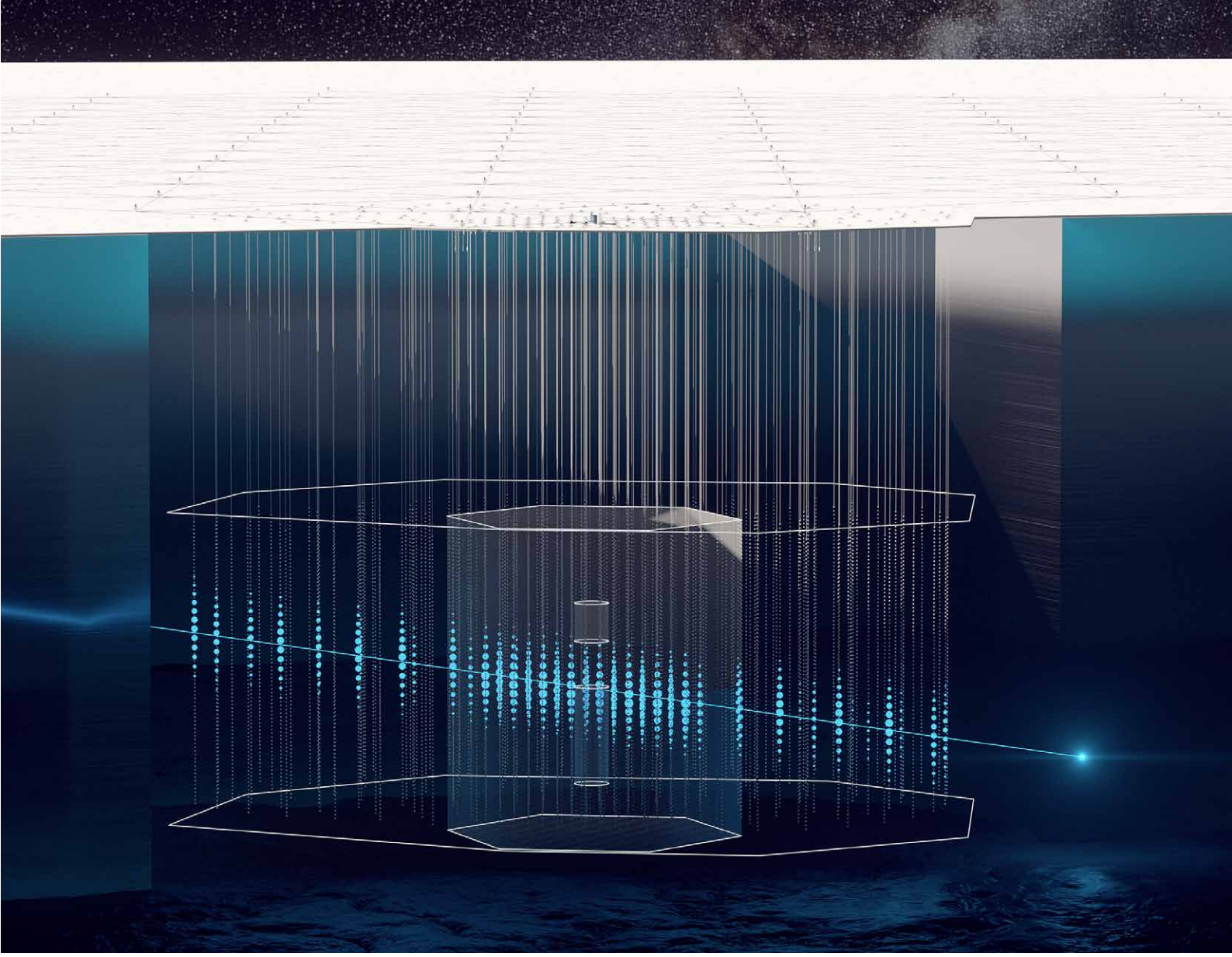


ASTROPARTICLE PHYSICS 2025.

Highlights and Annual Report

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

ASTROPARTICLE PHYSICS 2025.

Highlights and Annual Report

Cover
Key milestone for IceCube-Gen2, the planned expansion of the IceCube neutrino observatory at the South Pole: In July 2025, the German research ministry announced that it had shortlisted both proposals submitted by DESY – its next-generation synchrotron radiation source PETRA IV and the German participation in IceCube-Gen2 – as research infrastructures of national importance.

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Three classes of telescopes are required to cover the full energy range of the CTAO gamma-ray observatory: the Small-Sized Telescope (SST), the Medium-Sized Telescope (MST) and the Large-Sized Telescope (LST). DESY is playing a major role in the construction of the MSTs and the development of camera components for the SSTs.

The year 2025 at DESY

Dear Colleagues and Friends of DESY

As I reflect on the year 2025, I am proud to present this annual report of DESY. It is the first time that I have the honour to do this, having started as Chair of the DESY Board of Directors on 1 April. I have very much enjoyed this first half year in my new job, most of all as every day I learn something new about DESY, and I get to work with so many talented and committed people.

In 2025, there were many changes in the Directorate: Britta Redlich started on 1 January as the new Director in charge of Photon Science, taking over from Franz X. Kärtner, who had filled this role ad interim for a year after Edgar Weckert's term finished at the end of 2023. On 1 April, Iris Wilhelm took up her position as Administrative Director. And, on 1 November, Ulrich Husemann started as new Director in charge of Particle Physics. My deep gratitude goes to the former and interim directors, Christian Harringa, Edgar Weckert, Arik Willner, Ties Behnke and in particular Helmut Dosch, for their tireless commitment to advance DESY. Together with the experienced directors Wim Leemans and Christian Stegmann, we form a team that is steering DESY – in collaboration with the deputy directors, group and team leaders, all employees as well as the members of our advisory boards and the funding agencies – through these somewhat turbulent times.



Figure 1
Ceremonial transition at DESY on 31 March 2025: Outgoing Chair of the DESY Board of Directors Helmut Dosch (right) transfers leadership to Beate Heinemann (left), with Manja Schüle (Minister of Science, Brandenburg) and Katharina Fegebank (Senator and Second Mayor of Hamburg) in attendance.



Figure 2
The DESY Board of Directors with newly appointed members in November 2025 (from left): Miriam Hufnagl (Delegate of the Directorate for Innovation, CTO (interim)), Iris Wilhelm (Director of Administration), Christian Stegman (Director in charge of Astroparticle Physics), Wim Leemans (Director of the Accelerator Division), Britta Redlich (Director in charge of Photon Science), Beate Heinemann (Chair of the DESY Board of Directors) and Ulrich Husemann (Director in charge of Particle Physics)

Science faces profound challenges in today's world. The pace of technological and geopolitical change has blurred the lines between open knowledge and strategic competition. Global crises, such as pandemics, climate change, conflicts and wars, underscore the need for international collaboration, and simultaneously trust and cooperation across borders are eroding. At the same time, the spread of misinformation and the politicisation of scientific facts threaten public confidence in evidence-based decision and policy making. Researchers must balance openness with responsibility – safeguarding integrity, transparency and security while ensuring that science continues to serve humanity as a shared, global endeavour.

DESY as a premier research institution plays an important role in the national and international science landscape. Each year, thousands of scientists from around the world come to us to perform measurements, attend workshops and conferences or collaborate with colleagues on our sites in Zeuthen and Hamburg. We have collaborations with institutions across Europe and the entire world, and our scientists travel across the globe to advance their research.

The success of DESY is founded on the design, construction and operation of fantastic research infrastructures, on cutting-edge contributions to science, on the thriving of many scientists at all career levels, who pursue their ideas and engage in collaborations worldwide, and – above all – on the skilled and dedicated employees of DESY, who enable all this at a technical and administrative level.

This year, DESY has once again demonstrated its scientific excellence. In February 2025, a panel of international scientists appointed by the Helmholtz Association visited and reviewed DESY. All areas of our research and of the operation of our facilities were rated with the highest marks, and many useful recommendations

were given for the next funding period of the Helmholtz Association's programme-oriented funding (PoF V). The panel was also impressed by our activities in the areas of diversity, international cooperation, sustainability, innovation and talent development. Later in the year, we were thrilled that six Clusters of Excellence with DESY contributions were selected for funding by the German Research Foundation (DFG), and at the European level one European Research Council (ERC) Starting Grant and two Synergy Grants were awarded.

A major achievement this year has been the completion of the upgrade project FLASH2020+. The implementation of external seeding and the newly installed variable-gap undulators will significantly enhance the capabilities of the FLASH free-electron laser facility, so that it remains at the forefront of extreme ultraviolet and soft X-ray science. In Zeuthen, a key accomplishment has been the completion of the construction of new sensor modules (mDOMs) for the upgrade of the IceCube neutrino detector at the South Pole: 201 mDOMs were shipped to Antarctica to be installed there during the Antarctic summer. During the second half of 2025, the accelerator of the European XFEL X-ray laser was warmed up for the first time since its start-up in 2017 to allow the mandatory inspection of helium valves, perform maintenance tasks and install a new electron source at the beginning of the accelerator, which was newly developed at DESY's photoinjector test facility (PITZ) in Zeuthen. DESY's efforts for on-site experiments in particle physics are also beginning to pay off: The results of the search for very light dark matter particles from the ALPS II experiment have been published.

2025 has also seen DESY at the forefront of critical political and strategic initiatives. The selection of our two future projects, IceCube-Gen2 and PETRA IV, in the "National Prioritisation Process for Extensive Research Infrastructures", alongside seven other large research infrastructures in Germany, underscores our important role in shaping the national and European research agendas. In 2026, we expect to get the final go-ahead for the PETRA IV project and continue to advance the detailed planning, with the goal of delivering the project on time and on budget. 2026 will also bring an update of the European Strategy for Particle Physics, to which DESY scientists are contributing significantly; the update might shape the future of the field for a long time.



Figure 3
Celebrating a milestone for German science: On 8 July 2025, DESY employees gathered in the auditorium to mark the BMFTR's decision to prioritise IceCube-Gen2 and PETRA IV as key research infrastructures. In the front row (from left): new directors Iris Wilhelm and Britta Redlich.

