sup>1</sup> *Ruhr-Universität Bochum, Germany*

<sup>2</sup> *University of Wisconsin–Madison, USA*

\* Presenter

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



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

## 1. Introduction

High-energy neutrinos play a crucial role in multimessenger astronomy by providing unique insights into cosmic ray (CR) accelerators. Unlike gamma ( $\gamma$ ) rays, which can originate from both leptonic and hadronic processes, neutrinos are unambiguous signatures of hadronic interactions. Produced through hadronuclear and photohadronic processes, they travel unimpeded by matter or magnetic fields and preserve directional information about their sources, making them ideal messengers for identifying distant astrophysical accelerators. Because of their extremely small interaction cross section, their detection is highly challenging, requiring kilometer-scale Cherenkov detectors embedded in natural transparent media such as ice or water. These detectors capture Cherenkov light emitted by secondary particles produced when neutrinos interact with nuclei and travel faster than the local speed of light in the medium.

The IceCube Neutrino Observatory at the South Pole [1], currently the largest operating neutrino telescope, made the first detection of a diffuse astrophysical neutrino flux in 2013 [2]. Since then, IceCube has provided strong evidence for extreme CR accelerators, likely of extragalactic origin, although no dominant source class has been conclusively identified. In the multimessenger framework, combining neutrino detections with electromagnetic (EM) and gravitational-wave observations is essential for locating and characterizing the sources of high-energy particles. Neutrinos offer precise timing and directional information that can guide follow-up searches for EM counterparts. Moreover, Cherenkov-based neutrino detectors continuously monitor the sky and can promptly notify the scientific community of interesting events.

IceCube has been operating a real-time alert system since 2016 [3]. Although the system includes multiple event types, the focus here is on track-like alerts. These events originate from charged-current interactions between muon neutrinos and quarks in the ice nuclei. Due to their excellent angular resolution, which improves with energy, track-like alerts are particularly valuable for neutrino astronomy. The system allows to rapidly notify the multimessenger community about likely astrophysical neutrino track-like events detected by IceCube, initiating follow-ups to detect source candidates. A major breakthrough occurred in September 2017, when a neutrino with an energy of approximately 300 TeV (IC-170922A) was found in spatial and temporal coincidence with the flaring blazar TXS 0506+056. This association, supported by  $\gamma$ -ray data from *Fermi*-LAT, had a significance of  $\sim 3\sigma$  [4]. Archival analysis revealed a possible earlier neutrino flare from the same source between September 2014 and March 2015, with a significance of  $3.5\sigma$  independent of the 2017 alert [5]. These observations demonstrate the potential of real-time multi-messenger astronomy.

In 2019, the real-time framework for track-like events was upgraded to improve event selection and alert message content [6]. Following this upgrade, IceCube released its first catalog of alert events, named *IceCat-1* [7]. This catalog includes all real-time alerts issued since 2016, and earlier events since 2011 that would have triggered an alert under the current system, and it was periodically updated until October 2023. A recent enhancement was introduced in September 2024 [8]. IceCube is adopting a revised follow-up reconstruction strategy that applies different algorithms based on the event's energy deposition or topology. This hybrid approach enhances angular resolution across a broad energy range and ensures robust statistical coverage of the reported localization uncertainties. Thus, an updated catalog, named *IceCat-2*, is now under processing.

Sec. 2 presents a preliminary overview of the IceCat-2 catalog, highlighting refined event selection criteria, the inclusion of newly processed alerts, and improvements in reconstruction. In relation to this, Sec. 2.1 provides a comparison with IceCat-1, focusing on directional estimates and associated uncertainties. In Sec. 3, we assess whether previously identified coincidences with candidate neutrino sources remain valid under the new reconstruction. Preliminary results from a cross-correlation with known gamma-ray catalogs are presented in Sec. 4. A summary is given in Sec. 5.

## 2. IceCat-2: Updated IceCube Event Catalog of Alert Tracks

We present a preliminary overview of the IceCat-2 catalog, which updates and extends the previous IceCat-1 collection of likely astrophysical neutrino track-like events detected by IceCube. The main features of IceCat-2 are:

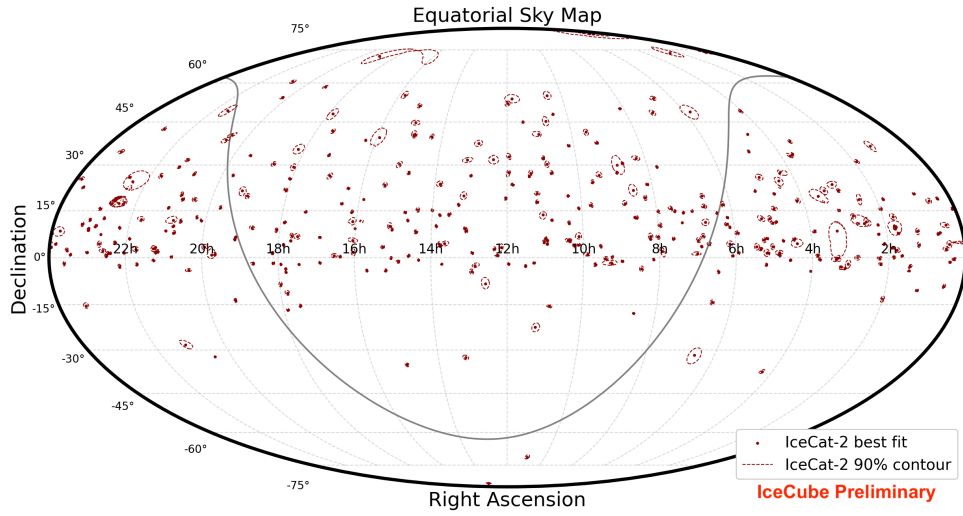
- Reconstructed directions for all IceCat-1 events have been updated using the latest reconstruction algorithms, implemented in the real-time alert system since September 2024.
- Events likely caused by atmospheric muons or other background sources have been excluded from the sample. Since October 2022, a *veto* method has been used to reject atmospheric muons that might pass the alert selection criteria. This veto utilizes IceTop, an array of ice-Cherenkov tanks located on the surface, to detect CR-induced air showers accompanying track-like events observed in the ice. As a result, the refined IceCat-1 dataset contains 340 events out of the original 348<sup>1</sup>.
- Inclusion of additional track-like alerts since the last IceCat-1 update in October 2023, extending the catalog coverage up to January 2, 2025 (IC-250102A). This results in 25 additional events compared to the last IceCat-1 update. Alerts occurring before September 29, 2024 were originally reconstructed with older algorithms and have now been reprocessed using the latest reconstruction framework.
- Reprocessing of all events (both the original IceCat-1 and the additional alerts) using the most up-to-date data processing framework and calibrations to ensure a uniform and refined dataset.

