IceCube Neutrino Observatory Management & Operations

PY3 Annual Report

The IceCube Laboratory with three IceCube Upgrade generators (left), January 2024. Connor Duffy, IceCube/NSF

March 1, 2023 – February 1, 2024

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This PY3 Annual Report is submitted as required by the NSF Cooperative Agreement OPP-2042807. This report covers the period beginning March 1, 2023, and ending February 1, 2024.

1 IceCube Science Overview (F. Halzen)

In its first decade of operation, IceCube collected on the order of one million neutrinos, mostly of atmospheric origin. Among these, it discovered neutrinos of TeV–PeV energy originating beyond our Galaxy, providing us with the only unobstructed view of the cosmic accelerators that power the highest energy radiation reaching us from the extreme universe [1]. Increasingly precise measurements of their energy spectrum using multiple methodologies revealed two surprises. First, unlike the case for all wavebands of light, the contribution to the cosmic neutrino flux from our own Galaxy is only at the 10% level [2]. Second, the flux of gamma rays from the decay of the neutral pions accompanying the charged pions that decay into the cosmic neutrinos exceeds the total extragalactic flux observed by gamma-ray detectors. It implies that the targets in which the cosmic accelerators produce neutrinos are opaque to gamma rays. This has been confirmed by the identification of the first neutrino sources.

After 10 years of accumulated statistics, the active galaxy NGC 1068 has been associated with the hottest spot in the neutrino sky map. It is also the dominant source in a search at the positions of 110 preselected high-energy gamma-ray sources. At the location of NGC 1068, we observe an excess of 79+22-20 neutrinos with TeV energies [3]. Additionally, we find evidence for the active galaxies PKS 1424+240 and TXS 0506+056. TXS 0506+056 had already been identified as a neutrino source in a multimessenger campaign triggered by a neutrino of 290 TeV energy, IC170922 [4], and by the independent observation of a neutrino burst from this source in archival IceCube data in 2014 [5]. The observations point to active galaxies opaque to gamma rays, with the obscured dense cores near the supermassive black holes emerging as the sites where neutrinos originate, typically within 10-100 Schwarzschild radii. We are thus closing in on the resolution of the century-old problem of where cosmic rays originate.

The background of atmospheric neutrinos provides us with a high-statistic sample to study the oscillations of neutrinos. In a paper to be submitted soon to the journal *Physical Review Letters*, we present measurements of the so-called atmospheric neutrino parameters with a precision like what has been achieved by accelerator experiments. Our measurements are performed at higher energies and will be further improved after the deployment of the IceCube Upgrade.

These highlights were very much made possible by the M&O team, which delivered an improved calibration of the detector and a more precise calibration of all optical modules, which are now read out and simulated individually. These improvements were applied to more than a decade of archival data and resulted in the observation of NGC 1068. The same efforts also resulted in improved simulations.

References

[1] *Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector*, IceCube Collaboration: M. G. Aartsen et al., Science **342** (2013) 1242856.

[2*] Observation of high-energy neutrinos from the Galactic plane*, IceCube Collaboration: R. Abbasi et al., Science **380**, 6652 (2023).

[3] *Evidence for Neutrino Emission from the Nearby Active Galaxy NGC 1068*, IceCube Collaboration: R.Abbasi et al., Science **378** (2022) 538-543.

[4] *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922,* The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams, Science **361**, eaat1378 (2018).

[5] *Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert*, IceCube Collaboration: M.G. Aartsen et al., Science **361**, 147-151 (2018).

2 Management and Operations Status and Performance

2.1 Financial/Administrative Performance (L. Mercier)

The University of Wisconsin–Madison has established two separate accounts with supporting charge numbers for collecting IceCube M&O funding and reporting related costs: 1) the NSF M&O Core account, and 2) the U.S. Common Fund account.

The three PY3 installments of $89,930, $5,650,504, and $1,913,479 total $7,653,913, were released by NSF to UW-Madison to cover the costs of management and operations for PY3. An increment of $1,466,900 was directed to the U.S. Common Fund account based on the number of U.S. Ph.D. authors in the last version of the institutional MoUs, and the remaining $6,117,084 was directed to the IceCube M&O Core account (Table 1).

PY3: FY2022/FY2023	**Increment Funds Awarded (Apr 1, 2023–Dec 31, 2023)**	**Final Increment for PY3 (Jan 1, 2024–Mar 31, 2024)**
IceCube M&O Core account	$4,473,464	$1,733,546
U.S. Common Fund account	$1,266,970	$ 179,930
TOTAL NSF Funds	**$5,740,434**	**$1,913,476**

Table 1: NSF IceCube M&O funds – PY3 (FY2023/FY2024).

In addition, we received a Supplement award during PY3, Amendment 007 for Proposal number 2335743 in the amount of $335,000. These funds are for the Antarctic Rodwell Apparatus Drill System and Instrumentation Winch plus tower, as a special deferred maintenance / IceCube facility upgrade action. None of these funds are spent as of this report.

Of the IceCube M&O PY3 Core funds, $1,188,997 was committed to the U.S. subawardee institutions based on their statement of work and budget plan. The original proposed subawardee fund was $1,175,968 for PY3. A Change Request addressing PY3–PY5 increase for subawardee University of Maryland was submitted and approved November 22, 2023. This CR Included a description of the changes and solutions. The net change for PY3 subawards is +$13,027. Penn State University is currently operating on a PY2 no-cost extension, with reduced expenses in PY2 due to personnel turnover and subsequent ramp-up.

The institutions submit invoices to receive reimbursement against their actual IceCube M&O costs. Table 2 summarizes M&O responsibilities and total PY3 funds for the sub awardee institutions.

Institution	**Major Responsibilities**	**Original PY3 funds**	**Current PY3 Funds**
Lawrence Berkeley National Lab	computing and data archival; DAQ	$95,571	$95,571
Penn State University	Computing and data mgmt; sim production; DAQ	$96,850	$0
University of Delaware	IceTop calibration, monitoring and maintenance	$181,075	$181,075
University of Maryland	Software frameworks, online filter, simulation	$652,605	$762,484
University of Alabama	Detector calibration, reco & analysis tools	$31,318	$31,318
Michigan State University	Simulation software & production	$118,549	$118,549
Total		**$1,175,968**	**$1,188,997**

Table 2: M&O subawardee responsibilities and funding for PY3. See text for discussion of changes.

2.1.1 IceCube NSF M&O Award Budget, Actual Cost, and Forecast

The current IceCube NSF M&O 5-year award was established in the middle of Federal Fiscal Year 2021, on April 1, 2021. The following table presents the PY1–3 financial status and estimated balance at the end of PY3.

PY3 awarded funds to UW–Madison (UW) for supporting IceCube M&O from the beginning April 2023 through January 2024 are $7,653,910. PY1–3 total actual cost as of January 31, 2024 is $20,518,762, and open commitments against purchase orders and subaward agreements total $698,720. The current balance as of January 2024 is $840,873. With a projection of $948,315 for the remaining expenses during the final months of PY3, the estimated balance at the end of PY3 is -$107,442, which is -0.5% of the PY1–3 budget (Table 3). The balance is in line with the University of Wisconsin's accounting system (WISER).

(a)	(b)	(c)	(d)= a-b-c	(e)	(f)= d-e
PY1-PY3 Budget (Apr 2021-Mar 2024)	**Actual Cost** to date Through Sept. 30, 2023	**Open Commitments**	**Current Balance**	**Remaining Projected Expenses through March 31, 2024**	**End of PY3 Forecast Balance as of Mar. 31, 2024**
$22,058K	**$20,518K**	**$699K**	**$841K**	**$948K**	**-$107K**

TABLE 3 – BUDGET

The current projected negative balance is due to labor inflation in PY1–PY3 exceeding the award escalation. State institutions, in particular UW–Madison and the University of Maryland, mandate cost-of-living salary increases. In 2023, there was a legislated +4% adjustment to UW–Madison salaries. Furthermore, personnel departures and re-hires at elevated rates increase the effective inflation to the project.

Despite remaining under the budgeted FTE headcount (Figure 1), without action we would have expected a balance of approximately -$300K at the end of PY3. However, we have partially covered this gap by rebalancing appropriate labor between the U.S. and Non-U.S. Common Funds. This did not affect capital equipment purchases from the Non-U.S. Common Fund in PY3, but some planned equipment purchases in PY4 and PY5 will be reduced and/or deferred. Common Fund usage is governed by the Cooperative Agreement and described in the following section.

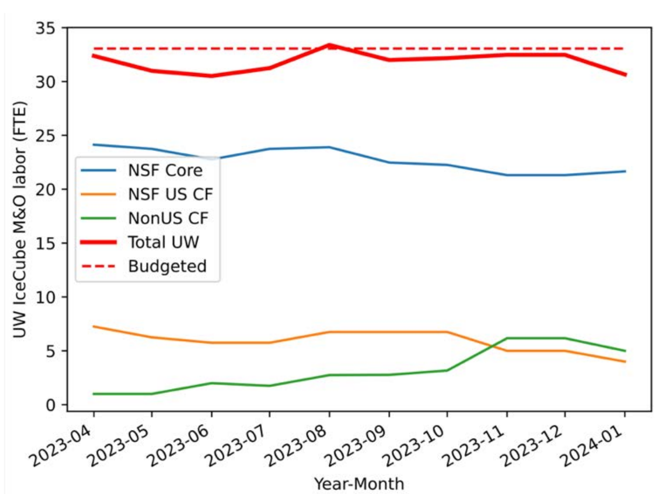

Figure 1: M&O labor (UW, FTEs) in PY3. Rebalancing labor between the U.S. and non-U.S. Common Fund (November 2023) temporarily alleviates the shortfall caused by labor inflation.