It is particularly important to attract young talents to DESY. At any time, we have about 130 apprentices, 250 doctoral students and 250 postdoctoral researchers at DESY. Among the PhD students and postdoctoral researchers, about two thirds are not from Germany, and our International Office plays a key role in ensuring that these young people are supported during the first weeks, so that they quickly feel at home. This year, we also welcomed three new Lead Scientists, who bring fresh perspectives and expertise to DESY: Elina Fuchs in theoretical particle physics, Samaya Nissanke in gravitational and multimessenger astrophysics and Nønne Prisle in physical chemistry and aerosol research.

Innovation is a very important part of DESY's mission. We want to contribute to ensuring that science also results in making life better for society at large. The successful participation in the Startup Factories competition of the Federal Ministry for Economic Affairs and Energy, resulting in the "Impossible Founders", which strengthen the innovation ecosystem in Hamburg, as well as our strategic cooperation with the Fraunhofer-Gesellschaft exemplify our commitment to translating research into practical applications. These collaborations, along with our many regional, national and global partnerships with industry partners and academic institutions, position DESY as a leader in both scientific and industrial innovation.

Our campuses in Hamburg and Zeuthen continue to evolve. We had three topping-out ceremonies this year, celebrating the structural completion of the Centre for Accelerator Science and Technology (CAST) building and the two DESY Innovation Factory buildings. The new visitor centre DESYUM in Hamburg will open in early 2027. Together with our campus partners, we are striving to make our campuses more sustainable and greener, and we have been awarded prizes this year: for the roof terrace of the Max Planck Institute for the Structure and Dynamics of Matter and the DESY Building 36, a big hall from 1977 on the Hamburg campus.

In an increasingly interconnected world, international collaboration is more important than ever. Our partnerships with institutions such as the SESAME synchrotron light source in Jordan and our engagement in science diplomacy reflect our belief in the power of global cooperation. As we navigate geopolitical challenges, DESY remains committed to fostering transparency, exchange and collaboration on both local and international levels.



Figure 4
Impression of the roof of DESY's award-winning Building 36

In closing, I would like to express my gratitude to the entire DESY community – our experienced and early-career scientists, engineers, technicians, administrators, users and partners – for their dedication and hard work. My special thanks go to the funding agencies – the Federal Ministry of Research, Technology and Space (BMFTR) and the Science Ministries in Hamburg and Brandenburg (BWFG and BMWK) – which have been supporting DESY for many decades. I would also like to extend my heartfelt thanks to my predecessor Helmut Dosch for his outstanding leadership and long-standing commitment to DESY, which have laid the foundations for much of what we are building on today. Together, we continue to push the boundaries of knowledge and innovation, ensuring that DESY remains at the forefront of global research.

Warm regards,



Beate Heinemann
Chairperson of the DESY Board of Directors

Astroparticle physics at DESY

Director's foreword



Dear friends of DESY,

In 2025, the DESY Astroparticle Physics Division made significant strides towards the realisation of several of its projects, underscoring DESY's prominent position both in the development of modern detector technology and on the global stage of international astroparticle physics.

The upcoming Cherenkov Telescope Array Observatory (CTAO) – a world-class gamma-ray observatory with over 60 telescopes to be installed at two sites in Chile and on the Canary Island of La Palma – has entered the construction phase. DESY is playing a key role in the development of the online software, the construction of the Medium-Sized Telescopes (MSTs), the development of camera components for the Small-Sized Telescopes (SSTs) as well as computing and data processing activities. Two MST Pathfinder telescopes for the southern site in Chile were built in 2025, nearing completion and subsequent installation in 2027. Electronic components for the SST cameras were produced for an engineering and test model of the cameras.

On 7 January 2025, the European Commission established CTAO as a European Research Infrastructure Consortium (ERIC). DESY is represented on both the CTAO ERIC Council and the Administrative and Finance Committee. With the CTAO Science Data Management Centre (SDMC) located on its campus in Zeuthen, DESY is providing a key infrastructure for state-of-the-art scientific data processing.



Figure 1
Meeting of the newly formed CTAO ERIC Council at DESY in Zeuthen in November 2025

The IceCube Upgrade is an extension of the IceCube neutrino telescope at the South Pole, designed to enable significantly more precise measurements of fundamental neutrino properties and to improve the calibration of the detector. To this end, a total of 670 new optical sensors were to be installed on six strings, together with innovative calibration instruments, and embedded up to 2.5 km deep in the Antarctic ice. Together with German universities, DESY in Zeuthen developed one of the two sensor types for the upgrade: the multi-photomultiplier digital optical module (mDOM), 227 of which were produced and tested at DESY. The final batch of mDOMs left for Antarctica in July 2025, marking the successful completion of sensor production activities for the IceCube Upgrade at DESY. The year closed with three DESY staff members at the Amundsen–Scott South Pole Station contributing to the drilling, installation and commissioning of the first new detector string.

The IceCube Upgrade is an important step towards IceCube-Gen2, the future expansion of the detector to a measurement volume of eight cubic kilometres. In July 2025, the German Federal Ministry of Research, Technology and Space announced that it had shortlisted both proposals submitted by DESY – its next-generation synchrotron radiation source PETRA IV and the German participation in IceCube-Gen2 – as research infrastructures of national importance. This selection marks a major step towards the final approval of both projects.

Essential preparatory work for IceCube-Gen2 was also carried out at the Radio Neutrino Observatory Greenland (RNO-G), where the detection of neutrinos with petaelectronvolt (PeV) energies using radio waves will be studied as an important future addition to IceCube. The experiment, which is currently under construction, made significant progress during the last field season, particularly through successful drilling campaigns and hardware improvements. Together with a better understanding of the detection chain, these findings are of great importance for future seasons and data acquisition in general.

After a three-year start-up phase, which was evaluated very positively in the summer of 2025, the German Centre for Astrophysics (DZA) was formally established as a non-profit limited liability company (GmbH) at the beginning of September. The DZA thus completed all the steps required to operate independently from January 2026. Together with TU Dresden University of Technology, DESY played a major role in getting the DZA project up and running: As the organisation responsible for the project, DESY was partly in charge of financing the start-up phase and contributed its extensive experience from setting up other large-scale research projects. The newly established research group of Samaya Nissanke bridges the activities at DESY and DZA in joint multimessenger explorations, in particular regarding sources of gravitational waves.

DESY is currently designing, building and testing the ultraviolet (UV) camera for the ULTRASAT space telescope, a satellite mission led by the Weizmann Institute of Science and the Israel Space Agency. A development model of the camera for calibrating and testing the telescope was completed, while work on characterising the CMOS UV sensor continued. At the same time, the components for the camera's flight model are being manufactured.

The scientific achievements of the Astroparticle Physics Division in 2025 included highlights spanning a wide range of subjects, a selection of which we are pleased to present to you in this report. A broad study explored CTAO's potential to detect and investigate Galactic transients, with DESY contributing major insights on fast flares from pulsar wind nebulae and gamma-ray emission from novae. DESY is also developing AI agents to support the operation and scientific output of CTAO. The RNO-G collaboration has shown that signals recorded from aircrafts flying over Greenland can be used to calibrate the in-ice antennas, making expensive calibration campaigns obsolete. In February 2025, the collaboration running the KM3NeT neutrino detector in the Mediterranean Sea – including scientists from DESY – announced a groundbreaking discovery: the detection of the neutrino event with the highest energy ever observed. Various analyses were conducted to determine possible astrophysical origins of the event, to which DESY groups made leading contributions. And studies of the ultrahigh-energy cosmic-ray (UHECR) skymap over a range of energies provided insights that could help to explain a mysterious anisotropy observed in the arrival directions of UHECRs raining down on Earth.

On the Zeuthen campus itself, the successful completion of the first phase of the campus development has created a modern, functionally integrated infrastructure. New buildings and outdoor facilities enhance both academic performance and the quality of the campus environment. With the completion of the CTAO SDMC and canteen, the CTAO functional expansion and the first construction phase of the outdoor facilities, the first part of the campus masterplan has thus been successfully implemented.

To promote public understanding of science and inspire young people in particular to take an interest in science, the Astroparticle Physics Division continued to actively support young talent and engage in outreach activities. Examples include its School Lab and Cosmic Lab, participation in the Long Night of Economy and the 650th anniversary celebrations of the municipality of Zeuthen, the organisation of the annual International Cosmic Day, which was attended by young people from 28 countries, the traditional summer student programme and a physics camp organised in cooperation with the Brandenburg Ministry of Education, Youth and Sport.

I would like to express my sincere thanks to our entire team and our partners in Germany and around the world for their dedication and contributions to our joint achievements in 2025. I look forward to continuing to deliver outstanding scientific results together with you in the years to come.

Christian Stegmann
Director in charge of Astroparticle Physics

News and events

Highlights in 2025

January

Mathematics Olympiad awards ceremony

The awards ceremony for the regional round (Stage 2) of the Mathematics Olympiad in the Dahme-Spreewald district for the 2024/2025 school year took place on 22 January at DESY in Zeuthen. The prize winners from grades 5 to 12 were honoured in the presence of their family members. The programme included a talk on astroparticle physics by DESY scientist Anna Nelles, an expert in the radio detection of neutrinos and cosmic rays.



Anna Nelles talking at the awards ceremony of the regional round of the Mathematics Olympiad

February

Talks on innovation and transfer



From left: Beate Heinemann (DESY), Andrea Lübcke (member of the Bundestag from Bündnis 90/Die Grünen for Brandenburg), Michael Kellner (Parliamentary State Secretary at BMWK), Sabine Brock and Christian Stegmann (both DESY)

During a visit to DESY in Zeuthen, Michael Kellner, Parliamentary State Secretary at the German Federal Ministry for Economic Affairs and Climate Action (BMWK), gained insight into current and planned research projects. The focus was particularly on pioneering technologies being developed at DESY that have the potential to address big societal challenges, such as accelerator developments at the PITZ photoinjector test facility and medical innovations like *FLASH* radiation therapy to combat tumours.

DESY also presented its work in quantum technologies within the Centre for Quantum Technology and Applications (CQTA) and its collaboration with industry to strengthen innovation. Kellner praised DESY's technological expertise and regional impact, emphasising the importance of research, technology transfer and training for future-oriented innovation.

Scientific evaluation of DESY

In February, a committee of 23 leading scientists in their field carried out a comprehensive evaluation of DESY, which examined the international scientific excellence of the research programmes, the role of DESY within the Helmholtz Association and in the international science landscape as well as the DESY user facilities. Particular attention was paid to the importance of DESY's unique research infrastructures for groundbreaking science.