The preliminary IceCat-2 catalog includes 365 track-like alerts, with their sky distribution shown in Fig. 1. Issued at an average rate of 26.8 events per year,  $\sim 9.9$  and 17 fall into the Gold and Bronze channels, corresponding to average astrophysical probabilities of 50% and 30%, assuming a power-law spectrum with index 2.19. This selection, adopted in IceCat-1 and currently used in real-time alerts, is based on an earlier IceCube measurement. Future versions of the catalog will incorporate an updated spectral index value, reflecting the softer spectrum observed in muon track events by IceCube. The impact of this change will be investigated in forthcoming studies.

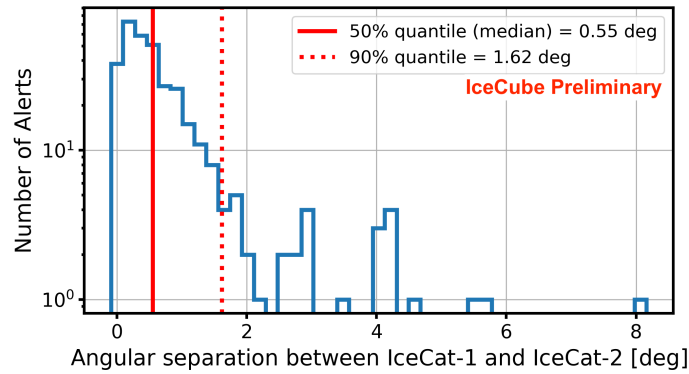
### 2.1 Comparison of IceCat-2 with IceCat-1

Due to the updates introduced in the IceCat-2 processing pipeline, described in Sec. 2, the new catalog significantly improved the directional reconstruction of neutrino events. For a detailed description of the updated reconstruction algorithms used in this work, we refer to [9–11], which focuses on the new reconstruction approach and outlines improvements in directional precision and the treatment of systematic uncertainties.

<sup>1</sup>IceCat-1 included vetoed events because the cosmic-ray veto criteria were introduced after the catalog compilation.



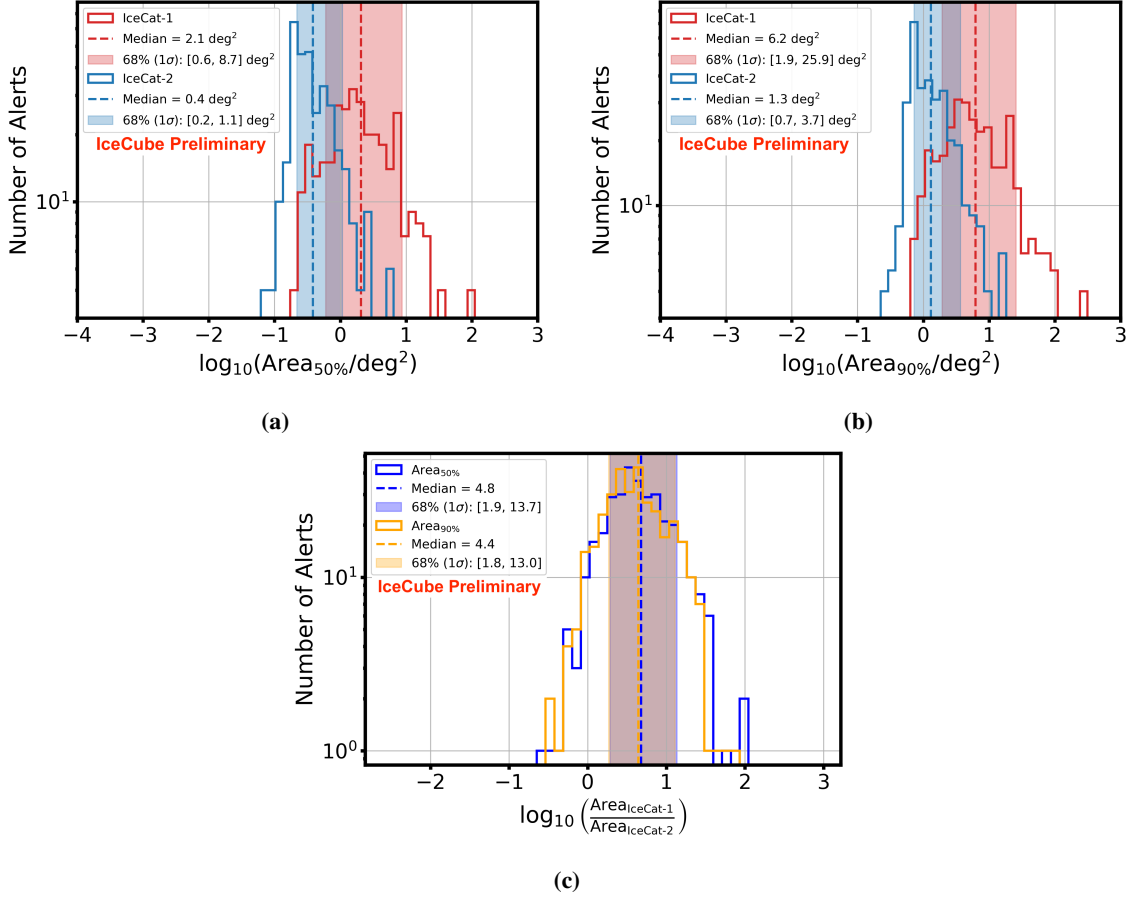
**Figure 1:** The all-sky distribution of alerts from the IceCat-2 catalog in equatorial coordinates, including the corresponding 90% containment contours. The thin line indicates the location of the Galactic Plane.



**Figure 2:** Difference in reconstructed directions for IceCat-1 events reprocessed in the IceCat-2 sample ( $N = 340$ , excluding vetoed events). The red solid and dashed lines indicate the 50% (median) and 90% quantiles of angular separations, respectively.