2.1.2 IceCube M&O Common Fund Contributions

The IceCube M&O Common Fund was established to enable collaborating institutions to contribute to the costs of maintaining the computing hardware and software required to manage experimental data prior to processing for analysis. Each institution contributes to the Common Fund, based on the total number of the institution's Ph.D. authors, at the established rate of $13,650 per Ph.D. author. The Collaboration updates the Ph.D. author count twice a year before each collaboration meeting in conjunction with the update to the IceCube Memorandum of Understanding for M&O.

The M&O activities identified as appropriate for support from the Common Fund, as listed in the IceCube M&O Cooperative Agreement, are those core activities that are agreed to be of common necessity for reliable operation of the IceCube detector and computing infrastructure. These activities directly support the functions of winterover technical support at the South Pole, hardware and software systems for acquiring and filtering data at the South Pole, hardware and software systems for transmitting data via satellite and disk to the UW data center, systems for archiving the data in the central data warehouse at UW, and UW data center operations.

Table 4A summarizes the planned and actual Common Fund contributions for the period of April 1, 2023–March 31, 2024 based on v33.0 of the IceCube Institutional Memorandum of Understanding, from March 2023. U.S. contributions to the Common Fund are provided directly via the NSF M&O award. A change in the number of U.S. authors does not change the total award amount, only the fraction reserved in the U.S. Common Fund account. The remaining contributions from non-U.S. collaborators are still underway, and it is anticipated that the planned contributions will be fulfilled. Table 4B shows the Ph.D. author count for PY1–PY3; the author count continues to increase, +7% from PY2 to PY3.

	Ph.D. Authors	**Planned Contribution**	**Received To Date**
U.S.	106	$1,446,900	$1,446,900
Non-U.S.	77.5	$1,057,875	$ 868,570
Totals	**183.5**	**$2,504,775**	**$2,315,470**

Table 4A: Planned and actual Common Fund contributions for the period April 1, 2023–January 31, 2024.

Ph.D. Authors	**PY1**	**PY2**	**PY3**
U.S.	88	97	106
Non-U.S.	73	75	77.5
Totals	**161**	**172**	**183.5**

Table 4B: Ph.D. author counts for U.S. and non-U.S. institutions, for PY1–PY3.

2.1.3 Program Coordination

2.1.3.1 Education and Outreach (Jim Madsen)

The IceCube education and outreach team continued to promote IceCube science to the public through educational programs, in-person outreach events, and virtual offerings. Our highlights on activities for this reporting period are:

- A day-long IceCube Masterclass for area high school students hosted at WIPAC.
- An IceCube educational virtual workshop for early career science teachers taught by former IceCube PolarTREC educator Dr. Katherine Shirey. Shirey later led 5 teachers from the workshop in designing and implementing a 2-week science immersion enrichment course for high school students in the UW-River Falls Upward Bound Program.
- The second ThaisCube workshop held in Chiang Mai, Thailand, a summer school covering multimessenger astrophysics, neutrino physics, and other topics for high school, undergraduate, and Master's students from Thailand, the U.S., and the Philippines.
- A two-day experience for UW-Madison alumni and their grandchildren, Grandparents University.
- Interactive booths at the UW-Madison Physics, Science Expeditions, and the Madison Metropolitan School District's (MMSD) STEAM Fairs drew hundreds of visitors at each venue.
- Hosting high school and undergraduate student groups for day-long visits to introduce IceCube science and scientists.
- Participating in four community building events that bring music, arts, and science opportunities to Madison neighborhood parks.
- Hosting artist Tristan Duke for a week-long residency to capture IceCube science imagery using his custom large-format ice-lens camera.
- Holding a launch event to start development of the online IceCube astrophysics-themed video game and teacher support materials for middle school students with the UW–Madison Field Day Lab.
- Developing and delivering a 10-week program for Madison high school students who learned about IceCube science while helping to design and construct an interactive IceCube display for UW-Madison Physics Department Museum.

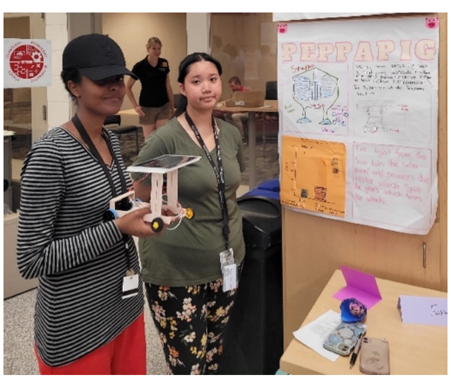

Figure 2: UWRF Upward Bound students showing their solar-powered car and sustainable station poster.

Figure 3: The WIPAC Grandparents University group with WIPAC Communications Director Alisa King-Klemperer (back, right).

In the tenth installment of the IceCube Masterclass, over 250 students participated in hands-on data analysis at over 20 IceCube institutions. WIPAC hosted 17 students for a day full of science talks, learning about graduate school, and data analysis activities.

WIPAC continues to engage with PolarTREC educators to leverage their South Pole experience and bring it to new audiences. IceCube PolarTREC educators Katey Shirey (2010) and Elaine Krebs (2020) worked with Jim Madsen to develop a multiweek professional development workshop for early career high school science teachers that utilized IceCube science and engineering curricula developed by Shirey. Five of the teachers, led by Shirey with support from Madsen and Krebs, developed a 2-week summer science experience for high school students in the UW-River Falls Upward Bound program, July 10-20, 2023. The theme of the workshop was developing a sustainable science station in a remote environment. Students learned about Krebs' and Shirey's experiences living and working at the South Pole.

WIPAC also participated in Grandparent's University, an intergenerational learning experience designed to expose grandparents and their grandkids to research across the UW–Madison campus. WIPAC hosted a two-day session for nine grandparent-grandchild pairs that included hands-on activities and talks from guest speakers.

In summer 2023, WIPAC arranged a visit to the UW Physical Sciences Lab and a series of talks at WIPAC for the South Dakota Davis-Bahcall scholars program that connects first- or second-year science-curious undergraduates with peers and mentors involved in modern STEM research. WIPAC also hosted students from the Madison Country Day School Summer Research Academy, a summer program that allows high school students to explore areas in science outside the classroom.

Figure 5: IceCube virtual reality, hot water drilling, and cold-weather gear activities.

Other in-person events where WIPAC had a booth include the spring 2023 Wisconsin Science Expeditions at the Discovery Building, the UW–Madison Physics Fair, and the MMSD's STEAM Fair. Each of these events drew hundreds of participants, and the MMSD's STEAM Fair hosted over 400 learners from minoritized groups in STEM. The IceCube virtual reality experience continues to be a big hit for all ages at these events. WIPAC personnel also attended four Parks Alive events including Madison's Juneteenth Celebration that reach diverse audiences in their own neighborhoods. The extreme cold weather gear, an ice 'drilling' activity where visitors learn about IceCube hot water drilling using tap water and pipettes, and the IceCube virtual reality experience, are all big draws.

Figure 6: Naoko Nielsen, Steve Sclafani and Albrecht Karle announcing the Galactic Plane result at Drexel University.

On June 29, 2023 Drexel University hosted an in-person collaboration-wide event that was also offered virtually, to announce the first image of our Milky Way Galaxy in neutrinos as measured by IceCube. A webinar was live-streamed on Zoom and YouTube that presented results from a *Science* paper published on June 30, 2023. The webinar featured opening remarks from dignitaries from Drexel, Dortmund and NSF followed by a panel of IceCube scientists discussing the findings. More than 70 people attended the event in person while over 1,000 attendees watched the live stream across Zoom and YouTube. As of Oct. 1, 2023, the recorded webinar has garnered over 25,000 views on YouTube.

Figure 7: (Left) Artist Duke in the center with his two student assistants. The silver cube behind them is the camera body; the ice lens is behind the black diamond. (Right) An image of an IceCube digital optical module taken with an ice lens.

Tristan Duke, a Los-Angeles-based artist reached out to WIPAC with a proposition to utilize a new technique he is exploring to make super-large-format prints using a lens made from ice. Internal funding was used to host Duke and two of his students at UW-Madison who took a variety of images using a couple of techniques to produce photographic negative exceeding 3’ x 6’ dimensions. Preliminary images were shown in a pop-up gallery event in Madison at the end of his week there, and at a gallery show in Svalbard, Norway held in conjunction with the Scientific Committee on Antarctic Research Astronomy and Astrophysics from Antarctic meeting, September 19–21, 2023.

Figure 8:Thai students Yannee Tangjai and Wassachon Kammeemoon give a talk at the 2nd ThaisCube workshop about their summer student visit to WIPAC in Madison, Wisconsin.