The committee analysed and assessed DESY's contributions in recent years to the Research Field *Helmholtz Matter*, in which DESY is involved in eight of nine Programme Topics. At the end of the DESY evaluation, Daniel Zajfman, Chair of the Evaluation Committee, concluded: "If I were 30 years old, I would clearly consider this place."



Members of the Evaluation Committee visited DESY in Zeuthen on 7 February.

CTAO ERIC Council officially established



Inaugural meeting of the CTAO ERIC Council in Bologna

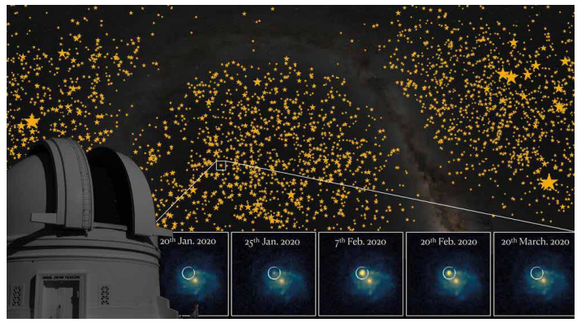
The Council of the European Research Infrastructure Consortium for the Cherenkov Telescope Array Observatory (CTAO ERIC) was formally established on 12 February during an inaugural meeting in Bologna, Italy. Following the founding of the CTAO ERIC by the European Commission in January 2025, the newly formed Council plays a fundamental role in steering the organisation's future. As the observatory's governing body, it brings together delegates from all parties that form the CTAO ERIC to oversee strategy and decision-making in pursuit of CTAO's mission and objectives.

DESY is strongly involved in CTAO, particularly with the CTAO Science Data Management Centre (SDMC), which is located on the campus in Zeuthen, and the construction of the Medium-Sized Telescopes (MSTs) for the observatory. Christian Stegmann, DESY Director in charge of Astroparticle Physics, is a member of the German delegation to the CTAO ERIC Council.

ZTF publishes most extensive supernova record

The international Zwicky Transient Facility (ZTF) Working Group, in which DESY is also involved, released the most comprehensive data set of Type Ia supernovae to date, doubling the number of known cosmic explosions of this type. The collection of 3628 high-resolution data sets recorded between March 2018 and December 2020 was published in a special issue of the journal *Astronomy and Astrophysics*. Type Ia supernovae are used to measure distances in the universe.

"The publication reveals new insights into the nature of Type Ia supernovae and their use as cosmological candles, and heralds the dawn of the high-precision era in supernova cosmology," said Marek Kowalski, Lead Scientist at DESY and Professor at Humboldt University of Berlin, whose research group is involved in the experiment.



The title page of the special edition of *Astronomy and Astrophysics* shows the Type Ia supernovae recorded by ZTF.

Workshop on Numerical Multi-Messenger Modelling

From 26 to 28 February, a workshop at DESY in Zeuthen brought together the community working on numerical codes to simulate multimessenger – i.e. photon, neutrino and cosmic-ray – emission from astrophysical sources. As the third meeting of its kind, it allowed extensive time for discussion and co-working, covering topics such as code developments and code comparison, applications to hot sources in the photon/neutrino sky as well as multimessenger fitting.



Participants of the Workshop on Numerical Multi-Messenger Modelling

March

AstroCentPlus kicks off in Warsaw

AstroCentPlus (AC+) – a major project aimed at advancing astroparticle physics in Poland – was launched in Warsaw in mid-February. AC+ is funded by the EU United in Excellence programme and seeks to expand the AstroCent Institute at the Nicolaus Copernicus Centre of the Polish Academy of Sciences into an international centre for cutting-edge research and innovation.

As a close partner of AC+, DESY particularly supports the commercialisation of scientific developments. With its many years of experience in technology transfer and innovation promotion, DESY is helping to ensure that findings from developments in astroparticle physics can also be translated into industrial applications and technological developments.



Christian Stegmann presented DESY's activities in innovation and technology transfer at the AstroCentPlus kick-off event in Warsaw.

April

Tschüss Helmut. Moin Beate.



Helmut Dosch hands over the DESY master key – and with it, the management – to Beate Heinemann.

On 1 April, Helmut Dosch, who had been leading DESY for more than 16 years, handed over the Chair of DESY's Board of Directors to Beate Heinemann. A professor at Universität Hamburg, she had previously served as a member of the Directorate in her capacity as Director in charge of Particle Physics and is the first woman to head the research centre. Also on 1 April, Iris Wilhelm took over as Administrative Director. The Zeuthen staff members bid farewell to Helmut Dosch during his parting visit to the Zeuthen site in May.

May

Public lectures resume on the Zeuthen campus

After a break of several years due to the COVID-19 pandemic and to extensive construction work on the Zeuthen campus, the first public lecture was held again at DESY in Zeuthen on 20 May. In the brand-new lecture room, David Berge, Lead Scientist at DESY and Professor at Humboldt University of Berlin, presented the current research projects at DESY that focus on the study of cosmic objects and events using photons, neutrinos and gravitational waves.



David Berge held the first public lecture in the new lecture room.

June

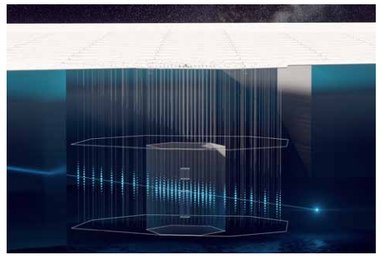
Long Night of Economy

On the evening of 20 June, alongside many companies and research institutions in the Dahme-Spreewald District, DESY in Zeuthen opened its doors to offer insights into its workshops, laboratories and research facilities. What is the world made of? Where do cosmic rays come from? And what technologies enable us to find answers to these questions? Through guided tours, presentations and discussions with DESY staff, visitors learned more about the training opportunities and research projects at DESY, as well as the Centre for Quantum Technology and Applications (CQTA) and CTAO, the world's largest gamma-ray observatory and an important partner on the DESY campus.



Visitors in the DESY workshops during the Long Night of Economy

July

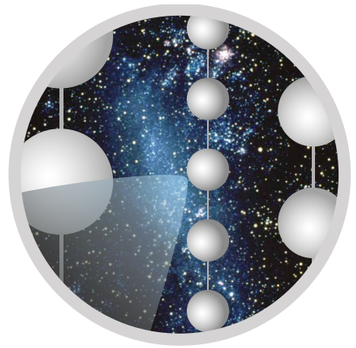


IceCube-Gen2 will significantly expand the capabilities of the IceCube neutrino observatory at the South Pole.

PETRA IV and IceCube-Gen2 selected as prioritised research facilities

Two projects with DESY participation were selected in the "National Prioritisation Process for Extensive Research Infrastructures" of the Federal Ministry of Research, Technology and Space (BMFTR): On 8 July, Federal Research Minister Dorothee Bär announced that both projects submitted by DESY were shortlisted as research infrastructures of national importance.

The X-ray source PETRA IV will enable researchers to analyse a wide range of structures, systems and processes at the nanoscale with unprecedented resolution and speed. Its fields of application range from bio- and quantum technologies, through sustainable materials and new batteries, to microelectronics and materials research. IceCube-Gen2 is a powerful upgrade of the IceCube neutrino observatory, which has been in operation at the South Pole since 2010. It will detect significantly more cosmic neutrinos and yield new insights into their sources, the Earth's atmosphere and the properties of the Antarctic ice.



Production of sensors for IceCube Upgrade completed

The final sensors for the upgrade of the IceCube neutrino observatory left for Antarctica in July, marking the successful completion of sensor production activities for the IceCube Upgrade at DESY. Together with German universities, DESY in Zeuthen had developed one of the two sensor types for the upgrade: the multi-photomultiplier digital optical module (mDOM), 227 of which were produced at DESY.

In addition to the final hardware production and meticulous testing, considerable effort was devoted at DESY in 2025 to the development and implementation of calibration routines to enable the reliable reconstruction of neutrino events. The mDOMs therefore arrived at the South Pole as fully characterised instruments, allowing calibration and commissioning to proceed efficiently. On-site acceptance tests confirmed that all delivered modules remained operational. By the end of 2025, the first new string of sensors had been successfully installed in the Antarctic ice. The remaining strings were to be deployed in January 2026.



The last batch of sensors for the IceCube Upgrade was shipped to Antarctica in July.

Assembly of Medium-Sized Telescopes for CTAO begins

The first two towers for the Medium-Sized Telescopes (MSTs) of the upcoming CTAO gamma-ray observatory arrived at the assembly hall in Bohnsdorf near DESY in Zeuthen, which is responsible for designing and manufacturing the MSTs within the CTAO collaboration. After many years of intensive planning, development and preparation, the delivery marked a key milestone: the start of assembly of the observatory's first two MST Pathfinder telescopes, which will be installed at the southern CTAO site in the Atacama Desert in Chile.





Delivery of two towers for the CTAO MSTs and start of assembly of the MSTs

Celebrating 650 years of Zeuthen



Enjoying hands-on experiments at DESY on the occasion of the 650th anniversary of Zeuthen

Under the motto "Zeuthen creates knowledge", DESY took part in the 650th anniversary celebrations of the municipality of Zeuthen. Visitors were able to find out more about training opportunities at DESY, try out hands-on activities and experiments and gain insights into the world of research – science made understandable, tangible and fascinating.

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IN ZEUTHEN



Samaya Nissanke

Samaya Nissanke joins DESY as Lead Scientist

Samaya Nissanke, a world-leading expert in gravitational-wave and multimessenger astrophysics, was jointly appointed Lead Scientist at DESY and Professor at the University of Potsdam. The appointment, which was made possible by the Helmholtz Distinguished Professorship programme, will significantly strengthen this fast-growing research area at DESY and in Germany.

Nissanke is a pioneer in multimessenger astronomy with gravitational waves and electromagnetic observations. Her work played a key role in the first observation of a neutron star merger on 17 August 2017, marking the dawn of a new era in astronomy where cosmic events can be seen and "heard" for the first time. She is also one of the most visible figures in the international astrophysics community with gravitational waves. In addition to her research at DESY and the professorship, she will contribute to the German Centre for Astrophysics (DZA), where she will help build up the multimessenger programme with a focus on gravitational-wave follow-up observations – a strategic pillar of the centre's scientific mission.