Fig. 2 shows the difference in reconstructed directions for IceCat-1 events reprocessed in the IceCat-2 sample, with 50(90)% of the alerts with angular separation below 0.55(1.62) deg. The most notable improvement is the significant reduction in localization uncertainties around the best-fit direction, as illustrated in Fig. 3. In particular, Figs. 3a and 3b show that the median areas of the 50% and 90% containment contours in IceCat-2 are reduced by factors of approximately 5 and 4, respectively, compared to IceCat-1 (see also Fig. 3c). Furthermore, the distributions are considerably narrower, with the spread around the median, quantified by the standard deviation  $\sigma$ , reduced by a factor between 7 and 9. Small containment errors around best-fit directions are also evident in Fig. 1, which shows the all-sky distribution of alerts from the IceCat-2 catalog in equatorial coordinates, including the corresponding 90% containment contours.

This substantial gain in angular precision directly enhances the efficiency of EM and multi-messenger follow-up observations, increasing the chances of identifying astrophysical counterparts



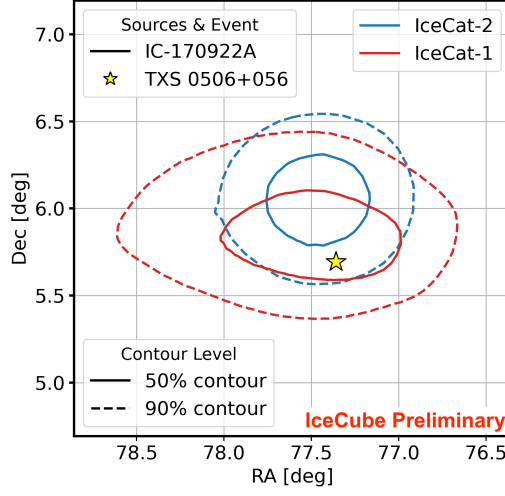
**Figure 3:** Comparison of IceCat-1 and IceCat-2 containment performance: (a)–(b): Distributions of 50% and 90% containment areas for IceCat-1 (red) and IceCat-2 (blue). (c): Ratio of IceCat-1 to IceCat-2 areas at 50% (blue) and 90% (orange). Dashed lines mark medians, and shaded regions represent the corresponding 68% quantile intervals.

and advancing the search for CR accelerators. In Sec. 3, we revisit the spatial coincidences with several potential high-energy neutrino sources previously identified through IceCube track alerts, now evaluated again in light of the updated reconstructions and improved uncertainty estimates.

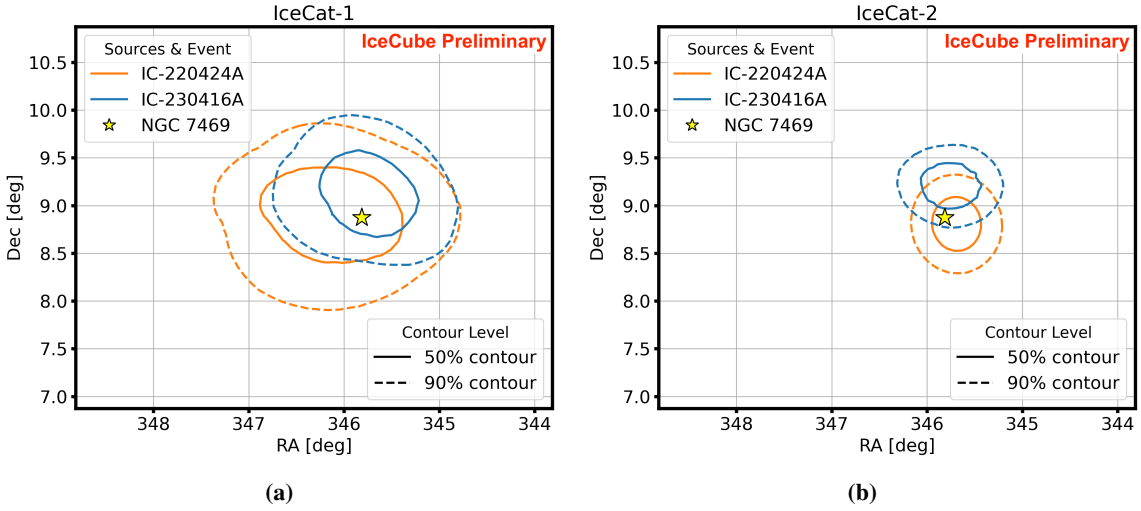
### 3. Revision of spatial coincidences with relevant sources

Over the years, several candidate sources of high-energy astrophysical neutrinos have been identified through IceCube track-like alerts. Among the most prominent is TXS 0506+056, a blazar that gained significant attention following the detection of a high-energy neutrino (IC-170922A) in spatial and temporal coincidence with a gamma-ray flare from this source [4]. This marked the first compelling multimessenger association between a neutrino and an astrophysical object, providing evidence that blazars can act as CR accelerators. As shown in Fig. 4, TXS 0506+056 remains spatially coincident with the revised IC-170922A localization, although it now lies within the 90% containment region rather than the 50% contour.

Another notable candidate is the Seyfert galaxy NGC 7469, proposed as a potential neutrino emitter based on its directional coincidence with two IceCube alerts (IC-220424A and IC-230416A) [12]. The chance probability of both neutrinos being spatially coincident with NGC 7469 was