The 2nd ThaisCube workshop was held in Chiang Mai, Thailand, on August 8–11, a program that developed from a partnership between Chiang Mai University (CMU) in Thailand, the National Astronomical Research Institute of Thailand (NARIT), and the IceCube Neutrino Observatory. The workshop brought together IceCube researchers, Thai scientists, and 40 aspiring students from Thailand, the U.S., and the Philippines. A multitude of subject areas were covered, including multimessenger astrophysics, neutrino physics, gamma-ray astronomy, and other topics.

On February 9, a day-long kick-off event was held at UW-Madison for the team developing a new IceCube themed on-line game for middle school students. The team includes Wisconsin teachers and librarians who were selected for fellowships to help create and incorporate games into their curricula. The video game project is a collaboration between the Wisconsin Department of Public Instruction (DPI), the Field Day Learning Games Lab in the Wisconsin Center for Education Research at the University of Wisconsin Madison (UW–Madison), and WIPAC.

Figure 9: Workshop participants in front of the UW-Madison Washburn Observatory (left) and Assistant Professor Lu presenting to the group (right). Photos courtesy of Jim Mathews, Field Day.

The workshop included talks Jim Madsen, John Kelley, UW–Madison assistant professor of physics Lu Lu, and WIPAC scientist and polar instrumentation specialist Delia Tosi.

The IceCube After School program hosted 23 area high school students for 9 weekly 1.5-hour sessions. The students heard talks from IceCube scientists, students and technical staff who described their work and career paths. Groups led by graduate students and WIPAC staff worked weekly to develop new software for the model, an engaging interface to "trigger" the display to show an IceCube event, on graphics, and on fabrication and assembly.

2.1.3.2 Communications

The communications team is responsible for promoting IceCube on social media and through other outlets such as the IceCube website, printed media, and its monthly newsletter. IceCube has continued to remain active on social media by posting timely events, sharing and promoting notable outreach events or activities, participating in global holidays, and promoting key developments in the field of particle physics, such as the P5 report advising the federal government on particle physics research.

The P5 report included a recommendation to fund the planned IceCube extension, IceCube-Gen2, and the Cherenkov Telescope Array. Over 35 media outlets covered the P5 report, including The New York Times (Particle Physicists Agree on a Road Map for the Next Decade).

Communication efforts for the IceCube Upgrade project have ramped up with the start of one of three field seasons. A story on a successful first field season was well received and promoted through campus-wide channels at the University of Wisconsin–Madison.

IceCube and WIPAC news articles were regularly published on timely events, research results, and outreach endeavors. The IceCube newsletter is released monthly to subscribers and includes a photo of the month, summaries of IceCube research papers, notices of recent IceCube PhD graduates, award announcements, IceCube press mentions, and links to outreach activities and events.

The top three posts based on the impressions/reach and the number of followers since October 2023 for each platform are summarized here:

X / Twitter (@uw_icecube) 18,046 followers (up 5%)

- *Winterover applications are now OPEN!*
- *Gold alert 11/3*
- *Winterover applications are still open*

Facebook (@icecubeneutrino) 12,963 followers (up 2%)

- *Farewell to our winterovers, Marc and Hrvoje!*
- *Winterover applications are now OPEN!*
- *Winterover applications are still open*

Instagram (@icecube_neutrino) 7,988 followers (up 5%)

- *Winterover applications are still open*
- *Winterover applications are now OPEN!*
- *Valentine's Day*

2.2 WBS 2.2: Detector Operations and Maintenance (M. Kauer)

During the period from March 1, 2023 to February 1, 2024, the detector uptime, defined as the fraction of the total time that some portion of IceCube was taking data, was 99.9%, exceeding our target of 99% and close to the maximum possible, given our current data acquisition system. The clean uptime for this period, indicating full-detector analysis-ready data, was 98.2%, exceeding our target of 95%. Other key performance metrics are listed in Table 5; in all cases performance metrics were met.

Performance Metric	**Objective**	**Achieved**	**Description**
Total Detector Uptime	> 99%	99.9%	Detector taking data in some configuration; remains sensitive to rare, transient events.
Clean Detector Uptime	> 95%	98.2%	Full IC86 detector data usable by all analyses.
IceCube Live Uptime	> 99.9%	99.999%	Experiment control and data monitoring functioning.
Supernova System Uptime	> 99%	99.9%	Supernova DAQ online.
L1 Processing Latency	< 60 sec	29 sec	90% quantile time from event in ice to processed event on disk.

Table 5: Detector operations key performance parameters from March 1, 2023 to February 1, 2024.

Figure 11 shows a breakdown of the detector time usage over the reporting period. The partial- detector good uptime was 0.89% of the total and includes analysis-ready data with fewer than all 86 strings. The excluded uptime of 0.74% includes maintenance, commissioning, and verification data. The unexpected detector downtime was limited to 0.13%.

The total number of active DOMs in the data stream remains 5403 (98.5% of deployed DOMs), plus three DOM-mainboard-based scintillator panels and two DM-Ice dark matter detector modules.

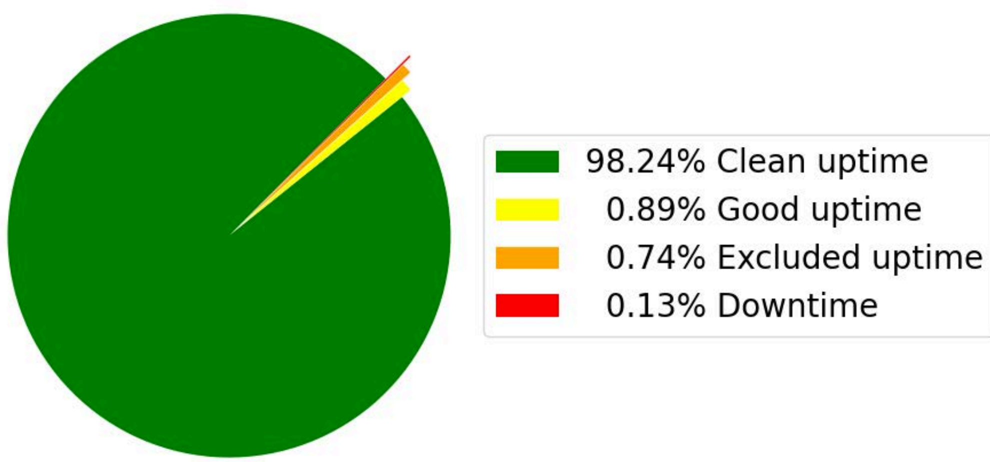

Figure 11: IceCube detector uptime for the period from March 1, 2023 to February 1, 2024.

Detector operations milestones for PY3 are shown in Table 6 (**WBS 2.2.1 Run Coordination**). A major milestone in this reporting period is a new release of the DAQ that supports new triggers based on non-local-coincidence hits. In addition to supporting new IceCube trigger concepts, this also lays the framework for supporting the Upgrade trigger.

The IC86-2023 physics run start was delayed from the usual May start date to facilitate a major online and offline data filtering rewrite. The new online filtering plan transfers most triggered events in a highly compressed form over the satellite and moves most data processing and reduction to the north. A software retriggering of events from 8 to 12 hits is employed to ensure that, on average, IceCube stays within our current satellite allocation of 105 GB/day.

WBS L3	Planned	Actual	Milestone
2.2.1	05/31/23	11/28/24	IC86-2023 physics run start
2.2.1	08/01/23	08/01/23	23/24 Winterovers begin training
2.2.1	10/27/23	11/11/23	Winterover crew exchange at South Pole
2.2.2	05/01/23	delayed*	Data acquisition Upgrade support
2.2.4	02/28/23	delayed*	Detector monitoring Upgrade support
2.2.5	06/15/23	delayed*	Support for Upgrade DOMs and calibration devices
2.2.9	08/04/23	08/07/23	Seasonal cargo ready for vessel shipment
2.2.9	12/01/23	12/15/23	SPS network switch upgrade
2.2.9	12/22/23	delayed	SPS UPS upgrade; delayed due to cargo delays

Table 6: WBS 2.2 Detector operations and maintenance PY3 milestones for this reporting period.
*See text for discussion of IceCube Upgrade integration milestones.

Two new winterovers, Connor Duffy and Kalvin Moschkau, started training at WIPAC in August 2023 which involves in-depth, hands-on exercises on all online computing and detector subsystems using the South Pole Test System (SPTS). The winterovers deployed to South Pole in November of 2023 and relieved last year's winterovers.

The **data acquisition software (DAQ, WBS 2.2.2)** was upgraded to the "Cyclops" major release in August 2023. The new release of the DAQ supports new triggers based on non-local-coincidence hits. In addition to supporting new IceCube trigger concepts, this also lays the framework for supporting the Upgrade trigger. Unlike the Gen1 DOMs, the Upgrade DOMs have no hardwired local coincidence along the string.

Several DAQ, monitoring, and IceCube Live milestones related to the integration of the IceCube Upgrade were originally scheduled for PY2. The IceCube Upgrade has now been re-baselined after the loss of 3 pole seasons due to COVID-19. Integration milestones are now being tracked as part of IceCube Upgrade WBS 1.6 and will be removed from subsequent M&O reports.