DESY welcomes 100 summer students from around the world

A total of 100 summer students from 33 different countries participated in DESY's summer student programme in Hamburg and Zeuthen this year, with 14 of them working on astroparticle physics projects at DESY in Zeuthen. Students from Ukraine, Spain and Italy were particularly well represented among the participants. The students spent their time working on research projects, attending lectures, touring the campus and enjoying cultural exchange – and of course doing some sightseeing.



The 2025 summer students at the DESY campus in Zeuthen

August



Herwig Schopper

DESY mourns the loss of Herwig Schopper

DESY and the physics community mourn the loss of a great scientist, science manager, diplomat and visionary. The physicist and former DESY and CERN Director General Herwig Schopper passed away in Hamburg on 19 August at the age of 101. He chaired the DESY Board of Directors from 1973 to 1980.

Herwig Schopper shaped the physics landscape in Germany and Europe like few others, guided by his vision of science without borders in the pursuit of understanding the fundamental workings of our world. In doing so, he also helped pave the way for DESY to become the international research centre it is today. DESY will make sure that his physics legacy lives on.

DEUTSCHES ZENTRUM ASTROPHYSIK

September

German Centre for Astrophysics (DZA) established

After a three-year start-up phase, the German Centre for Astrophysics (DZA) was formally established as a non-profit limited liability company (GmbH) at the beginning of September. It was entered in the commercial register of the Dresden Local Court that same month. The DZA had thus completed all the necessary steps to be able to operate independently from January 2026.

During the summer, the DZA had undergone a comprehensive evaluation of its start-up phase by the federal government and a panel of experts, who gave a thoroughly positive assessment of the work carried out so far. The successful evaluation paved the way for the official establishment of the centre. Together with TU Dresden University of Technology, DESY played a major role in getting the DZA project up and running: As the organisation responsible for the project, DESY was partly in charge of financing the start-up phase and contributed its extensive experience from setting up other large-scale research projects.



Following a successful evaluation, the DZA was officially established as a non-profit organisation in September 2025.



Lea Marcotulli

Lea Marcotulli becomes Helmholtz Investigator Group Leader

Lea Marcotulli, a high-energy astrophysicist who is also an Adjunct Professor at Clemson University in the USA, started as Helmholtz Investigator Group Leader in the Gamma Astronomy group at DESY in Zeuthen in September. Together with her group, she is focusing on the subject “From black holes to the expansion of the universe: discovering the high-energy sky with the Cherenkov Telescope Array Observatory”.

Florian Oest visits DESY in Zeuthen



Florian Oest (centre) together with Christian Stegmann (left) and Beate Heinemann (right)

Florian Oest, a member of the Committee on Research, Technology, Space and Technology Assessment of the German Bundestag and responsible for DESY within the CDU parliamentary group, visited DESY in Zeuthen on 15 September. Following a tour of the facilities on campus and in-depth discussions with DESY Directors Beate Heinemann and Christian Stegmann, he emphasised his support for PETRA IV, the planned upgrade of DESY’s existing X-ray source, and for the Einstein Telescope, a future European project to build a gravitational-wave detector, for which a site in the Lausitz region of Saxony, amongst others, has been proposed.

October

Astroparticle and Particle Physics Workshop

From 6 to 8 October, the Astroparticle and Particle Physics Workshop at DESY in Zeuthen brought together researchers from astroparticle physics and particle physics to share recent developments and discuss their impact across these closely related fields. Research in each of these areas increasingly overlaps, with progress in one field often influencing the others.

Through a combination of theoretical and experimental presentations and discussions, the workshop sought to strengthen the knowledge transfer between the communities and contribute to a more integrated understanding of the fundamental physics governing our universe. The programme included sessions on the Standard Models of cosmology and particle physics, neutrinos and feebly interacting particles, gravitational waves and multimessenger astronomy as well as detectors, algorithms and tools.



Participants of the Astroparticle and Particle Physics Workshop

DESY and DZA strengthen cooperation with Ukrainian astronomy

Christian Stegmann, DESY Director in charge of Astroparticle Physics, and Stefan Ohm, representative of the German Centre for Astrophysics (DZA), visited the western Ukrainian city of Lviv to deepen scientific relations with Ukrainian partner institutions and demonstrate solidarity with the Ukrainian scientific community. Together with Iryna Vavilova, Vice-President of the Ukrainian Astronomical Association, they signed a Letter of Intent on cooperation aimed at supporting the recovery and strengthening of Ukrainian astronomy and recognising the significance of the Rome Declaration of Intent for Science, Research and Innovation in Ukraine.



Christian Stegmann and Iryna Vavilova after signing the Letter of Intent in Lviv



Christian Stegmann and Thomas Naumann with the Max Planck statue by sculptor Bernhard Heiliger

Max Planck statue returns to the Zeuthen campus

The DESY campus in Zeuthen has long been home to a statue of renowned physicist Max Planck by sculptor Bernhard Heiliger. The original statue was moved to its intended destination, Humboldt University of Berlin, in 2006. DESY then commissioned the Heiliger Foundation to produce a new cast. During the extensive redevelopment of the campus, the statue had to be temporarily relocated. On 8 October, it was reinstalled in its central location on the DESY campus and unveiled by Christian Stegmann and former DESY physicist Thomas Naumann.

November

DESY Award for Exceptional Achievements for Carolin Gnebner

Carolin Gnebner received the DESY Award for Exceptional Achievements in recognition of her long-standing, sustained and internationally influential commitment to young people in the field of astroparticle physics through the Cosmic Lab, outreach initiatives and digital learning formats at DESY in Zeuthen. With her dedication and pedagogical expertise, she has introduced young people in Germany and around the world to astroparticle physics at DESY in new and varied ways, showing them how science works.



Carolin Gnebner

December

International Cosmic Day

On 13 November, the annual International Cosmic Day (ICD) took place for the 14th time, organised by DESY in Zeuthen. The ICD is dedicated to the unnoticed cosmic particles that flood our universe and constantly rain down on Earth. In 2025, it brought together 112 groups at schools, universities and research institutions across 28 countries, inspiring students to learn about cosmic particles, conduct experiments and exchange their findings in global video conferences.

Guided by scientists and teachers, participants stepped into the shoes of researchers for one day, gaining first-hand experience of the power of international cooperation and of how science transcends borders, languages and cultures to unite people in the pursuit of knowledge.



The DESY ICD team



Physics camp at DESY strengthens young talents in Brandenburg



The young people attending the physics camp at DESY in Zeuthen with Christian Stegmann (left), Brandenburg's Minister of Education Steffen Freiberg (centre rear) and some of the camp supervisors

From 1 to 5 December, 14 teenagers from Brandenburg had the opportunity to gain a deep and practical view into world-class research at a physics camp at DESY in Zeuthen. The camp was organised in cooperation with the Brandenburg Ministry of Education, Youth and Sport (MBJS) and funded by the German federal state of Brandenburg. It was part of the MBJS's new student academy programmes to promote gifted pupils, made possible by a three-year cooperation agreement signed in 2024 between DESY and the Ministry.

The camp brought research to life, offering young people a varied programme that introduced them, step by step, to the world of modern physics – from astroparticle physics through particle physics to accelerator technology. Brandenburg's Minister of Education Steffen Freiberg attended the closing event and praised the teenagers' commitment.

GENERA-COPA – promoting gender and diversity in STEM

The GENERA-COPA project, coordinated by members of the DESY Astroparticle Physics Division, was selected as one of 25 projects funded out of 124 proposals submitted in the latest Erasmus+ call in Germany. Launched in September 2025, the project will receive 400 000 euros in EU funding over three years, supplemented by 30 000 Swiss francs from Switzerland.

The project focuses on innovative approaches in teaching, learning and mentoring as well as on integrating a gender and diversity perspective into the maths-intensive STEM fields (science, technology, engineering and mathematics). The motivation for the project is that research is becoming increasingly international, interdisciplinary, diverse and team-based, a challenge for everyone involved. With the provided funding, GENERA-COPA is poised to make a significant contribution to the European STEM landscape, promoting equality, diversity and inclusion across educational and research institutions.



The DESY campus in Zeuthen

Astroparticle physics

Astroparticle physics at DESY rests on three pillars: (i) observations of gamma rays, (ii) observations of neutrinos and (iii) their interpretation and understanding through astroparticle physics theory. Gamma rays and neutrinos are neutral messengers that are not deflected by magnetic fields on their way to Earth and therefore point back to their sources, allowing astronomical observations to be performed. Further undeflected messengers are photons at smaller energies (radio waves to X-rays) and gravitational waves. In their contemporaneous observation and combination lies great strength, which will increasingly drive progress in our understanding of the astrophysics of the most violent objects and events in the universe.

Experiments, theory, projects and infrastructures

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All that remains visible of a fully installed station of the Radio Neutrino Observatory Greenland (RNO-G) are these two towers, carrying solar panels, a wind turbine and communications antennas.

A nuisance, a curiosity, an opportunity

Detecting signals from airplanes with radio neutrino detectors

When flying from London to Tokyo, you may be concerned about the route the plane takes because it will influence your dinner plans. Passengers are mostly not so concerned about the astrophysical measurements that may be affected by their flight. The Radio Neutrino Observatory Greenland (RNO-G), however, routinely detects airplanes flying over Greenland, leading to elevated trigger rates and neutrino-like signals. While these signals are a nuisance for routine operation, the RNO-G collaboration has also shown that they can be used to calibrate the in-ice antennas to centimetre precision, making expensive surveying campaigns obsolete.

RNO-G looks for short radio pulses that follow a neutrino interaction in the polar ice. In this age where electronic equipment is all around us, though, these radio pulses have become more common. Thankfully, the power received by a scientific instrument decreases with one over the distance squared from the emitter. So the further away from civilisation and human technology, the better for the radio observatory. Or in other words: On the top of the Greenland ice sheet, it is far less likely that someone will walk right through the detector with their mobile phone, disturbing the measurements. However, the received power also scales with the emitted power. This means that, even at great distance, something very powerful can still be detected by the extremely sensitive instruments. Given a line of sight, it is easy to see a 100 kW emitter at distances of tens of kilometres. Then again, kilowatt emitters are very rare in remote locations. However, they tend to fly over the instrument.