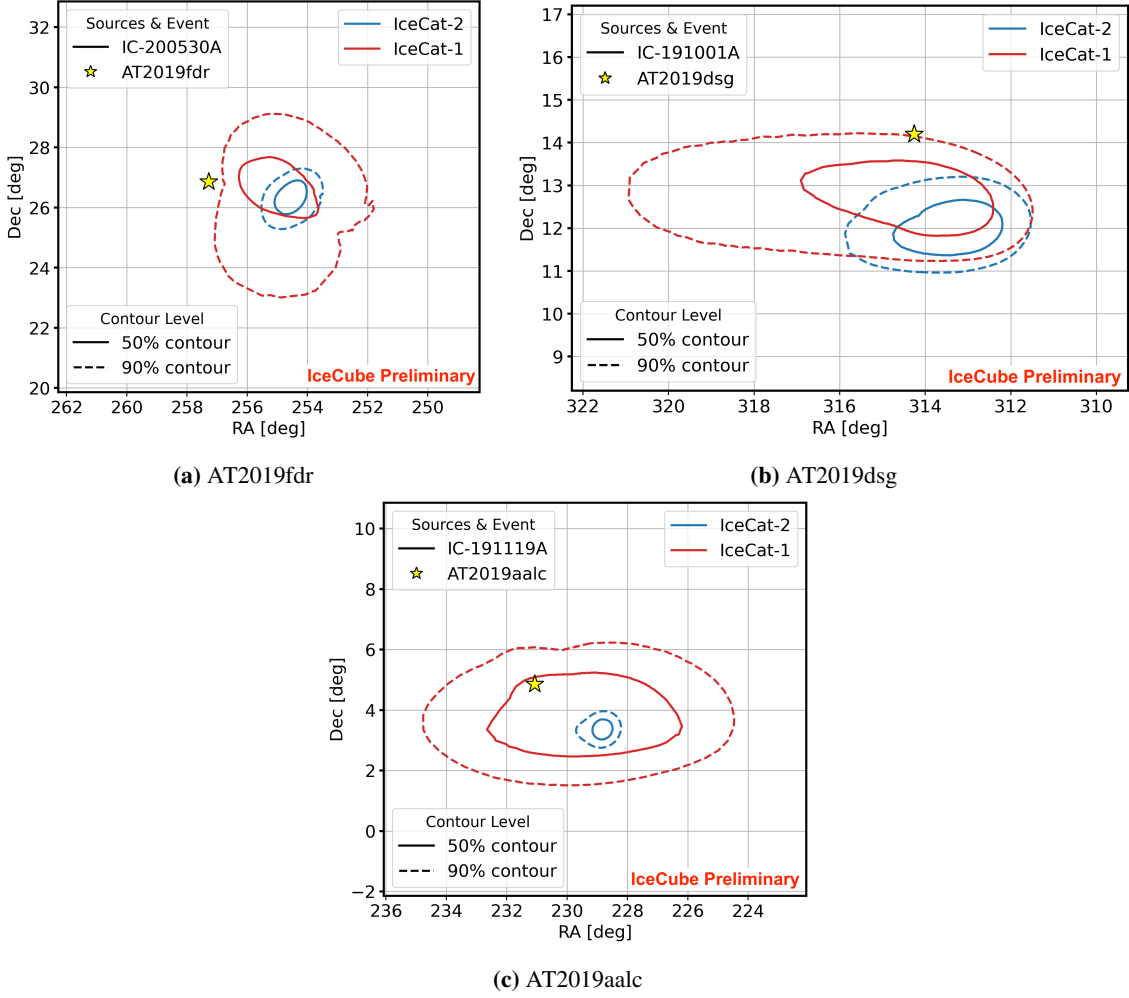
**Figure 4:** Sky map showing spatial coincidences between IC-170922A and TXS0506+056 (yellow star). The tighter angular reconstruction contours highlight improvements in event localization from IceCat-1 (in red) to IceCat-2 (in blue), with solid and dashed lines representing the 50% and 90% containment regions, respectively.



**Figure 5:** Sky maps showing spatial coincidences between IC-220424A (in orange) and IC-230416A (in blue), and NGC 7469 (yellow star). Solid and dashed lines represent the 50% and 90% containment regions, respectively. Panels (a) and (b) display the contours of the two alerts in IceCat-1 and IceCat-2, respectively.

estimated to correspond to a  $3.2\sigma$  significance. Panels (a) and (b) of Fig. 5 show the position of NGC 7469 relative to IC-220424A and IC-230416A in IceCat-1 and IceCat-2, respectively. While the contour areas around the best-fit directions for the track alerts are significantly reduced in IceCat-2, the source position is still contained within the contours of both neutrino alerts.

Additionally, a few tidal disruption event (TDE) candidates (e.g., AT2019dsg, AT2019fdr, and AT2019aalc) have been associated in recent years with IceCube track alerts through multimessenger follow-up searches [13–15]. In each case, the neutrino detection occurred approximately 100 days



**Figure 6:** Sky maps showing spatial coincidences between IceCat track alerts and several TDEs (yellow stars). Each panel highlights improvements in event localization from IceCat-1 (red) to IceCat-2 (blue), with solid and dashed lines showing the 50% and 90% containment regions, respectively.

after the peak of the optical–ultraviolet luminosity. In some of these associations, the TDE positions were located near the edge of the neutrino localization contours, leaving room for uncertainty. Thanks to the improved reconstructions provided by IceCat-2, these associations can now be revisited with greater accuracy. We find that the TDE positions are, in all cases, well outside the updated containment regions, effectively ruling out an association with the corresponding IceCube alerts (see Fig. 6).

#### 4. Search for correlation with potential source candidates for association

Following the approach previously adopted for IceCat-1, we also re-evaluated the directional correlation of the updated alert tracks with several gamma-ray catalogs (3FHL, 4FGL-DR4, 3HWC, TeVCat) as well as the Swift-BAT X-ray catalog. For each of the 365 alerts in the preliminary IceCat-2 sample, we searched the aforementioned catalogs for sources located within the 90% uncertainty contour of the alert’s updated reconstructed direction. In addition, to estimate the number of

Catalog	Observed Coincidences	Expected Coincidences
4FGL-DR4	93	89
3FHL	29	28
3HWC	2	2
TeVcat	6	5
Swift-BAT	35	32

**Table 1:** Observed number of alerts containing a catalog source within the 90% error contours, and the number expected from random coincidences.

coincidences expected by chance, we randomized the alert directions in right ascension 1000 times and recorded the number of matches for each iteration. For each catalog, we find that the number of coincidences is consistent with the median expectation due to chance correlation (see Tab. 1). The reduced number of expected coincidences with respect to IceCat-1 [7] is consistent with the significant improvement in directional reconstruction introduced in IceCat-2.