The online data **processing and filtering system (PnF, WBS 2.2.3)** was upgraded to V23-06-00 in July 2023 which includes enhanced functionality for monitoring the IceTop PMT gain and single photo-electron charge. A new filtering concept was released with V23-11-00 and running since the IC86-2023 physics run start in November 2023. The new filtering scheme reduces online processing by transferring most triggered events north after data compression. To remain within the satellite transfer bandwidth limit of 105 GB/day, the DOM multiplicity trigger is increased to 12 (previously 8) or more DOMs with a software retriggering. Archival raw data are not affected by the retriggering.

A new major release of the IceCube Live **experiment control and monitoring software (WBS 2.2.4 & 2.2.5)** was installed in April 2023, I3Live v4.7.0 "Hyperion". This release provides support for receiving supernovae Fast Response System (FRS) alerts sent from the north and initiates SNDAQ analysis over the specified time window of interest. This new functionality allows IceCube to quickly follow up and respond to supernovae alerts initiated by the broader astronomy community through the public SNEWS system.

IceTop and the surface array (WBS 2.2.6) have been functioning smoothly. No self-induced snow accumulation or drifting was noted around the elevated instrumentation. The White Rabbit system (timing and data transfer via ethernet over optical fiber) continues to operate as expected. New surface station deployments have been postponed due to logistics constraints.

The **supernova data acquisition system (SNDAQ, WBS 2.2.7)** continues operating with 99.9% uptime. Work continues on a Python-based upgrade of the supernova DAQ (PySNDAQ) and Fast Response System, planned for deployment mid-March 2024. Deployment of PySNDAQ is planned for August-September 2024.

The **realtime event stream and alert system (WBS 2.2.8)** continues to deliver public neutrino alerts through the GCN system to the multimessenger astronomy community for followup observation. During the period March 1, 2023, to February 1, 2024, IceCube reported 25 track event alerts ("gold" or "bronze" depending on the estimated probability of astrophysical origin) and 8 cascade event alerts.

The **South Pole System (SPS, WBS 2.2.9)** computing cluster continues operating. Significant computing hardware upgrades planned for previous seasons were delayed by cargo constraints due to COVID. A lifetime-replacement upgrade of the SPS uninterruptible power supplies (UPSes) was completed this 2023–24 season in parallel with the network upgrade originally planned for 2021–22.

2.2.1 Detector Operations Labor Assessment

A detailed list of M&O supported labor is included in the Appendix *Staffing Matrix by WBS L3*. After two software developer departures in 2021 and the subsequent shortage, labor is now largely back to planned levels. Long-time IceCube contributor John Jacobsen (NPX Designs, LLC) continues software development on a part-time (50%) contractual basis which started in October 2022, as a partial replacement for web and database developer Colin Burreson, and to assist with DOM software development.

The online software plan for expansions like the IceCube Upgrade relies on tight integration into the current IceCube DAQ and filtering systems rather than a new design, saving significant time and labor. This is possible because the IceCube operations software has been well-maintained and modernized over the course of previous M&O periods. However, significant effort is still needed across all L3 areas to expand the system to incorporate new sensors, calibration instruments, and their data products. We anticipate additional labor will be needed before the Upgrade deployment in 25–26, in particular for IceCube Live Upgrade integration.

An additional 0.5 FTE DevOps engineer in WBS 2.2.9 South Pole Systems is needed to facilitate modernization of the configuration management and monitoring systems of the computing cluster at South Pole. This hire is now underway and planned as a shared system administrator with WBS 2.3.

2.2.2 Impact of Logistics Constraints on the 2023–24 South Pole Season

The austral summer population that supported the IceCube maintenance during the 23–24 austral summer season was significantly below operational notice levels. In total, 5 people (including 2 winterovers) were deployed, whereas a typical season supports 12 or more deployers that rotate in and out for 3- to 4-week intervals (Figure 12).

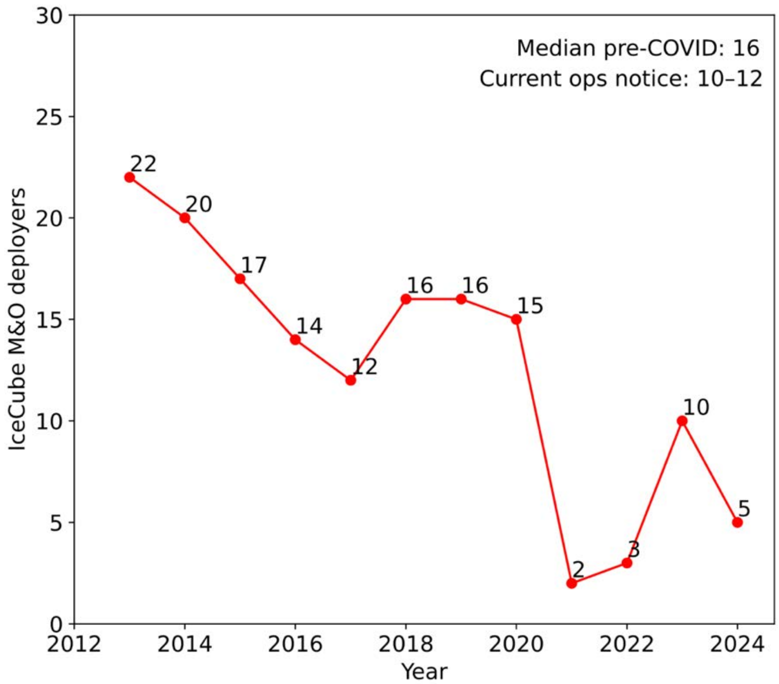

Figure 12: IceCube M&O deployer count by season, after construction. Population levels have not returned to pre-COVID levels due to various logistics constraints.

Personnel rotation is critical for IceCube maintenance given the variety of specialized tasks during the brief summer season. Operations Subject Matter Experts (SMEs) are unable to deploy for full summer seasons due to other IceCube and IceCube Upgrade responsibilities. For the 23–24 season, all SMEs departed by early January, leaving only the Winterovers for the latter part of the season.

Limited cargo and contractor support further reduced the planned task list. All graduate student deployments for 23–24 were cancelled, eliminating this unique training opportunity for the next generation of IceCube scientists.

Critical ICL maintenance was prioritized, in particular the networking and UPS life-cycle replacements. Table 7 shows the status of all originally planned activities for 23–24.

Maintenance activity	**Status for 23–24**	**Primary constraint(s)**
ICL networking	Prioritized, complete	—
UPS replacement	Prioritized, incomplete	cargo delivery, crane support
DAQ and Upgrade support	Prioritized, complete	—
ICL prototype wind turbine upgrade	complete	—
IceACT upgrade / maintenance	scaled back, incomplete	population

additional surface array station installations	deferred	population, cargo capacity, contractor support
renewable energy testbed	deferred	population, cargo capacity
Askaryan radio array maintenance	deferred	population

Table 7: Status of 2023–24 pole activities given reductions in logistics support.

The life-cycle UPS replacements were scheduled to be completed in November and December, when SMEs would be present to assist the Winterovers with this task. However, the necessary cargo delivery was delayed from a ROS date of 11 November 2023 to 26 January 2024, after all summer M&O population had departed. While the Winterovers are continuing with this task into the winter, the lack of on-site support has resulted in increased downtime and hardware failures. For example, during UPS replacements on 14 February, an accidental trip of the server room's power-shutdown system resulted in 1.25 hours of downtime, four power supply failures, and a custom precision clock fanout failure. The Winterovers successfully recovered with remote support from Northern experts.

We note that while this season's M&O activities are largely independent of the IceCube Upgrade Field Season 1 milestones related to drill refurbishment, the planned M&O activities for 2024–25 and 25–26 become increasingly critical for a successful IceCube Upgrade installation and integration.

2.3 WBS 2.3: Computing and Data Management Services (B. Riedel)

IceCube M&O owns and operates several key pieces of cyberinfrastructure for the IceCube collaboration. A summary of the various components and definitions can be found in Tables 8 and 9.

Cyberinfrastructure	Size
Data and Simulation Filesystem	10 PB
User and Analysis Filesystem	10.7 PB
Dedicated CPU Cores	4500
Dedicated GPUs	300
Virtualized Hosts	200
Power Usage	250 kW
Distributed CPU Cores	6000-10,000
Distributed GPUs	600-800

Table 8: Summary of IceCube Cyberinfrastructure.

During the period from March 1, 2023 to February 1, 2024 , the core infrastructure uptime, defined as the fraction of the total time that the core infrastructure located at UW-Madison was accessible to the collaboration, was 95–99% depending on the service. This meets or exceeds our target of an average uptime of 95%.

We completed deployment of a major data and simulation filesystem upgrade. This increased our storage footprint from 7.3 PB to 10 PB, providing an additional ~5 years of storage capacity at current growth rates. The new filesystem runs Ceph rather than Lustre, to address scalability and stability issues with the latter. This upgrade solves the temporary reduction in our ability to produce background simulation datasets since December 2022 due to limited storage capacity. During the interim period, we have prioritized data products over simulation products to ensure that the newest data are available to scientists. We have also started an initiative to reduce the simulation dataset footprint by only transferring new and in-use simulation datasets to the new filesystem.