As shown in Fig. 1, three airplanes could be easily identified in the RNO-G data as an increase of the received amplitude above the baseline. It should be noted that the amplitudes recorded by RNO-G are typically very stable and lie close to the baseline shown in Fig. 1 before the first airplane arrives. There used to be very little air traffic over northern Greenland, as most flights from North America to Europe followed routes much further south. However, given geopolitical developments, most airlines are now avoiding Russian airspace, meaning that the fastest route from Eastern Asia to Europe is often a polar route. This specific route is more weather-dependent, but often passes over RNO-G. As RNO-G is less sensitive to neutrino signals with an airplane flying overhead, these signals have to be accounted for internally, which prompted a study led by a DESY postdoctoral researcher [1].

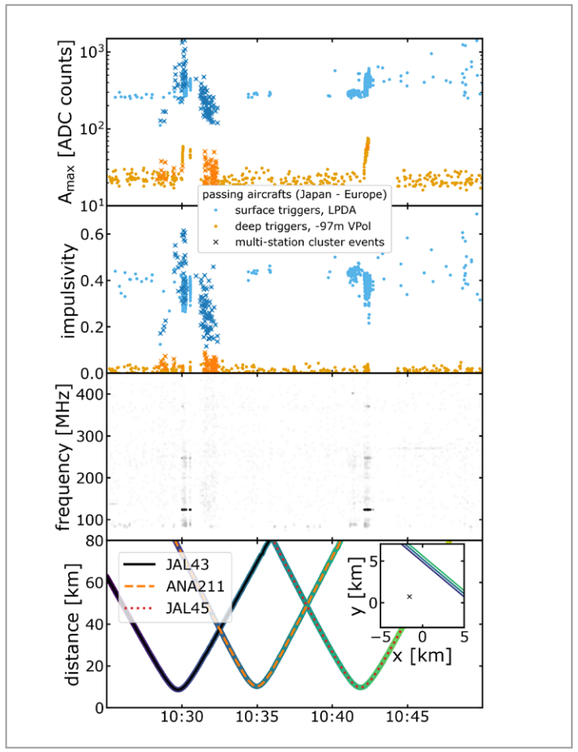


Figure 1
Airplane signals in RNO-G as a function of local time for one morning in 2022. First panel: Maximum amplitude recorded. Second panel: Signal impulsivity. Different trigger streams of RNO-G are grouped according to colour, showing that antennas deep in the ice record less signals than those close to the surface. Third panel: Corresponding frequency spectrum, with baseline subtracted, revealing preferred frequencies of some signals. Fourth panel: Flights recorded with their publicly transmitted position data above RNO-G. A Japan Airlines (JAL) flight is followed by an All Nippon Airways (ANA) flight, followed by another JAL flight. All airplanes fly one after each other along the same route from London to Tokyo. From [1].

What is RNO-G seeing?

Anyone with half an interest in airplanes must immediately ask themselves: what are these signals? This is not easy to answer conclusively, partly because the aviation industry has non-public technical specifications. In particular for military aircraft flying over RNO-G that do not even officially reveal their position, it is impossible to tell what system on the aircraft the detector is seeing. However, circumstantial evidence from RNO-G suggests that different things are at play. As shown in Fig. 1, the two Japan Airlines (JAL) flights mostly appear on a frequency used for plane-to-plane communication. Might one speculate that pilots are chattier when they belong to the same company? This does not explain the high impulsivity of some signals, however. A highly impulsive signal might originate from altitude radars or other powerful control systems.

Or is RNO-G simply seeing inefficiencies in the engines that manifest as power emissions? Without going into the details of how aircraft engines work – how would we know this?

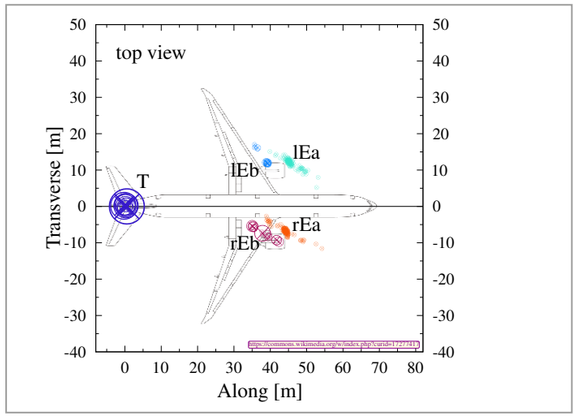


Figure 2
Signals related to an aircraft landing at Amsterdam Airport, as detected coincidentally with the LOFAR radio telescope during a lightning observation. Coloured points indicate the emission detected by LOFAR. The size of the circles indicates the emission strength. From [2].

Airplane detection with LOFAR

Coincidentally, at around the same time, the LOFAR radio telescope observed an aircraft landing at Amsterdam Airport. During a regular lightning observation – in which DESY scientists are also involved – an airplane tried to avoid the clouds and found itself within LOFAR's field of view [2]. Thanks to LOFAR's superior timing resolution and the imaging algorithms developed for lightning detection, it was possible to triangulate the signals back to the aircraft to an accuracy of tens of centimetres. For an airplane performing a banking manoeuvre during landing, this demonstrates a surprisingly high performance of the algorithm.

As shown in Fig. 2, it is quite obvious that the strongest signals stem from the tail of the aircraft, where some intentional transmitter for position determination is presumably located. Sources at the intake and exhaust of the engines are clearly subdominant. Given that the airplane was flying through statically charged clouds, this is a not a surprising finding. What is surprising, however, is that no signal was observed from the wingtips. The wingtips carry little charge wicks that are intended by the aircraft industry to prevent the plane from becoming statically charged in clouds. As the efficiency of these charge wicks is impossible to test in the laboratory – you would need a plane at full speed and a bunch of clouds at rest – it might simply be that LOFAR is the first instrument to indicate that these devices seem rather pointless. The engines do all the discharging for the aircraft, and wingtip discharging devices do not add anything.

Back to RNO-G

If such accurate measurements are possible with LOFAR, does this also open up a possibility for RNO-G? RNO-G has neither the expensive timing synchronisation that LOFAR has, nor the long baselines that enable high resolution, but the problem can be turned around. If we know where the airplane is, does this help RNO-G?

When installing antennas in the ice, it is quite complicated to position them with the accuracy required for neutrino reconstruction. Imagine using a big shovel and having to place something in a hole with a precision of less than 5 cm. Anyone who has ever tiled a patio will know how hard that is. Consequently, the antenna positions typically have to be surveyed afterwards, entailing additional costs and effort.

However, using the airplane signals and their known positions, the antennas can be triangulated to the required specifications, as at distances of more than 10 km, the airplane can be treated as a point source. This eliminates the need for expensive calibration campaigns, which will be particularly important for the even larger IceCube-Gen2 detector at the South Pole.

And should the global situation change and affect flight routes, there are always the few airplanes that land at Summit Station and bring in the scientists and equipment. They fly close by and right overhead, so they light up RNO-G like a Christmas tree.

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[1] S. Argawal et al. (RNO-G Collaboration), JINST 20, P11015 (2025)
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IceCube Upgrade: Completion of DESY mDOM production and first deployment

From final production to first string in the Antarctic ice

The year 2025 marked the completion of the production, quality assurance testing and shipment of all multi-photomultiplier tube (PMT) digital optical modules (mDOMs) for the IceCube Upgrade, which were delivered in time for installation at the South Pole. In parallel, significant effort went into developing the calibration framework required to turn these sensors into precision physics instruments. The year closed with three DESY staff members at the Amundsen–Scott South Pole Station contributing to the drilling, installation and commissioning of the first new detector string.

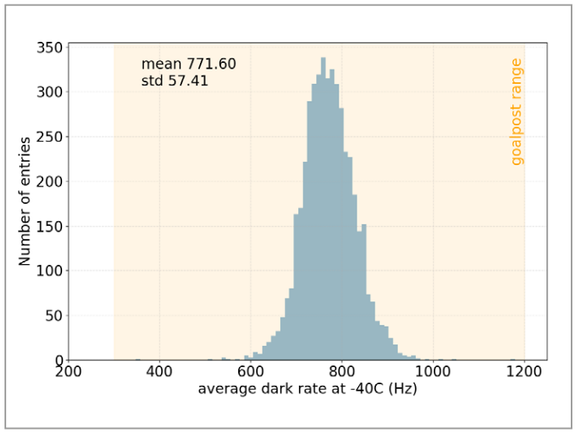


Figure 2
Average trigger rate per PMT from background events measured during final acceptance testing of 178 mDOMs in a dark freezer at -40°C. The shaded region indicates the accepted operational range. From [3].

The IceCube Upgrade

After more than a decade of operation, the IceCube neutrino observatory at the South Pole has made major contributions to particle and astroparticle physics. It has established the existence of high-energy, astrophysical neutrinos and identified evidence for a small number of sources. It has also measured atmospheric neutrino oscillations with world-leading precision. Moreover, it continues to operate as a unique facility for studies of cosmic-ray air showers and provides excellent sensitivity to many phenomena beyond the Standard Model [1]. To push the scientific programme further and enable more discoveries over the next decades, IceCube is getting an upgrade [2].

The IceCube Upgrade includes deep-ice drilling and installation of several new strings of instrumentation, densely populating the ice with new photosensors and calibration devices. This instrumentation will lower the energy threshold for neutrino detection down to a few GeV, allowing for high-precision studies of neutrino oscillations, dark matter searches and increased sensitivity to core-collapse supernova neutrinos. In addition, the new instrumentation can be used to improve our understanding of the glacial ice and thereby also the reconstruction of neutrinos at the TeV energy scale and above. Finally, the design and installation of new photosensors are also part of the R&D programme for the next-generation neutrino telescope planned at the South Pole, IceCube-Gen2, which was selected for the shortlist of Germany's prioritised national research infrastructures in July 2025.

DESY has played a leading role in the design, production and testing of one type of new photosensor: the multi-photomultiplier tube (PMT) digital optical module (mDOM). The mDOM is a 36 cm pressure-resistant glass sphere that houses 24 three-inch PMTs oriented in multiple directions, along with cameras and LEDs for calibration. This design provides nearly isotropic photon acceptance, with a direction-averaged detection efficiency more than twice that of the existing IceCube DOMs, and constitutes roughly half of the IceCube Upgrade instrumentation.