## 5. Summary

To enhance multi-messenger capabilities, IceCube has developed an improved reconstruction method for its real-time alert system. As a result, the original IceCube Event Catalog of Alert Tracks (IceCat-1) has been revised. IceCat-2 incorporates the new reconstructions, updated calibrations, exclusion of likely CR-induced events, and new alerts since the last release. We present the preliminary IceCat-2 catalog, which contains 365 track-like alerts from May 2011 (IC-110514A) to January 2, 2025 (IC-250102A). Studies of spatial correlations with astrophysical sources will take advantage of IceCat-2 significantly (e.g., [16]). Notably, it improves the angular uncertainty areas by a factor  $\sim 5$ , with median 50% and 90% containment areas of 0.4 and 1.3 square degrees, respectively. A public release of the full catalog will follow a peer-reviewed publication, alongside several analyses on source population correlations.

## References

- [1] **IceCube** Collaboration, M. Abbasi *et al.*, *NIMPR A* **601** no. 3, (Apr., 2009) 294–316.
- [2] **IceCube** Collaboration, M. G. Aartsen *et al.*, *Science* **342** no. 6161, (Nov., 2013) 1242856.
- [3] **IceCube** Collaboration, M. G. Aartsen *et al.*, *JINST* **12** no. 03, (2017) P03012.
- [4] **IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift NuSTAR, VERITAS, VLA/17B-403** Collaboration, M. G. Aartsen *et al.*, *Science* **361** no. 6398, (July, 2018) eaat1378.
- [5] **IceCube** Collaboration, M. G. Aartsen *et al.*, *Science* **361** no. 6398, (July, 2018) 147–151.
- [6] **IceCube** Collaboration, E. Blaufuss, T. Kintscher, L. Lu, and C. F. Tung, *PoS ICRC2019* (2019) 1021.
- [7] **IceCube** Collaboration, R. Abbasi *et al.*, *ApJS* **269** no. 1, (Nov., 2023) 25.
- [8] **IceCube** Collaboration, *GRB Coordinates Network* **37625** (Sept., 2024) 1.
- [9] **IceCube** Collaboration, G. Sommani, C. Lagunas Gualda, and H. Niederhausen, *PoS ICRC2023* (2023) 1186.
- [10] **IceCube** Collaboration, T. Yuan, *PoS ICRC2023* (2023) 1005.
- [11] **IceCube** Collaboration, G. Sommani and T. Yuan, *PoS ICRC2025* (2025) 1184.
- [12] G. Sommani, A. Franckowiak, M. Lincetto, and R.-J. Dettmar, *ApJ* **981** no. 2, (Mar., 2025) 103.
- [13] R. Stein *et al.*, *Nature Astronomy* **5** (Feb., 2021) 510–518.
- [14] S. Reusch *et al.*, *PRL* **128** no. 22, (June, 2022) 221101.
- [15] S. van Velzen *et al.*, *MNRAS* **529** no. 3, (Feb., 2024) 2559–2576.
- [16] **IceCube** Collaboration, T. Pernice and G. Sommani, *PoS ICRC2025* (2025) 1145.