One core service, the user directory service (LDAP), had downtime totaling roughly 4 hours during the reporting period, causing disruption in user analyses. The downtimes were caused by temporary hardware failures in our virtualization infrastructure, which is running on older servers. While we do automatically restart services, this service appears to have issues when starting up after being moved to a different host. We are still investigating the cause of this issue and potential solutions. To address the underlying instability, we have purchased new servers for the virtualization farm, discussed further below.

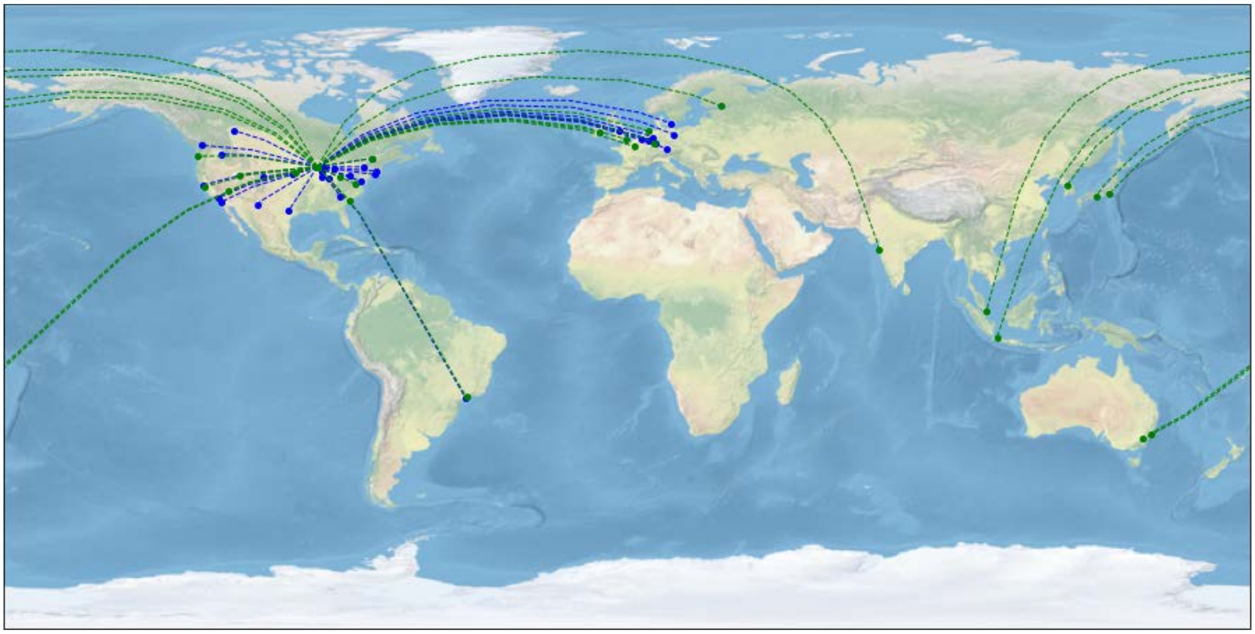

Figure 13. Location of IceCube distributed computing sites across the globe. Distributed resources are contributed from the collaboration, collaboration institutions, and other federally funded sources, e.g. Advanced Cyber-infrastructure Coordination Ecosystem: Services Support (ACCESS), Partnership to Advance Throughput Computing (PATh), and others.

The non-core infrastructure was available at 97%. This exceeds our target of an average uptime of 90%. Since the transition to new hardware and software, the new user and analysis filesystems have been used extensively. We have had no further issues and significantly reduced the impact of hardware failure on data safety and user experience.

The workflow management software (IceProd) has been up >98% of the time. We stayed constant at 13 users, though most of the datasets are now submitted by users instead of central simulation production. We continue to recruit new users and improve the system user-friendliness; an IceProd workshop is planned for the March 2024 collaboration meeting.

Filtered data from the South Pole is generally transferred to Madison within less than 24 hours. In late January 2024, we experienced about a two-week delay in data transfer, mostly affecting the data needed for detector monitoring (Figure 14). This was caused by a combination of satellite outage on 22 January 2024, transition to a new data filtering scheme at the South Pole at the end of November 2023, higher data rate during the austral summer, data priority and settings within the IceCube data transfer software, and reduced flexibility in the satellite data transfer rate. While the situation has stabilized, we still have approximately a 200 GB backlog and two-day delay. We are working with NSF and other satellite users to re-evaluate allocations among projects.

The replication of our processed data to archive is currently up to date. While we have automated the archival process, monitoring file integrity and retrieval is still a manual process. This will require additional resources we have yet to identify.

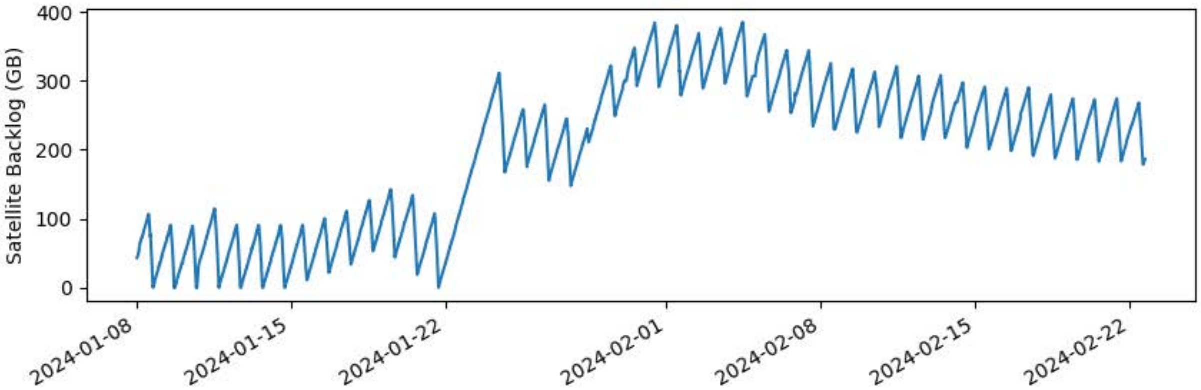

Figure 14: IceCube ongoing SPTR satellite backlog. The sawtooth pattern shows individual daily transfers. Large jumps are not from additional data generation but from missed / reduced satellite passes.

Computing and Data Management milestones for PY3 are shown in Table 9. We have completed the experimental data ingested to NERSC ahead of schedule. It took us less than 90 days from data arrival from the South Pole via retro cargo in Madison until the data was archived at NERSC. The complete archive at NERSC now includes over 11 years of trigger-level IceCube data.

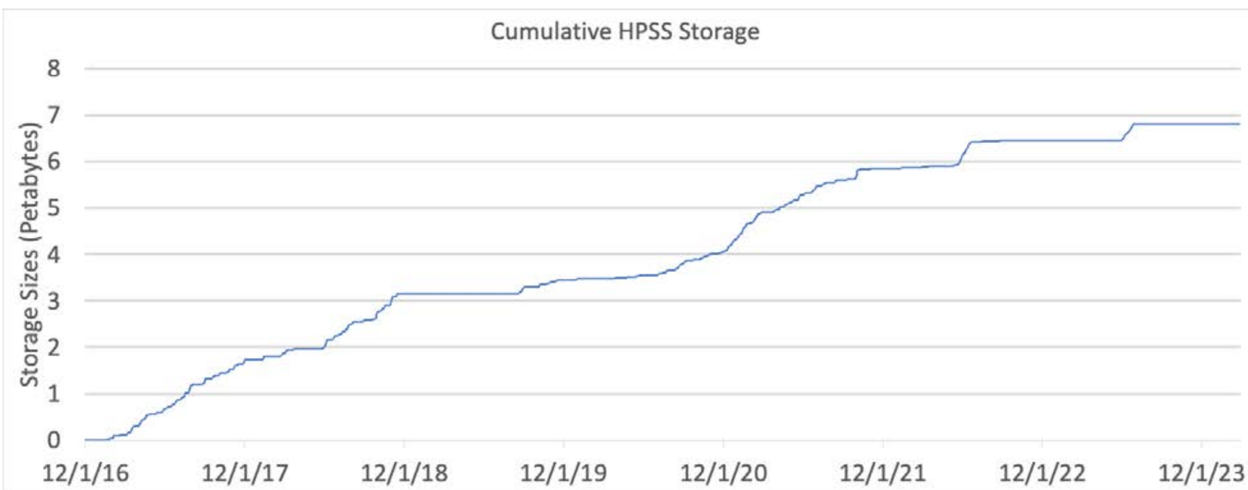

Figure 15: Ingestion of experimental data to archive at NERSC from 2016 to present.

We are also transitioning our self-hosted communication and collaboration services (email, email lists, and document management) to Google Workspace. The transition to Google Workspace will provide the collaboration a modern and well-liked interface to frequently accessed services and reduce the maintenance burden on the team by reducing the number of distinct services that need to be supported and reducing the reliance on our self-hosted virtualization infrastructure. This transition is occurring in phases: we have transitioned most of the administrative services at UW from self-hosted to Google Workspace, we are in the process of transitioning of email lists, have moved nearly all user emails to Google Workspace, and are working with users to use the new Google Drive.