From production line to South Pole ice

Building on the production ramp-up described in last year's report, 2025 saw the completion of the mDOM production programme. The final modules rolled off parallel production lines at DESY in Zeuthen and Michigan State University (MSU) in the USA in the summer of 2025, closing out a multi-year manufacturing effort that sustained a pace of approximately five modules per week. Despite the complex assembly of PMTs, optical gel, cables and electronics in a compact pressure vessel, the critical failure rate remained low, at approximately 1%, across the entire production run at DESY. This reflects both robust subsystem design and extensive pre-integration testing performed in collaboration with many universities across Germany.



Figure 1
Final shipment of mDOMs prepared for transport to the South Pole

The final shipments left DESY and MSU in late July and August 2025, respectively, to join the 128 mDOMs already at the South Pole since December 2024 (Fig. 1). On-site acceptance tests, designed with significant input from DESY personnel, confirmed that all delivered modules remained operational, with sufficient spares available for deployment.

Calibration: Preparing for physics

Completing the hardware is only part of the challenge. To realise the scientific potential of the IceCube Upgrade, each mDOM must be calibrated with sufficient precision to enable reliable reconstruction of neutrino events. In 2025, significant effort at DESY went into developing and implementing the calibration routines that will accompany the mDOMs into operation.

The mDOMs are designed to detect Cherenkov photons produced by neutrino interactions in the ice. However, photons from background processes, such as radioactive decays in the glass components and muons passing nearby, also trigger the PMTs. A team at DESY characterised the rate (Fig. 2) and overall signatures of these background events and devised strategies to use these signatures as precision calibration sources [3–5]. This work, developed in parallel with final production, means that the mDOMs arrived at the South Pole as fully characterised instruments, allowing calibration and commissioning to proceed efficiently toward physics-quality operation.

First string in the ice

The year ended with a milestone that brought the project full circle. In late 2025, three members of the DESY team travelled to the Amundsen–Scott South Pole Station to contribute directly to the IceCube Upgrade deployment (Fig. 3). Working alongside the broader IceCube collaboration, they took part in hot-water drilling of the new boreholes, installation of modules in the ice and the initial commissioning steps to bring the new sensors online.

By the close of 2025, the first new string had been successfully installed in the Antarctic ice. The remaining strings were scheduled for deployment through January 2026, completing the IceCube Upgrade detector. After years of design, production, testing and calibration work at DESY, the mDOMs are deployed as intended: deep in the ice at the bottom of the world, watching for neutrinos.



Figure 3
Three members of the mDOM team – Karl-Heinz Sulanke, Matthias Schust and Satoshi Fukami – travelled to the South Pole to assist with drilling, installation and commissioning of hardware for the IceCube Upgrade.

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The highest-energy neutrino ever observed

Searching for possible sources of a record-breaking neutrino event detected by KM3NeT

On 12 February 2025, the KM3NeT collaboration – including scientists from DESY – announced a groundbreaking discovery: the detection of the neutrino event with the highest energy ever observed. Called KM3-230213A, the neutrino's energy was estimated to be about 220 PeV – significantly higher than any neutrino detected before. The event provided the first evidence that neutrinos of such high energies are produced in the universe. Following the observation, various analyses were conducted to determine possible astrophysical origins of the event, to which members of the Gamma Astronomy and Theoretical Astroparticle Physics groups at DESY in Zeuthen made leading contributions.

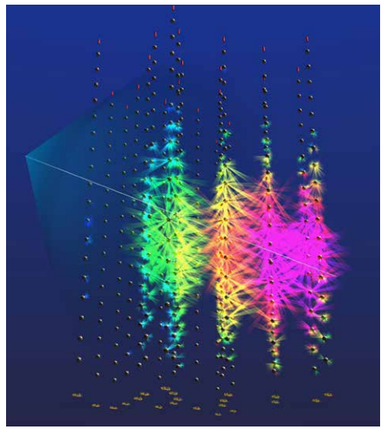


Figure 2
Visual display of the ultrahigh-energy neutrino event observed in KM3NeT within the ARCA detector, travelling from right to left (straight light blue line). The colours indicate the light registered by the photo-multipliers on each module, where the different colours represent different observation times.

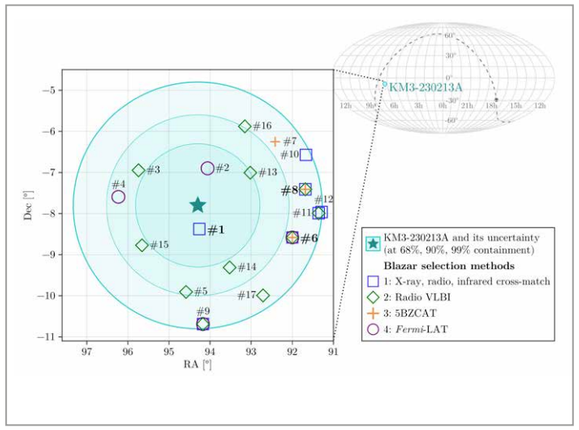


Figure 3
Summary of KM3-230213A and the 17 candidate blazar counterparts identified in the study. Both the location of the KM3NeT event in equatorial coordinates (J2000) and its uncertainty regions are shown. The three main candidate blazars are labelled in bold: #1 (MRC 0614-083), #6 (0605-085) and #8 (PMN J0606-0724). From [2].

KM3-230213A

The KM3NeT neutrino telescope in the depths of the Mediterranean Sea comprises two detectors: ARCA, located at a depth of 3450 m about 80 km off the coast of Sicily, Italy, is designed to study high-energy neutrinos and search for the sources of cosmic neutrinos. ORCA, located at a depth of 2450 m about 40 km off the coast of Toulon, France, is optimised to investigate the fundamental properties of the neutrinos themselves.

On 13 February 2023, the digital optical modules of ARCA registered the Cherenkov light generated by an extremely high-energy muon traversing the entire detector, which had 21 detection lines with almost 12 000 photomultipliers in operation at the time (Fig. 1 and 2). The level of illumination was so high that more than 25% of the photomultipliers that detected a signal saturated. Detailed analyses led to an estimate of the muon's energy at a record value of 120 (+110 -60) PeV. This implied that the primary neutrino that generated the muon had an even higher energy, estimated at around 220 PeV, about 30 times the highest neutrino energy detected so far.



Figure 1
Workers install digital optical modules for the KM3NeT underwater neutrino detector, which is currently under construction in the Mediterranean Sea.

The KM3NeT collaboration, which includes scientists from DESY, reported the observation of the record-breaking event, named KM3-230213A, in *Nature* in February 2025 [1].

Searching for possible sources

The direction of KM3-230213A was reconstructed as near-horizontal, originating 0.6° above the horizon. As atmospheric muons cannot travel long distances through seawater without being absorbed, the near-horizontal inclination of the muon's trajectory, combined with its enormous energy, provided compelling evidence that it originated from a cosmic neutrino interacting in the vicinity of the detector.

The high-energy universe is the realm of cataclysmic events, such as accreting supermassive black holes at the centre of galaxies, supernova explosions, gamma-ray bursts, all not yet fully understood. These powerful cosmic accelerators generate streams of particles known as cosmic rays. Some cosmic rays may interact with matter or photons near the source, thereby producing photons and neutrinos. As the highest-energy cosmic rays travel through the universe, some of them may also interact with photons from the cosmic microwave background radiation, generating extremely energetic "cosmogenic" neutrinos.

Characterising candidate blazar counterparts

Prime candidates for possible sources of KM3-230213A are blazars – active galactic nuclei powered by supermassive black holes that emit much more radiation than their entire galaxy. By combining multimessenger observations, the MessMapp project at DESY and the University of Würzburg, funded by the European Research Council (ERC), aims to unravel the connection between neutrinos and blazars. After the detection of KM3-230213A, the MessMapp team and collaborators explored a possible blazar origin of the ultrahigh-energy (UHE) neutrino [2].

The study combined a vast number of observations from archival data and dedicated follow-up observations with ground- and space-based telescopes. It provided complete multiwavelength coverage across the radio, infrared, optical, X-ray and gamma-ray bands, resulting in the most complete data set available for these sources to date. Seventeen blazars were identified as possible astrophysical counterparts of the UHE neutrino (Fig. 3). Among them, three stood out for their electromagnetic properties. One blazar exhibited a radio flare coinciding with the neutrino arrival time (PMN J0606-0724). Another candidate displayed a rising trend in X-ray flux in a one-year window around the neutrino arrival time (MRC 0614-083), while a third underwent a gamma-ray flare during the same period (0605-085).

Although none of these blazars could so far be conclusively linked to the UHE neutrino, improvements in the calibration of the KM3NeT telescope are expected to decrease systematic uncertainties in the directional reconstruction of KM3-230213A, thereby reducing the degeneracy in identifying possible counterparts. The comprehensive multiwavelength observational data presented in the study will be crucial for reliable candidate selection in future analyses, providing an essential baseline for understanding the electromagnetic behaviour of these sources.

Elaborating an accretion flare interpretation of the event

A further study investigated the blazar MRC 0614-083 [3], which was pinpointed in [1] as the directionally closest source to KM3-230213A exhibiting variable multiwavelength emission. A joint interpretation of the optical, infrared and X-ray light curves suggested that MRC 0614-083 had undergone a super-Eddington accretion flare – a violent transient event resulting in a dramatic increase in luminosity, often in conjunction with powerful outflows – accompanied by efficient proton acceleration. That flare then initiated a delayed infrared echo within the surrounding dust torus.

While the proton acceleration site could not be inferred directly, the injection of non-thermal protons in an isotropic wind and their interaction with the infrared photons from the dust echoes resulted in i) a neutrino signal correlated with the delayed dust echoes, explaining the delay of the neutrino emission with respect to the peak mass accretion rate, and ii) an electromagnetic cascade driven by π^0 gamma rays, which describes the observed X-ray flare as a function of both time and spectrum. MRC 0614-083 thus emerged as an interesting candidate for the origin of KM3-230213A, owing to its proximity and its capability of producing UHE neutrinos during an accretion flare phase, leading to the observed optical flare, dust echoes and X-ray flare.