## Full Author List: IceCube Collaboration

R. Abbasi<sup>16</sup>, M. Ackermann<sup>63</sup>, J. Adams<sup>17</sup>, S. K. Agarwalla<sup>39, a</sup>, J. A. Aguilar<sup>10</sup>, M. Ahlers<sup>21</sup>, J.M. Alameddine<sup>22</sup>, S. Ali<sup>35</sup>, N. M. Amin<sup>43</sup>, K. Andeen<sup>41</sup>, C. Argüelles<sup>13</sup>, Y. Ashida<sup>52</sup>, S. Athanasiadou<sup>63</sup>, S. N. Axani<sup>43</sup>, R. Babu<sup>23</sup>, X. Bai<sup>49</sup>, J. Baines-Holmes<sup>39</sup>, A. Balagopal V.<sup>39, 43</sup>, S. W. Barwick<sup>29</sup>, S. Bash<sup>26</sup>, V. Basu<sup>52</sup>, R. Bay<sup>6</sup>, J. J. Beatty<sup>19, 20</sup>, J. Becker Tjus<sup>9, b</sup>, P. Behrens<sup>1</sup>, J. Beise<sup>61</sup>, C. Bellenghi<sup>26</sup>, B. Benkel<sup>63</sup>, S. BenZvi<sup>51</sup>, D. Berley<sup>18</sup>, E. Bernardini<sup>47, c</sup>, D. Z. Besson<sup>35</sup>, E. Blaufuss<sup>18</sup>, L. Bloom<sup>58</sup>, S. Blot<sup>63</sup>, I. Bodo<sup>39</sup>, F. Bontempo<sup>30</sup>, J. Y. Book Motzkin<sup>13</sup>, C. Boscolo Meneguolo<sup>47, c</sup>, S. Böser<sup>40</sup>, O. Botner<sup>61</sup>, J. Böttcher<sup>1</sup>, J. Braun<sup>39</sup>, B. Brinson<sup>4</sup>, Z. Brisson-Tsavoussis<sup>32</sup>, R. T. Burley<sup>2</sup>, D. Butterfield<sup>39</sup>, M. A. Campana<sup>48</sup>, K. Carloni<sup>13</sup>, J. Carpio<sup>33, 34</sup>, S. Chattopadhyay<sup>39, a</sup>, N. Chau<sup>10</sup>, Z. Chen<sup>55</sup>, D. Chirkin<sup>39</sup>, S. Choi<sup>52</sup>, B. A. Clark<sup>18</sup>, A. Coleman<sup>61</sup>, P. Coleman<sup>1</sup>, G. H. Collin<sup>14</sup>, D. A. Coloma Borja<sup>47</sup>, A. Connolly<sup>19, 20</sup>, J. M. Conrad<sup>14</sup>, R. Corley<sup>52</sup>, D. F. Cowen<sup>59, 60</sup>, C. De Clercq<sup>11</sup>, J. J. DeLaunay<sup>59</sup>, D. Delgado<sup>13</sup>, T. Delmeulle<sup>10</sup>, S. Deng<sup>1</sup>, P. Desiati<sup>39</sup>, K. D. de Vries<sup>11</sup>, G. de Wasseige<sup>36</sup>, T. DeYoung<sup>23</sup>, J. C. Díaz-Vélez<sup>39</sup>, S. DiKerby<sup>23</sup>, M. Dittmer<sup>42</sup>, A. Domi<sup>25</sup>, L. Draper<sup>52</sup>, L. Dueser<sup>1</sup>, D. Durnford<sup>24</sup>, K. Dutta<sup>40</sup>, M. A. DuVernois<sup>39</sup>, T. Ehrhardt<sup>40</sup>, L. Eidenschink<sup>26</sup>, A. Eimer<sup>25</sup>, P. Eller<sup>26</sup>, E. Ellinger<sup>62</sup>, D. Elsässer<sup>22</sup>, R. Engel<sup>30, 31</sup>, H. Erpenbeck<sup>39</sup>, W. Esmail<sup>42</sup>, S. Eulig<sup>13</sup>, J. Evans<sup>18</sup>, P. A. Evenson<sup>43</sup>, K. L. Fan<sup>18</sup>, K. Fang<sup>39</sup>, K. Farrag<sup>15</sup>, A. R. Fazely<sup>5</sup>, A. Fedynitch<sup>57</sup>, N. Feigl<sup>8</sup>, C. Finley<sup>54</sup>, L. Fischer<sup>63</sup>, D. Fox<sup>59</sup>, A. Franckowiak<sup>9</sup>, S. Fukami<sup>63</sup>, P. Fürst<sup>1</sup>, J. Gallagher<sup>38</sup>, E. Ganster<sup>1</sup>, A. Garcia<sup>13</sup>, M. Garcia<sup>43</sup>, G. Garg<sup>39, a</sup>, E. Genton<sup>13, 36</sup>, L. Gerhardt<sup>7</sup>, A. Ghadimi<sup>58</sup>, C. Glaser<sup>61</sup>, T. Glüsenkamp<sup>61</sup>, J. G. Gonzalez<sup>43</sup>, S. Goswami<sup>33, 34</sup>, A. Granados<sup>23</sup>, D. Grant<sup>12</sup>, S. J. Gray<sup>18</sup>, S. Griffin<sup>39</sup>, S. Griswold<sup>51</sup>, K. M. Groth<sup>21</sup>, D. Guevel<sup>39</sup>, C. Günther<sup>1</sup>, P. Gutjahr<sup>22</sup>, C. Ha<sup>53</sup>, C. Haack<sup>25</sup>, A. Hallgren<sup>61</sup>, L. Halve<sup>1</sup>, F. Halzen<sup>39</sup>, L. Hamacher<sup>1</sup>, M. Ha Minh<sup>26</sup>, M. Handt<sup>1</sup>, K. Hanson<sup>39</sup>, J. Hardin<sup>14</sup>, A. A. Harnisch<sup>23</sup>, P. Hatch<sup>32</sup>, A. Haungs<sup>30</sup>, J. Häßler<sup>1</sup>, K. Helbing<sup>62</sup>, J. Hellrung<sup>9</sup>, B. Henke<sup>23</sup>, L. Hennig<sup>25</sup>, F. Henningsen<sup>12</sup>, L. Heuermann<sup>1</sup>, R. Hewett<sup>17</sup>, N. Heyer<sup>61</sup>, S. Hickford<sup>62</sup>, A. Hidvegi<sup>54</sup>, C. Hill<sup>15</sup>, G. C. Hill<sup>2</sup>, R. Hmaid<sup>15</sup>, K. D. Hoffman<sup>18</sup>, D. Hooper<sup>39</sup>, S. Hori<sup>39</sup>, K. Hoshina<sup>39, d</sup>, M. Hostert<sup>13</sup>, W. Hou<sup>30</sup>, T. Huber<sup>30</sup>, K. Hultqvist<sup>54</sup>, K. Hymon<sup>22, 57</sup>, A. Ishihara<sup>15</sup>, W. Iwakiri<sup>15</sup>, M. Jacquart<sup>21</sup>, S. Jain<sup>39</sup>, O. Janik<sup>25</sup>, M. Jansson<sup>36</sup>, M. Jeong<sup>52</sup>, M. Jin<sup>13</sup>, N. Kamp<sup>13</sup>, D. Kang<sup>30</sup>, W. Kang<sup>48</sup>, X. Kang<sup>48</sup>, A. Kappes<sup>42</sup>, L. Kardum<sup>22</sup>, T. Karg<sup>63</sup>, M. Karl<sup>26</sup>, A. Karle<sup>39</sup>, A. Katil<sup>24</sup>, M. Kauer<sup>39</sup>, J. L. Kelley<sup>39</sup>, M. Khanal<sup>52</sup>, A. Khatee Zathul<sup>39</sup>, A. Kheirandish<sup>33, 34</sup>, H. Kimku<sup>53</sup>, J. Kiryluk<sup>55</sup>, C. Klein<sup>25</sup>, S. R. Klein<sup>6, 7</sup>, Y. Kobayashi<sup>15</sup>, A. Kochocki<sup>23</sup>, R. Koirala<sup>43</sup>, H. Kolanoski<sup>8</sup>, T. Kontrimas<sup>26</sup>, L. Köpke<sup>40</sup>, C. Kopper<sup>25</sup>, D. J. Koskinen<sup>21</sup>, P. Koundal<sup>43</sup>, M. Kowalski<sup>8, 63</sup>, T. Kozyrnets<sup>21</sup>, N. Krieger<sup>9</sup>, J. Krishnamoorthi<sup>39, a</sup>, T. Krishnan<sup>13</sup>, K. Kruijswijk<sup>36</sup>, E. Krupczak<sup>23</sup>, A. Kumar<sup>63</sup>, E. Kun<sup>9</sup>, N. Kurahashi<sup>48</sup>, N. Lad<sup>63</sup>, C. Lagunas Gualda<sup>26</sup>, L. Lallement Arnaud<sup>10</sup>, M. Lamoureux<sup>36</sup>, M. J. Larson<sup>18</sup>, F. Lauber<sup>62</sup>, J. P. Lazar<sup>36</sup>, K. Leonard