A change in ownership of our virtualization software vendor (VMWare) and subsequent changes in their licensing of the virtualization software have caused us to delay updates to our virtualization infrastructure. The vendor has significantly increased prices, depending on size of deployment anywhere from 10% to 1000%. We are working with UW central IT to determine the prices for 2025. We have transitioned some of our virtualized infrastructure to containers using Kubernetes, but still require some services to be deployed in a virtualized infrastructure. As the current out-of-warranty hardware has developed issues, we decided to replace the servers ahead of schedule (originally planned for later 2024). We have evaluated the cost of moving the services to UW central IT and have determined that it is still more cost-effective to host the infrastructure ourselves. We are currently evaluating free or cost-effective alternatives to our current virtualization software.

WBS L3	Planned	Actual	Milestone
2.3.1	12/31/23	07/13/23	CY 2022 experimental data ingested into NERSC LTA
2.3.3	03/01/24	TBD	VM infrastructure hardware upgrade complete

Table 9: WBS 2.3 Computing and data management PY3 milestones.

2.3.1 Computing and Data Management Labor Assessment

Recent retirements and a parsimonious labor environment in technology fields has kept the computing team lean. While operations continue to meet the key performance metrics, infrastructure improvement has slowed significantly and the risk of losing critical institutional knowledge has increased. Ultimately, modernizing systems to make use of contemporary computing technology (cloud, containers) is slow given the competing demands on the team. We are shifting staff responsibilities to improve the ability of the M&O program to respond to the changing technology landscape. We had paused the recruiting process for a system administrator position given the uncertain budgetary situation after the inflation of the last 2 years; this recruitment is now moving forward again and will be a shared position with WBS 2.2.

An expected change within IceCube and the Upgrade is the transition to more machine learning (ML) based data analysis. This will require rethinking the data analysis cyberinfrastructure (CI) currently deployed. The current dedicated CI is at least 5 years old and was purchased with a focus on mass data processing and simulation production. We are expecting (and already experiencing in some cases) an increasing demand for accelerated hardware (GPU and FPGAs) to accommodate ML model training and inference. These workloads have different resource requirements and will require updates and additions to existing infrastructure to meet those requirements.

We are exploring additional NSF funding through cross-directorate and CISE programs. We are focusing on the Cyberinfrastructure for Sustained Scientific Innovation program and re- questing additional from ACCESS and PATh as well as influencing future resources NSF-funded cyberinfrastructure projects. We also plan to expand or start using other federally funded cyberinfrastructure, particularly the DOE-funded National Energy Research Scientific Computing Center, Oak Ridge Leadership Computing Facility, and Argonne Leadership Computing Facility. Oak Ridge and Argonne; however, these have significant workflow and security restrictions that cost significant human effort to overcome.

2.4 WBS 2.4: Data Processing and Simulation Services (J.C. Díaz-Vélez)

WBS L3	Planned	Actual	Milestone
2.4.1	04/14/23	09/22/23	Offline filter requirements captured for IC86-2023 run
2.4.2	06/01/23	06/23/23	Re-simulate 2020 Datasets with new spice bfr-v2 ice model
2.4.2	01/01/24	TBD	Reparameterization of MuonGun with SIBYLL2.3d

Table 10: WBS 2.4 Data processing and simulation PY3 milestones.

Data processing and simulation milestones are summarized in Table 10. Key performance parameters for Computing and Data Management are tabulated in Table 11. With the recent release of the FTP-v2 ice model, we recently began the process of producing a new SnowStorm neutrino signal and systematics dataset using the LeptonInjector signal generator. We expect to periodically re-simulate most signal datasets and a significant portion of background Monte Carlo as new improvements in software and modeling of the optical properties of the ice are developed. Old and obsolete simulations are scheduled to be removed from disk to accommodate these new datasets as we migrate to the new file system.

Performance Metric	Objective	Achieved	Description
L2 processing latency	< 2 weeks	10.8 days	80% quantile time from event in ice to L2 processed file in the data warehouse
Simulation Production Efficiency	> 90%	92%	Total useful time (completed jobs) divided by total computing time
Simulation Requests	< 60 days	57.2 days	90% quantile request to production

Table 11: Data processing and simulation (WBS 2.4) performance parameters.

2.4.1 Data Processing

Current offline data processing is running on the IceProd2 framework that uses opportunistic grid computing resources distributed across the globe. The move required some coordination with the distributed infrastructure team to implement additional features needed to support this task.

The IC86-2023 physics run started on November 11, 2023, at 2023-11-28 20:52:12 (UTC) with run number 138615. The delay for the IC86–2023 processing with respect to the milestone indicated in Table 10 is the result of an ongoing effort by the IceCube Collaboration to shift to a new offline filtering scheme (see text below). However, delays in the design and testing of individual filters ultimately resulted in the need to postpone implementation of offline filtering improvements to the 2024 season.

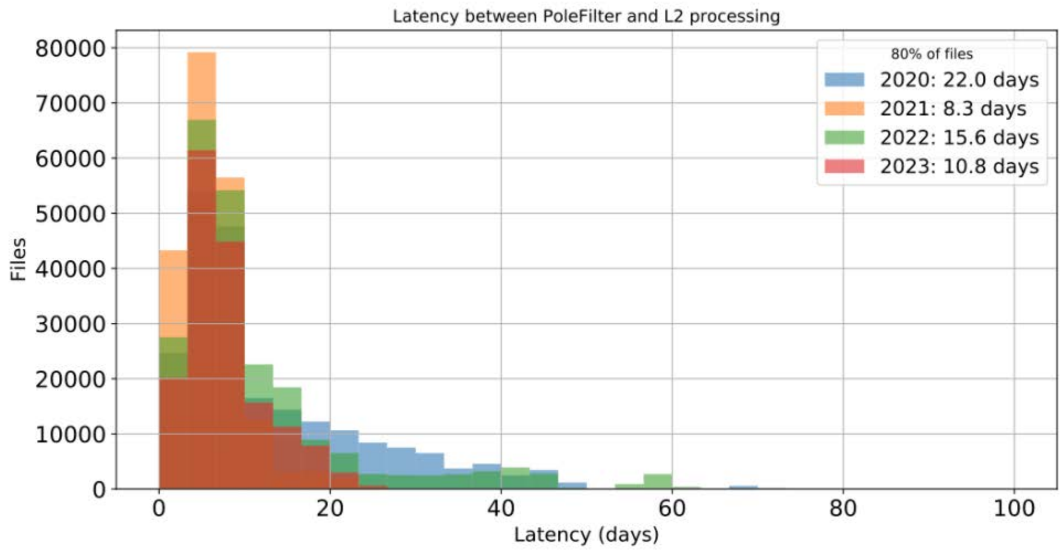

Figure 16: L2-processing latency distribution for the last four years. We define latency as the elapsed time between trigger to the time when L2 files are available on disk in the North. Minimum latency is determined by the weekly data validation process in the North.

During previous years, an effort was made to clean up filters reconstructions and libraries no longer needed in offline reconstruction resulting in a 36% reduction of CPU utilization and a comparable reduction in memory requirements. Resources consumed for the offline production resulted in approximate 480,000 CPU hours of processing time and consistent with prior estimates. We are currently reviewing existing filters and reconstructions with the aim of streamlining offline processing at Level 2 and Level 3.

There is a new effort to further clean, optimize and modernize the current filtering scheme including L1 (online), L2, and L3 (analysis working group) filters. Current proposals include the addition of machine learning event classifiers and simplification of online filters running at the South Pole. The new simplified L1 filters have been deployed with the IC86–2023 run start, and we plan to deploy the new offline L2/L3 filtering scheme for the IC86-2024 physics run. As a stop-gap measure, we are currently recreating the previous online (L1) filters as part of the L2 processing to produce data comparable to that of previous years. As part of this new scheme, IceTop calibration, which includes accounting for snow accumulation over the tanks, has been streamlined and is being applied prior to L2 processing. This will provide prompt access for analyzers to work with IceTop data. However, it will require additional time for validation and will reset our latency metric (Table 11) to approximately 4 weeks.

The *latency* performance metric for Level-2 processing corresponds to the elapsed time between when triggered events are recorded in ice, to the time they are processed offline in the North and the resulting L2 file are available in the data warehouse for 80% of the files. A result of our new focus on this metric was that this latency of data at L2 was reduced from almost 50 days in 2018 to only 8.5 days in 2021 but increased again to 15.5 in 2022 and 16.1 in 2023 (Figure 16) due to outlier runs that resulted from problems with the Lustre filesystem and an update to the database that triggered the reprocessing of many runs. The filesystem upgrade discussed previously will address some of these issues.

2.4.2 Monte Carlo Simulation Production

Current production of Monte Carlo simulations is based on the IC86-2020 detector configuration which covers a uniform detector configuration and filter scheme spanning from Spring 2012 through Spring of 2023. This configuration is representative of past previous trigger and filter configurations included in pass2. As with previous productions, direct generation of Level 2 background simulation data is used to reduce storage space requirements. The transition to the 2020 configuration was done in conjunction with a switch to a new combined simulation-reconstruction software suite.