Outlook

This first ever detection of a neutrino with hundreds of PeV opens a new chapter in neutrino astronomy and a new observational window on the universe. To learn more, however, more such events need to be detected. The ongoing expansion of KM3NeT with additional detection lines and the acquisition of additional data will improve its sensitivity and enhance its ability to pinpoint cosmic neutrino sources, further strengthening its leading role in advancing multimessenger astronomy.

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* With substantial scientific contributions from MessMapp team members

Gamma-ray transients explorations with CTAO

New opportunities for studying particle acceleration in rapidly evolving Galactic environments

The Cherenkov Telescope Array Observatory (CTAO), in which DESY is strongly involved, will revolutionise gamma-ray astronomy with unprecedented sensitivity and resolution. As part of a broad study that explored CTAO's potential to detect and investigate Galactic transients, members of the DESY Gamma Astronomy group working on the scientific exploration of CTAO focused on two science cases: pulsar wind nebulae flares and gamma-ray emission from novae. Both illustrate the new opportunities opened up by CTAO for studying particle acceleration in rapidly evolving Galactic environments.

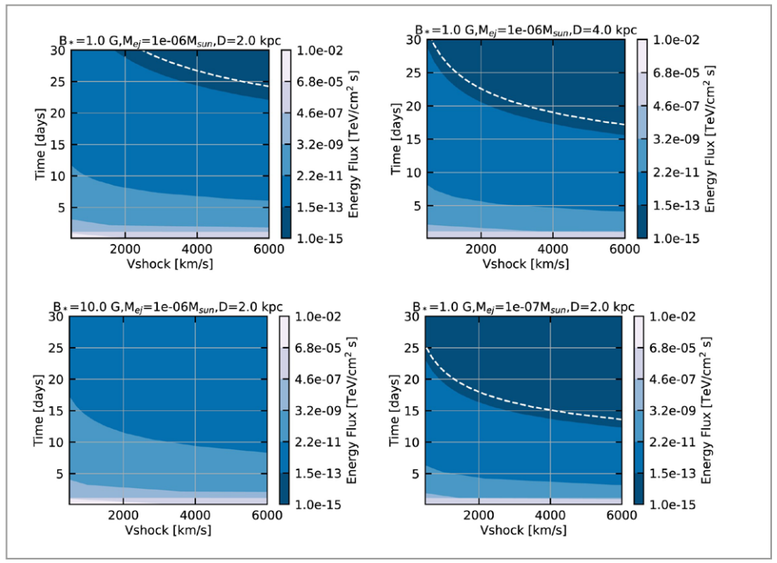


Figure 2
Expected energy flux in gamma rays with time after nova explosion as a function of shock velocity, integrated above 10 GeV.
Top left: For an RS Ophiuchi-like system at 2 kpc.
Top right: For the same physical properties, yet at a larger distance of 4 kpc.
Bottom left: With increased magnetic field strength.
Bottom right: With decreased mass loss rate.
In all plots, the white dashed line indicates the CTAO isoflux line at 10^{-13} TeV cm^{-2} s^{-1}. Below this line, the region should be easily accessible to CTAO. From [2].

Contributions to CTAO

The DESY Gamma Astronomy group is leading the construction of the CTAO's Medium-Sized Telescopes (MSTs), which will be crucial to the observatory's sensitivity. CTAO is designed to revolutionise gamma-ray astronomy, providing an order-of-magnitude improvement in sensitivity together with unprecedented temporal and angular resolution. This will enable the detection of sub-minute gamma-ray variability and detailed spectro-morphological studies of extended sources. These observations are essential to address fundamental questions, such as how magnetic energy is dissipated and converted into particle acceleration and radiation, or how charged particles are accelerated to extreme energies in our Galaxy.

As one of the main in-kind contributors to CTAO, DESY will be granted a fraction of the observation time. The Gamma Astronomy group aims to take a leading role in several topics, including the Transients Key Science Project [1]. The Astroparticle Physics Division has extensive expertise in transient phenomena, rapid-response observations and timing analyses. It is thus well placed to coordinate and interpret multiwavelength follow-ups of multimessenger events (e.g. neutrinos, gravitational waves, fast transients). Contributions include rapid identification and prioritisation of targets, which benefit from DESY's multi-wavelength activities, as well as timing and variability studies across different energy bands and interpretation within a multimessenger framework, including fast blue optical transients, gamma-ray bursts, active galactic nuclei and supernova explosions.

As part of these efforts, members of the Gamma Astronomy group were involved in a collaborative study that explored the feasibility of detecting new Galactic transients with CTAO and the prospects for studying them with target-of-opportunity observations [2]. Using realistic simulations, the work investigated CTAO's capabilities to detect new transient very-high-energy (VHE) phenomena from Galactic sources, ranging from microquasars to pulsar-wind nebulae (PWNe) flares, novae, transitional millisecond pulsars and magnetars. Experts on Galactic physics from the Gamma Astronomy group participated in this work, focusing on two science cases in particular: fast flares from PWNe and gamma-ray emission from novae. Both cases illustrate how CTAO will open up new possibilities for studying particle acceleration in rapidly evolving Galactic environments.

Fast flares from PWNe

For PWNe, the team investigated CTAO's capability to detect fast gamma-ray flares, using the Crab Nebula as a benchmark. The Crab has shown spectacular flaring activity at MeV to GeV energies, with variability down to time scales of hours, while no corresponding variable component has yet been established in any other bandwidth.

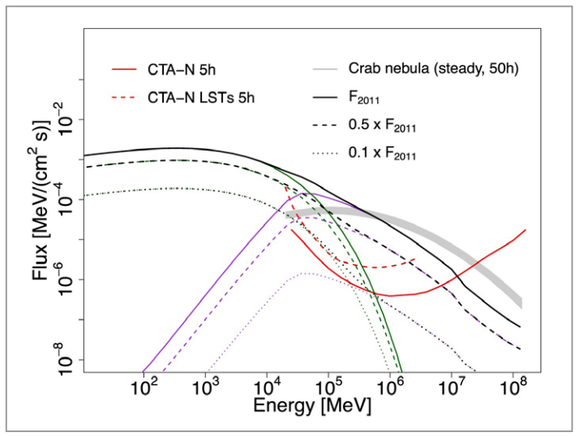


Figure 1
Synchrotron (green lines), inverse Compton (purple lines) and total (black lines) emission from the Crab Nebula for different flare models. See [2] for details.

Detecting a new component above a few GeV – or placing stringent limits on it – is crucial for understanding the acceleration mechanism responsible for the flares and the physical conditions of the electron–positron pair plasmas in the emitting region. The group's simulations show that CTAO will be able to probe bright Crab-like flares below 200 GeV on sub-hour time scales and investigate their possible TeV counterpart with observations of a few hours (Fig. 1). This will enable time-resolved studies of flare evolution and provide new constraints on extreme electron acceleration and magnetic-field dissipation in PWNe.

Understanding gamma-ray emission from novae

A second focus was the emerging class of gamma-ray novae. The detection of the recurrent nova RS Ophiuchi at TeV energies [3] demonstrated that nova explosions can accelerate particles to very high energies, establishing these apparently modest stellar explosions as laboratories for shock acceleration. Using the 2021 eruption of RS Ophiuchi as a reference, the team studied how such an event would be observed with CTAO. The simulations show that an RS Ophiuchi-like nova could be detected with very high significance in exposures as short as approximately 30 min. CTAO would furthermore be able to follow the evolution of the VHE emission over several weeks and reconstruct its spectrum down to energies of a few tens of GeV during the brightest phases (Fig. 2).

These results are particularly relevant because they move the study of novae from the detection of individual exceptional events towards population and time domain studies. Detailed monitoring with CTAO, combined with observations from radio to X-rays and GeV gamma rays, will make it possible to follow the evolution of the shock and determine how efficiently particles are accelerated as the ejecta interact with their environment. In particular, the evolution of the gamma-ray spectrum can constrain the maximum particle energy and help distinguish between leptonic and hadronic emission scenarios.

Transients discovery potential of CTAO

More generally, the publication demonstrates the discovery potential of CTAO for Galactic transients. Its combination of substantially improved sensitivity, a low energy threshold and rapid target-of-opportunity observations will allow transient phenomena to be studied on time scales that are difficult to access with the present generation of imaging atmospheric Cherenkov telescopes. For DESY, this work also establishes a direct connection between its major contribution to the realisation of CTAO – with the construction of the MSTs – and the scientific exploitation of the observatory – with development of the transients science programme that will exploit this capability.

Building on this work, the Gamma Astronomy group aims to take a leading role in transients and multimessenger observations with CTAO. The combination of expertise in VHE gamma-ray analysis, rapid-response observations, timing studies and multiwavelength coordination provides a strong basis for identifying and interpreting new transient phenomena. Through the CTAO Transients programme, these activities will extend from Galactic accelerators such as PWNe and novae to gamma-ray bursts, supernovae, fast blue optical transients and transient activity from active galactic nuclei, as well as electromagnetic counterparts of neutrino and gravitational-wave events.

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Gamma-ray astronomy meets agentic AI

Developing verified AI workflows for telescope software engineering and gamma-ray analysis

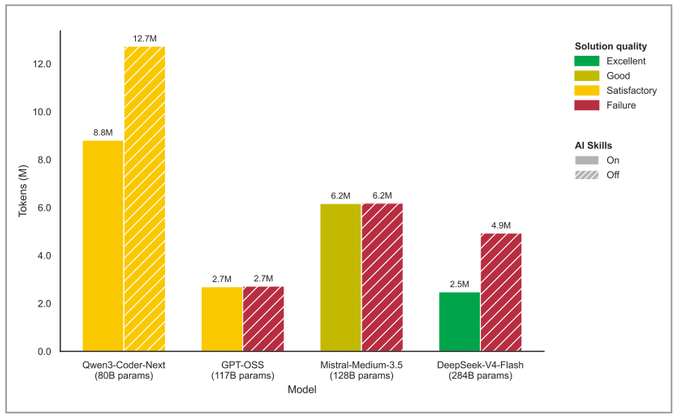


Figure 2
Preliminary comparison of four open-weight model families. Bar height shows token use for each attempt to reproduce an analysis with public H.E.S.S. data; colour indicates the manual quality rating. Solid bars denote runs with the Gammapy skill, hatched bars runs without it. All four skill-assisted runs were rated at least satisfactory, compared with one of the four controls. Each bar represents a single unblinded run, and the skill contained target-related sanity values; the comparison supports the value of curated context but does not quantify statistical variation.