DeHolton<sup>60</sup>, A. Leszczyńska<sup>43</sup>, J. Liao<sup>4</sup>, C. Lin<sup>43</sup>, Y. T. Liu<sup>60</sup>, M. Liubarska<sup>24</sup>, C. Love<sup>48</sup>, L. Lu<sup>39</sup>, F. Lucarelli<sup>27</sup>, W. Luszczyk<sup>19, 20</sup>, Y. Lyu<sup>6, 7</sup>, J. Madsen<sup>39</sup>, E. Magnus<sup>11</sup>, K. B. M. Mahn<sup>23</sup>, Y. Makino<sup>39</sup>, E. Manao<sup>26</sup>, S. Mancina<sup>47, e</sup>, A. Mand<sup>39</sup>, I. C. Mariş<sup>10</sup>, S. Marka<sup>45</sup>, Z. Marka<sup>45</sup>, L. Marten<sup>1</sup>, I. Martinez-Soler<sup>13</sup>, R. Maruyama<sup>44</sup>, J. Mauro<sup>36</sup>, F. Mayhew<sup>23</sup>, F. McNally<sup>37</sup>, J. V. Mead<sup>21</sup>, K. Meagher<sup>39</sup>, S. Mechbal<sup>63</sup>, A. Medina<sup>20</sup>, M. Meier<sup>15</sup>, Y. Merckx<sup>11</sup>, L. Merten<sup>9</sup>, J. Mitchell<sup>5</sup>, L. Molchany<sup>49</sup>, T. Montaruli<sup>27</sup>, R. W. Moore<sup>24</sup>, Y. Morii<sup>15</sup>, A. Mosbrugger<sup>25</sup>, M. Moulai<sup>39</sup>, D. Mousadi<sup>63</sup>, E. Moyaux<sup>36</sup>, T. Mukherjee<sup>30</sup>, R. Naab<sup>63</sup>, M. Nakos<sup>39</sup>, U. Naumann<sup>62</sup>, J. Necker<sup>63</sup>, L. Neste<sup>54</sup>, M. Neumann<sup>42</sup>, H. Niederhausen<sup>23</sup>, M. U. Nisa<sup>23</sup>, K. Noda<sup>15</sup>, A. Noell<sup>1</sup>, A. Novikov<sup>43</sup>, A. Obertacke Pollmann<sup>15</sup>, V. O'Dell<sup>39</sup>, A. Olivias<sup>18</sup>, R. Orsoe<sup>26</sup>, J. Osborn<sup>39</sup>, E. O'Sullivan<sup>61</sup>, V. Palusova<sup>40</sup>, H. Pandya<sup>43</sup>, A. Parenti<sup>10</sup>, N. Park<sup>32</sup>, V. Parrish<sup>23</sup>, E. N. Paudel<sup>58</sup>, L. Paul<sup>49</sup>, C. Pérez de los Heros<sup>61</sup>, T. Pernice<sup>63</sup>, J. Peterson<sup>39</sup>, M. Plum<sup>49</sup>, A. Pontén<sup>61</sup>, V. Poojyam<sup>58</sup>, Y. Popovych<sup>40</sup>, M. Prado Rodriguez<sup>39</sup>, B. Pries<sup>23</sup>, R. Procter-Murphy<sup>18</sup>, G. T. Przybylski<sup>7</sup>, L. Pyras<sup>52</sup>, C. Raab<sup>36</sup>, J. Rack-Helleis<sup>40</sup>, N. Rad<sup>63</sup>, M. Ravn<sup>61</sup>, K. Rawlins<sup>3</sup>, Z. Rechav<sup>39</sup>, A. Rehman<sup>43</sup>, I. Reinstroffer<sup>49</sup>, E. Resconi<sup>26</sup>, S. Reusch<sup>63</sup>, C. D. Rho<sup>56</sup>, W. Rhode<sup>22</sup>, L. Ricca<sup>36</sup>, B. Riedel<sup>39</sup>, A. Rifaie<sup>62</sup>, E. J. Roberts<sup>2</sup>, S. Robertson<sup>6, 7</sup>, M. Rongen<sup>25</sup>, A. Rosted<sup>15</sup>, C. Rott<sup>52</sup>, T. Ruhe<sup>22</sup>, L. Ruohan<sup>26</sup>, D. Ryckbosch<sup>28</sup>, J. Saffer<sup>31</sup>, D. Salazar-Gallegos<sup>23</sup>, P. Sampathkumar<sup>30</sup>, A. Sandrock<sup>62</sup>, G. Sanger-Johnson<sup>23</sup>, M. Santander<sup>58</sup>, S. Sarkar<sup>46</sup>, J. Savelberg<sup>1</sup>, M. Scarnera<sup>36</sup>, P. Schaile<sup>26</sup>, M. Schaufel<sup>1</sup>, H. Schieler<sup>30</sup>, S. Schindler<sup>25</sup>, L. Schlickmann<sup>40</sup>, B. Schlüter<sup>42</sup>, F. Schlüter<sup>10</sup>, N. Schmeisser<sup>62</sup>, T. Schmidt<sup>18</sup>, F. G. Schröder<sup>30, 43</sup>, L. Schumacher<sup>25</sup>, S. Schwirn<sup>1</sup>, S. Sclafani<sup>18</sup>, D. Seckel<sup>43</sup>, L. Seen<sup>39</sup>, M. Seikh<sup>35</sup>, S. Seunarine<sup>50</sup>, P. A. Sevle Myhr<sup>36</sup>, R. Shah<sup>48</sup>, S. Shefali<sup>31</sup>, N. Shimizu<sup>15</sup>, B. Skrzypek<sup>6</sup>, R. Snihur<sup>39</sup>, J. Soedingrekso<sup>22</sup>, A. Sjøgaard<sup>21</sup>, D. Soldin<sup>52</sup>, P. Soldin<sup>1</sup>, G. Sommani<sup>9</sup>, C. Spannfellner<sup>26</sup>, G. M. Spiczak<sup>50</sup>, C. Spiering<sup>63</sup>, J. Stachurska<sup>28</sup>, M. Stamatikos<sup>20</sup>, T. Stanev<sup>43</sup>, T. Stezelberger<sup>7</sup>, T. Stürwald<sup>62</sup>, T. Stuttard<sup>21</sup>, G. W. Sullivan<sup>18</sup>, I. Taboada<sup>4</sup>, S. Ter-Antonyan<sup>5</sup>, A. Terliuk<sup>26</sup>, A. Thakuri<sup>49</sup>, M. Thiesmeyer<sup>39</sup>, W. G. Thompson<sup>13</sup>, J. Thwaites<sup>39</sup>, S. Tilav<sup>43</sup>, K. Tollefson<sup>23</sup>, S. Toscano<sup>10</sup>, D. Tosi<sup>39</sup>, A. Trettin<sup>63</sup>, A. K. Upadhyay<sup>39, a</sup>, K. Upshaw<sup>5</sup>, A. Vaidyanathan<sup>41</sup>, N. Valtonen-Mattila<sup>9, 61</sup>, J. Valverde<sup>41</sup>, J. Vandenbroucke<sup>39</sup>, T. van Eeden<sup>63</sup>, N. van Eijndhoven<sup>11</sup>, L. van Rootselaar<sup>22</sup>, J. van Santen<sup>63</sup>, F. J. Vara Carbonell<sup>42</sup>, F. Varsi<sup>31</sup>, M. Venugopal<sup>30</sup>, M. Vereecken<sup>36</sup>, S. Vergara Carrasco<sup>17</sup>, S. Verpoest<sup>43</sup>, D. Veske<sup>45</sup>, A. Vijai<sup>18</sup>, J. Villarreal<sup>14</sup>, C. Walck<sup>54</sup>, A. Wang<sup>4</sup>, E. Warrick<sup>58</sup>, C. Weaver<sup>23</sup>, P. Weigel<sup>14</sup>, A. Weindl<sup>30</sup>, J. Weldert<sup>40</sup>, A. Y. Wen<sup>13</sup>, C. Wendt<sup>39</sup>, J. Werthebach<sup>22</sup>, M. Weyrauch<sup>30</sup>, N. Whitehorn<sup>23</sup>, C. H. Wiebusch<sup>1</sup>, D. R. Williams<sup>58</sup>, L. Witthaus<sup>22</sup>, M. Wolf<sup>26</sup>, G. Wrede<sup>25</sup>, X. W. Xu<sup>5</sup>, J. P. Yañez<sup>24</sup>, Y. Yao<sup>39</sup>, E. Yildizci<sup>39</sup>, S. Yoshida<sup>15</sup>, R. Young<sup>35</sup>, F. Yu<sup>13</sup>, S. Yu<sup>52</sup>, T. Yuan<sup>39</sup>, A. Zegarelli<sup>9</sup>, S. Zhang<sup>23</sup>, Z. Zhang<sup>55</sup>, P. Zhelmin<sup>13</sup>, P. Zilberman<sup>39</sup>