New features in the simulation software include individually calibrated PMT waveforms, optimized event re-sampling for low-energy background simulation, and improved models of the optical properties of the ice. Direct photon propagation is currently done on dedicated GPU hardware at several IceCube Collaboration sites and through opportunistic grid computing. The number of such resources continues to grow along with further software optimizations for GPU utilization.

In the short term, we are saving trigger-level simulations. As we transition to a new offline processing and filtering scheme, we need to provide un-filtered simulation for physics working groups to test their filters before deployment. Once the new filters are defined, we will substantially reduce the data volume produced by simulation production by applying these filters to the Monte Carlo processing chain.

The simulation production team organizes periodic workshops to explore better and more efficient ways of meeting the simulation needs of the analyzers. This includes software improvements, new strategies, and providing the tools to generate targeted simulations optimized for individual analyses instead of a one-size-fits-all approach. New strategies have been developed for dynamically simulating of systematic uncertainties in our understanding of ice properties, hole-ice and DOM sensitivity and determining their impact on physics analyses. Throughput has continually increased due to incorporation of an increasing number of dedicated and opportunistic resources and several code optimizations. New monitoring tools are currently being developed to keep track of efficiency and further optimizations. New procedures have been implemented for coordinating and allocating resources and priorities for simulations produced by working groups as well as individuals. These efforts include performance metrics to reduce the time between a request by a group or individual and the completion of such request (Table 11).

Table 12 shows the amount of simulation produced by generator at selected energies. Individual datasets are configured with different energy ranges and spectra tailored to the individual needs requested by analyzers. Neutrino simulations are done per request, but CORSIKA background simulations are generally produced as a "back-fill". During PY3, the limited storage limited the amount of background cosmic-ray simulations.

Energy (GeV)	0.01	1E+02	1E+05	1E+07	1E+08	1E+09	1E+10
NuGen (events)							
NuMu	0	8.6E+08	7.6E+05	1.9E+05	1.8E+04	0	0
NuE	0	1.3E+08	4.6E+05	5.1E+05	4.8E+04	0	0
NuTau	0	2.4E+08	9.1E+05	3.4E+05	3.2E+04	0	0
LeptonInjector (events)							
NuMu	0	1.0E+09	1E+06	4.1E+05	3.8E+04	0	0
NuE	0	4.6E+08	3.5E+05	1.9E+05	1.8E+04	0	0
NuTau	0	1.4E+08	5.8E+05	6.0E+05	5.6E+04	0	0
GENIE (events)							
NuMu	3.9E+08	0	0	0	0	0	0
NuE	3.0E+08	0	0	0	0	0	0

NuTau	5.2E+08	0	0	0	0	0	0
Background livetime (days)							
CORSIKA	0	8.58	1.6E+01	1.9E+02	9E+02	0	0
MuonGun	0	0	1E-01	1E-01	0	0	0

Table 12: Simulation generated during PY3 as function of energy, including neutrinos (NuGen, LeptonInjector, and GENIE) and cosmic-ray background (CORSIKA, MuonGun).

2.4.3 Computing Resource Needs

Simulation production requirements are primarily dominated by background simulations with CORSIKA given that there is roughly a factor of 10^6 cosmic ray-induced muons triggering the detector for each neutrino event. Background simulations for the in-ice array require roughly 30k years of CPU time and about 2.4k years of GPU time to produce and filter. This is in addition to IceTop surface array simulations and signal simulations (including systematics). In 2022, we deployed a recently developed Triggered-CORSIKA module that replaces CORSIKA's post-reaction particle stack with a C++11 plugin that provides an API that allows for optimizing memory and CPU usage as well as storage requirements for high energy simulations.

As an alternative to simulating full CORSIKA air showers, we also simulate final-state muons that can be weighted according to a parametrized flux calculated from CORSIKA simulations using the same approach of MUPAGE developed by the ANTARES Collaboration. These MuonGun simulations are significantly more efficient to produce, requiring about 6M CPU-hours and comparable GPU time in order to meet our goals. These simulations must be validated against CORSIKA, but this requires a significantly smaller data set. Since the original parametrization of MuonGun, there have been several improvements to the hadronic interaction models included in CORSIKA. As a result, there is currently a new effort to re-parametrize MuonGun based on the new SIBYLL 2.3d model. We expect this effort to be completed in early PY4.

In a similar manner, we have employed new a method for treating systematic uncertainties in a computationally efficient way by continuously varying multiple nuisance parameters (such as the depth-dependent optical properties of the ice) within a single simulation set. This method has been validated and is fully described in M.G. Aartsen *et al.*, JCAP 10 (2019) 048. This approach works with full neutrino and weighted final-state lepton simulations.

Key achievements include:

- improvements in hardware simulation including individually calibrated PMT waveforms;
- added support for new types of sensors;
- improved models of the optical properties of the ice, including birefringence;
- addition of support for future detector hardware;
- optimization to improve efficiency and utilization of resources;
- new catalog of Monte Carlo datasets and simulation requests;
- improved monitoring of data processing and simulation production.

2.4.4 Data Processing and Simulation Services Labor Assessment

There are currently 2.4 FTEs assigned to WBS 2.4. There are no current plans to increase the number of FTEs working on Data Processing and Simulation Service, though we anticipate an increase in labor demand from the extensions to the IceCube detector. Mitigation of risk of labor shortages due to this additional scope is being handled through promulgation of the simulation mass production middleware (IceProd) to permit individual users to profit from the scheduling and data provenance services provided by this software. Key personnel include Juan Carlos Díaz-Vélez (lead), Robert Snihur (offline data processing), Eric Evans (automated data validation tools), and Agnieszka Leszczynka (IceTop / surface array simulations).

2.5 WBS 2.5: Software (E. Blaufuss)

WBS L3	Date	Achieved	Milestone
2.5.1	03/15/2023	04/12/2023	Spring 2023 software release
2.5.1	06/15/2023	06/22/2023	Summer 2023 software release
2.5.1	09/17/2023	9/28/2023	Fall 2023 software release
2.5.1	01/15/2024	12/14/2023	Winter 2024 software release

Table 13: WBS 2.5 Software PY3 milestones.

The software team continues to target four quarterly, major releases of the IceTray software suite, which is used in South Pole and northern hemisphere filtering, simulation of data samples and in higher level reconstruction and analysis throughout the collaboration. Additionally, smaller, targeted releases are issued as needed in support of data processing needs. 4 major releases were issued to date in PY3 (v1.6.0, v1.7.0, v1.8.0, v1.9.0), with an additional five point releases made to address issues in data processing and production that arose between major release cycles. Work is already underway to prepare the project targets for the first PY4 major release in Spring 2024. Key software release milestones and performance parameters for Software in PY3 are tabulated in Table 13 and Table 14, respectively.

Performance Metric	Objective	Achieved	Description
Releases per year	4	4	Quarterly releases meeting minimal quality standards
Test coverage, minimum	66%	65.5% (C++) 64% (python)	Fraction of lines of code executed in the test suite
CI min uptime	90%	95%	Fraction of days tests pass on all supported platforms
CD min uptime	50%	-	Fraction of days full-chain tests pass on single platform (to be retired; see text)
Critical ticket max lifetime	1 month	2 month	At least 90% of critical tickets resolved within this timescale

Table 14: Physics software (WBS 2.5) performance metrics.

IceTray software development is fully organized in an active and robust IceCube software organization (https://github.com/icecube) in a GitHub organization, with over 100 additional software repositories (containing both private and public aimed software packages) contributed from the collaboration. Development effort and release planning are coordinated using GitHub enterprise tools for issue tracking, pull requests, code reviews and release coordination in Kanban-style project boards. Additionally, all CI systems are available after the transition to GitHub. These are implemented with a collection of self-hosted GitHub Action runners (CI) that provide rapid, automated unit testing of newly submitted software. After each commit or pull request to the software repository, several automated builds are initiated will full run of the automated test suite. Lifecycle replacement of the hardware cluster supporting the CI system has yielded improved responsiveness and system uptime (~99%), and improved workflows have resulted in tests passing for >95% of commits made to the main development trunk. Custom "full stack" software tests that check physics level output (CD) are manually performed near time of release. Automation of the CD system is not feasible at this time given staffing levels, and the related metric will be retired until further notice.

The Winter 2024 release is now in use for production of updated simulation samples. Two time-critical issues were identified during PY3, both related to issues identified in production of simulation samples, with each being fixed as quickly as possible (2-month and 3-week timeframes), with point releases made to support production. Release and testing of a point-level release fixing the critical issue were complete within 2 weeks. There are currently ≃100 open issues, many focused on long-term code cleanup, expansion of software functionality to support the IceCube Upgrade, and optimizations awaiting available manpower for completion. The increased number of tickets is largely driven by detailed planning work and identification of software tasks and issues related to support of the IceCube Upgrade. The test coverage has increased to 65.5% for C++ and 64% for Python code bases and is approaching our stated goal of 66%. Efforts are focused on ensuring any new code or identified issues are fixed with appropriate testing in place; this is being enforced during detailed reviews in the GitHub PR workflow.