<sup>1</sup> III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany

<sup>2</sup> Department of Physics, University of Adelaide, Adelaide, 5005, Australia

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

<sup>4</sup> School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA

<sup>5</sup> Dept. of Physics, Southern University, Baton Rouge, LA 70813, USA

<sup>6</sup> Dept. of Physics, University of California, Berkeley, CA 94720, USA

<sup>7</sup> Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

<sup>8</sup> Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany

<sup>9</sup> Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany

<sup>10</sup> Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium

- <sup>11</sup> Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium  
<sup>12</sup> Dept. of Physics, Simon Fraser University, Burnaby, BC V5A 1S6, Canada  
<sup>13</sup> Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA  
<sup>14</sup> Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA  
<sup>15</sup> Dept. of Physics and The International Center for Hadron Astrophysics, Chiba University, Chiba 263-8522, Japan  
<sup>16</sup> Department of Physics, Loyola University Chicago, Chicago, IL 60660, USA  
<sup>17</sup> Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand  
<sup>18</sup> Dept. of Physics, University of Maryland, College Park, MD 20742, USA  
<sup>19</sup> Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA  
<sup>20</sup> Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA  
<sup>21</sup> Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark  
<sup>22</sup> Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany  
<sup>23</sup> Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA  
<sup>24</sup> Dept. of Physics, University of Alberta, Edmonton, Alberta, T6G 2E1, Canada  
<sup>25</sup> Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany  
<sup>26</sup> Physik-department, Technische Universität München, D-85748 Garching, Germany  
<sup>27</sup> Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland  
<sup>28</sup> Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium  
<sup>29</sup> Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, USA  
<sup>30</sup> Karlsruhe Institute of Technology, Institute for Astroparticle Physics, D-76021 Karlsruhe, Germany  
<sup>31</sup> Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany  
<sup>32</sup> Dept. of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada  
<sup>33</sup> Department of Physics & Astronomy, University of Nevada, Las Vegas, NV 89154, USA  
<sup>34</sup> Nevada Center for Astrophysics, University of Nevada, Las Vegas, NV 89154, USA  
<sup>35</sup> Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA  
<sup>36</sup> Centre for Cosmology, Particle Physics and Phenomenology - CP3, Université catholique de Louvain, Louvain-la-Neuve, Belgium  
<sup>37</sup> Department of Physics, Mercer University, Macon, GA 31207-0001, USA  
<sup>38</sup> Dept. of Astronomy, University of Wisconsin—Madison, Madison, WI 53706, USA  
<sup>39</sup> Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin—Madison, Madison, WI 53706, USA  
<sup>40</sup> Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany  
<sup>41</sup> Department of Physics, Marquette University, Milwaukee, WI 53201, USA  
<sup>42</sup> Institut für Kernphysik, Universität Münster, D-48149 Münster, Germany  
<sup>43</sup> Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA  
<sup>44</sup> Dept. of Physics, Yale University, New Haven, CT 06520, USA  
<sup>45</sup> Columbia Astrophysics and Nevis Laboratories, Columbia University, New York, NY 10027, USA  
<sup>46</sup> Dept. of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom  
<sup>47</sup> Dipartimento di Fisica e Astronomia Galileo Galilei, Università Degli Studi di Padova, I-35122 Padova PD, Italy  
<sup>48</sup> Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA  
<sup>49</sup> Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA  
<sup>50</sup> Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA  
<sup>51</sup> Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA  
<sup>52</sup> Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA  
<sup>53</sup> Dept. of Physics, Chung-Ang University, Seoul 06974, Republic of Korea  
<sup>54</sup> Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden  
<sup>55</sup> Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA  
<sup>56</sup> Dept. of Physics, Sungkyunkwan University, Suwon 16419, Republic of Korea  
<sup>57</sup> Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan  
<sup>58</sup> Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA  
<sup>59</sup> Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA  
<sup>60</sup> Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA  
<sup>61</sup> Dept. of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden  
<sup>62</sup> Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany  
<sup>63</sup> Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, D-15738 Zeuthen, Germany  
<sup>a</sup> also at Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India  
<sup>b</sup> also at Department of Space, Earth and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden  
<sup>c</sup> also at INFN Padova, I-35131 Padova, Italy  
<sup>d</sup> also at Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan  
<sup>e</sup> now at 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 Forschung, Technologie und Raumfahrt (BMFTR), 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).