Continued software development and releases will focus on readiness for the IceCube Upgrade, now planned for deployment in the 2025–2026 season. The deployment of a wide variety of optical sensors and calibration devices, beyond just the standard IceCube DOMs, presents new challenges for the IceTray framework and IceCube reconstruction and simulation software packages. Adapting these software systems to deal with the new heterogeneous detector, while updating existing packages for more modern compiler and deployment environment, will require a continued coordinated effort over the next few years.

2.5.1 Software Labor Assessment

The IceCube M&O software program receives labor assistance under WBS 2.5 from resources, mostly graduate students and postdocs, contributed in-kind by IceCube collaborating institutions. These are coordinated through the semi-annual statements of work collected as part of the IceCube resource coordination process. This includes work to maintain core software infrastructure, development of new reconstruction and analysis software framework tools. Coordination of this effort is focused by software-focused activities and sessions at IceCube collaboration meetings, including discussions held at two 2023 meetings. These coordination efforts will continue through collaboration meetings and teleconferences in PY4.

Despite the large pool of contributed effort, maintenance of the IceCube software systems does require the daily attention of a dedicated, professional team of software engineers to handle the more complex aspects of rigorous software maintenance and maintenance of the development and build environments. UMD scientist Erik Blaufuss continues in the coordination and management role, with UMD scientist Michael Larson moved into the key IceTray and simulation systems developer role. The software development leadership team also receives effort from Don La Dieu (UMD), Kevin Meagher (UW), Tianlu Yuan (UW) and Juan Carlos Diaz-Velez (UW). Combined, these efforts total 4 FTE of effort on the M&O program. This team meets bi-weekly to coordinate development issues, prioritize tickets and drive release readiness.

The level of effort from core developers and in-kind contributed efforts has been sufficient over the first 3 years of the M&O grant to meet most key operational milestones and performance metrics for the IceCube software effort. Limited staffing has slowed some core software efforts, such as the deployment of new core filtering systems as improved pole filters. However, addressing the large increase in software issues and tasks from the integration of the IceCube Upgrade into the IceCube M&O program, both for core software tasks and support for Upgrade simulation and analysis, has lagged our planned efforts. For in-kind contributions, the delays in the Upgrade deployment have caused planned efforts for Upgrade tasks to be reassigned to meet graduation and career goals of the student and post-doc workforce. Core software efforts have been slowly reducing in level due to pressures from inflation. Addressing these lags in software effort remains a critical task for PY4 and beyond for the M&O management team.

2.6 WBS 2.6: Calibration (M. Rongen, D. Williams)

Calibration efforts in IceCube are focused on continuing to refine measurements of the optical properties of the South Pole ice that comprises the majority of our detector, as well as the IceCube DOM response to photons. Precise modelling of both is fundamental to converting detector observables into physical measurements such as neutrino direction, energy, and absolute flux.

2.6.1 Ice characterization

The perturbative fitter[1] has matured to the point where it has been used successfully to improve ice stratigraphy and tilt modeling[2] simultaneously. In addition, the new fitting method for the first time also yields a full covariance matrix for all parameters. This now allows us to access depth-correlated statistical uncertainties in the modeling and to generate perturbed ice model realizations for systematics studies. The updated ice model was presented at the 38th International Cosmic Ray Conference (ICRC2023), along with a unified analysis framework for the refrozen borehole ice ("hole ice"). A full ice-model release (called SpiceFTP), incorporating these improvements has been made available for simulation production in January 2024. The improvements inherent to SpiceFTP have also enabled us to evaluate the per-DOM relative detection efficiencies (RDEs). While this has been attempted already with previous ice model iterations, the resulting values showed strong correlations to the ice layer properties the respective DOMs are situated in. This made the resulting values unphysical and unsuitable for simulation production. This deficiency is now essentially resolved (Figure 17) and the deduced RDE values correlate to expectations from lab testing. Work is currently ongoing to quantify remaining deficiencies in the ice optical modeling.

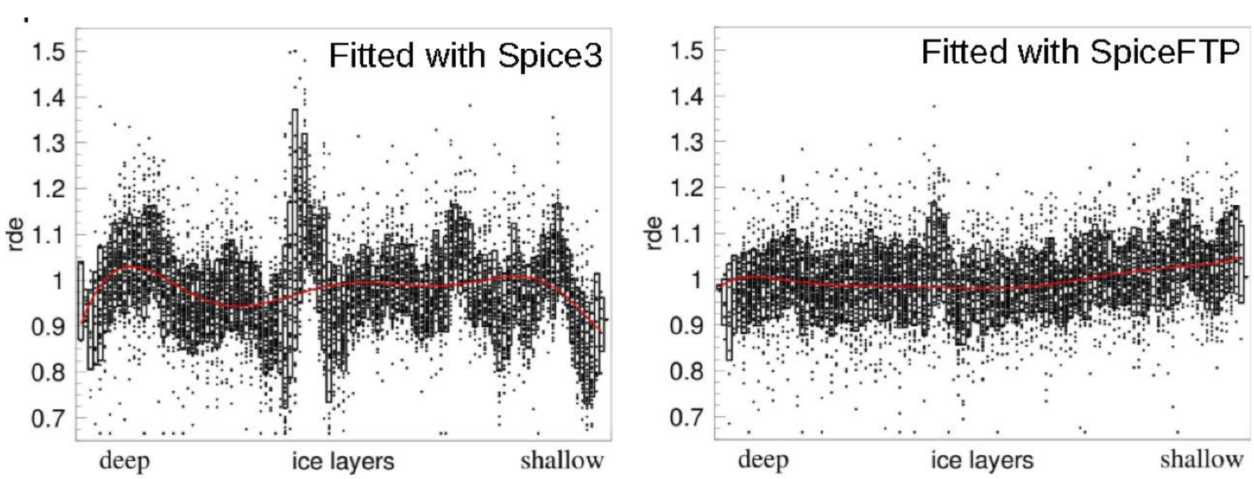

Figure 17: Relative DOM efficiencies (RDEs) as fitted using the new SpiceFTP and an old reference ice model (Spice3). Previously observed correlations to the stratigraphy of ice optical properties induced by an incomplete modeling of the ice have been strongly reduced.

[1] Generating a small set of simulations perturbing several thousand parameters at once in conjunction with a custom matrix solver which requires positive-definite solutions to predict solutions close to the global minimum.

[2] Tilt describes the undulation of layers of constant optical properties over the face of the detector and is e.g. required for precise cascade energy reconstruction.

2.6.2 DOM characterization

We continue to improve the modeling of the DOM single photoelectron (SPE) distribution. Most recently a minor inconsistency in how data from the FADC digitizers are processed in comparison to the ATWD digitizers has been discovered and rectified. Updated fitting code is being prepared which will include updated FADC pulse selection and fitting, and the procedure for correcting SPE peak location in data at Pole will be updated so that the most up to date SPE distribution characterization is used consistently across data and simulation. The evaluation of SPE charge distributions has also been applied to the most recent years of data taking. The year-to-year changes have proven to be small enough to not warrant an update to the calibration constants used to date.

Knowledge of the DOM positions in the ice is important for the event reconstruction. Results from two studies for the first time determining the geometry from in-ice optical data from muons and LED flashers were presented at ICRC2023. These studies are currently going through several checks, in particular to assure convergence of the result, before being incorporated in standard simulation.

2.6.3 Performance metrics

Many advances in IceCube's detector calibration, especially relating to the ice optical properties, are difficult to predict, and we continue to find that many advances are still possible.

Nevertheless, routine calibration, primarily regular updates to the DOMs calibration constants through DOMCal, remains of central importance. We here track key metrics of importance to the continued reliability of event reconstruction: module gain and timing resolution. Detector aging has not impacted these metrics to date; however, we continue to track these and can adapt calibration frequency as needed if this begins to play a role.

Performance Metric	Objective	Achieved	Description
DOM gain drift	< 2%	0.8%	Relative module gain change over time (95% quantile)
DOM timing stability	< 2.0 ns	1.8 ns	Spread in DOM timing calibration over time (95% quantile)
DOMCal result latency	< 1 week	< 4 days	Time to validate calibration results for online use

Table 15: Calibration (WBS 2.6) performance parameters.

2.6.4 Upgrade-related activities

The IceCube Upgrade will further boost our understanding of the ice properties and will also pose unique challenges as currently subdominant effects, such as the precise shape of the scattering function, become relevant.

In preparation for the IceCube Upgrade we are facilitating discussion of and simulation for the calibration devices (e.g. PencilBeam, POCAM, camera systems, LED flashers, and the dust logger). The calibration working group contributes subject matter expertise to design reviews for the Upgrade calibration devices and is evaluating the science case for special operations of devices in newly drilled Upgrade boreholes before they are frozen.

With the multitude of camera systems and measurements planned in the Upgrade, we have reviewed deployment data from the Sweden Camera system, installed as part of String 80, the last string to be deployed. Here we have been able to show that intensities, reconstructed from either white light illumination or from a laser shining roughly horizontally into the ice correlate remarkably well with the established stratigraphy from the Dust Logger.

During PY3 members of the calibration group contributed to quality assurance of the Upgrade sensors by helping to individually access the final acceptance testing results from 290 D-Eggs. This work will continue in PY4 with FAT testing of the D-Eggs concluding and the mDOMs being tested next.