The upcoming Cherenkov Telescope Array Observatory (CTAO) will depend on distributed control software and on scientific tools such as Gammapy. DESY is developing locally deployable AI agents to support both: checked assistants that turn reviewed project knowledge into code, tests and analysis artefacts, run conventional validation tools and return evidence for expert approval. The efforts range from telescope software engineering to a new end-to-end prototype for scientific gamma-ray analysis.

From CTAO operations to Gammapy analysis

Gamma rays from pulsars, exploding stars and black holes reveal extreme processes in the universe. In the Earth's atmosphere, they create particle cascades whose charged particles emit Cherenkov light. CTAO will observe these flashes with telescope arrays in Spain and Chile. At each site, the Array Control and Data Acquisition (ACADA) system – to which DESY makes significant contributions – will supervise instruments, handle data streams, execute plans and react to alerts [1]. Scientists will use the open-source Python package Gammapy [2] to select observations, estimate backgrounds, fit models and generate reproducible analyses [3].

Both settings rely on knowledge distributed across specifications, software and people. ACADA spans interacting subsystems, broad requirements and use cases as well as numerous monitoring points. Analyses depend on correct data, units, interfaces and physical assumptions. Agentic AI can help navigate this complexity, but an error could affect commissioning, observations or publications. AI contributions must therefore be traceable, executable, checked and reproducible.

Agentic work in a verified loop

Agentic AI couples a language model to a workspace, memory and tools, enabling it to plan, inspect files, run code and react to results. A harness adds a pinned environment, controlled data, limits, traces and tests. A skill adds domain rules, application programming interface (API) patterns, required artefacts and acceptance criteria. Keeping both outside the probabilistic model makes them inspectable and versioned and lets the same expertise work across agent hosts and open-weight models.

In the verified loop, an agent receives traceable sources and generates one bounded artefact, such as a data model, test or

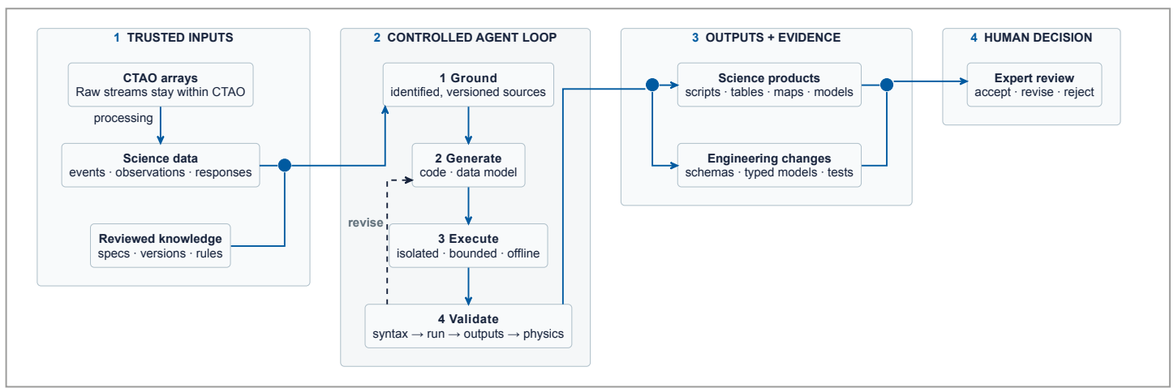


Figure 1
A verified agentic loop. Reviewed, versioned project sources and controlled analysis data enter an agent workspace. The agent generates, executes and validates a bounded artefact, such as an analysis script, software change or typed data model; a failed check triggers repair. Successful outputs are presented with source versions, code, logs and validation evidence for expert review. Raw camera streams remain in observatory systems, and direct telescope control is outside the demonstrated scope.

Gammapy script. Conventional tools check it. A failure returns a diagnostic for repair; a success brings sources, logs and evidence to a reviewer (Fig. 1). For CTAO, the loop links requirements, implementation and tests; for gamma-ray science, a question to an executable analysis with physics checks. Models reason flexibly, while tools and experts retain authority. All demonstrated agents work in development or offline analysis and do not command telescopes.

From specifications to verified telescope software

The first results came from the telescope software workflow, which turned heterogeneous specifications into typed Python data models, checked syntax and structure and returned errors for repair [4]. Applied to real CTAO specifications, it inferred naming conventions, created schema-conforming mock values and produced upload-ready data without manual correction. These trials showed practical value but were too limited for systematic assessment.

Current work expands this into a full development pipeline starting from approved requirements and use cases. Agents generate candidate code linked to source statements. Cross-checks flag gaps, contradictions and non-conformance across requirements, use cases, interfaces and implementation. The same traceability supports verification tests and reports stating what was checked, passed, failed or remains open. These are proposals: Toolchains and experts decide what enters the software baseline.

The challenge extends beyond astronomy. A structured field study supported by the DESY Start-Up Office as part of a Helmholtz Enterprise project found fragmented knowledge in most interviews; verification, documentation quality and unmapped dependencies also recurred [5]. The qualitative study is not statistically representative, but found similar needs in automation, manufacturing, transport, aerospace, infrastructure and IT. DESY addresses this broad problem from an observatory perspective: CTAO offers real specifications, software, experts and validation environments.

From observatory engineering to scientific analysis

On the science side, a versioned Gammapy skill packages domain rules and includes an evaluation harness based on open-source frameworks. It offers the Gammapy community an example of agentic development: An agent creates an analysis artefact, and the harness executes and checks it reproducibly [6].

All tests use only open-weight models provided by two institutional services, Helmholtz Blablador [7] and DESY Assistant [8]. In a preliminary comparison [9], four model families attempted an analysis of public data from the H.E.S.S. gamma-ray telescopes [10] with and without the skill. All four skill-assisted runs were rated satisfactory or better, versus one of four controls (Fig. 2), and token use was about a quarter lower. Each condition is a single unblinded run, and the skill contains target-related sanity values: The results support curated context, not a general benchmark or unseen-science test.

A new end-to-end research prototype combines a containerised coding agent with a searchable knowledge base of Gammapy documentation, examples and gamma-ray papers. Given a source description and simulated data, it is intended to plan, implement, test and interpret an analysis, produce a significance map and fit source position, extent and spectrum for comparison with published measurements. Robustness will be tested through repeated runs on unseen sources, physics checks and independent review.

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Local structure imprint on extragalactic cosmic rays

The memory of nearby structures in the universe

The Theoretical Astroparticle Physics (THAT) group at DESY in Zeuthen investigates the nature of the ultrahigh-energy cosmic-ray (UHECR) skymap over a range of energies. One interesting feature that requires explanation is an anisotropy in the arrival directions of UHECRs, observed by the Pierre Auger Observatory and the Telescope Array. Recent work has demonstrated that this observed anisotropy structure can be produced by cosmic rays being emitted from a single extragalactic source. The propagation of these cosmic rays through the magnetic fields embedded in local extragalactic structures results in the memory of these structures becoming imprinted on the UHECR skymap distribution. Furthermore, it has been shown that, at lower energies (<40 EeV), the Milky Way's own magnetic-field structure causes a washing-out of this memory, resulting in dipole-like skymaps at these lower energies.

Imprint of local structure on the cosmic-ray skymap

Cosmic rays arrive at Earth from all directions, with an almost uniform distribution. However, a departure from this uniformity was recently discovered by the Pierre Auger Observatory and the Telescope Array collaboration in the skymap of cosmic rays with energies above 40 EeV (Fig. 1) [1]. The dark red regions of the skymap reveal the presence of small-scale structure, which curiously appears to align with a local extragalactic ring structure that sits around the Milky Way – a ring of 12 large galaxies called the "Council of Giants" (Fig. 2). The plane of this ring is orientated approximately orthogonal to the plane of the Milky Way.

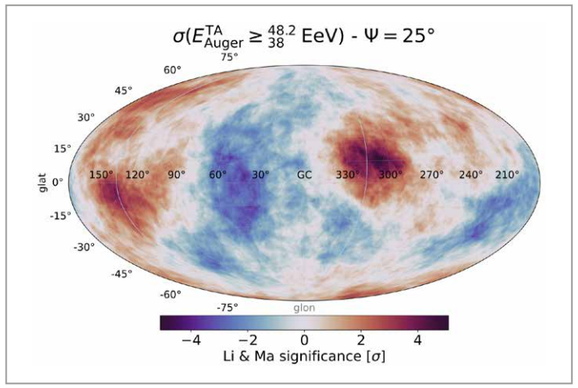


Figure 1
Skymap of the UHECR arrival distribution at Earth (Li–Ma statistical significance) in Galactic coordinates, as measured by the Pierre Auger Observatory and the Telescope Array (TA). A higher UHECR signal is indicated in dark red, a lower one in blue. The supergalactic plane is shown as a grey line. From [1].

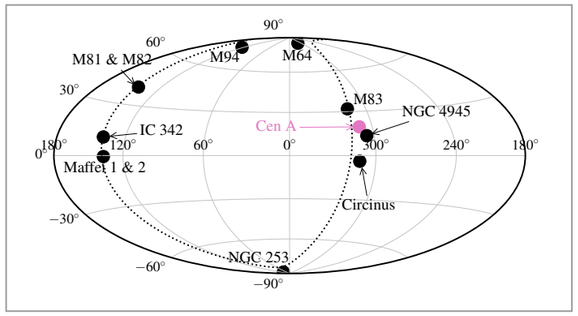


Figure 2
Skymap showing the positions in the sky of the galaxies that make up the Council of Giants. Centaurus A (Cen A) is marked with a pink circle, the others with black circles. The supergalactic plane is shown as a dotted line. From [2].

Centaurus A: Lord of the Ring

Not all members of the Council of Giants, however, are equal. Each of the galaxies has a level of power associated with it, which indicates the amount of energy it emits. Of all the galaxy members of the Council of Giants, the object Centaurus A (Cen A in Fig. 2) is by far the most powerful.

Motivated by the uniqueness of Centaurus A in the Council of Giants, the team performed numerical simulations of the propagation of UHECRs, following their emission from Centaurus A, through the Council of Giants system [2]. These simulations took into account the interactions of the cosmic rays with the magnetised structures associated with each of the galaxy members of the Council of Giants.

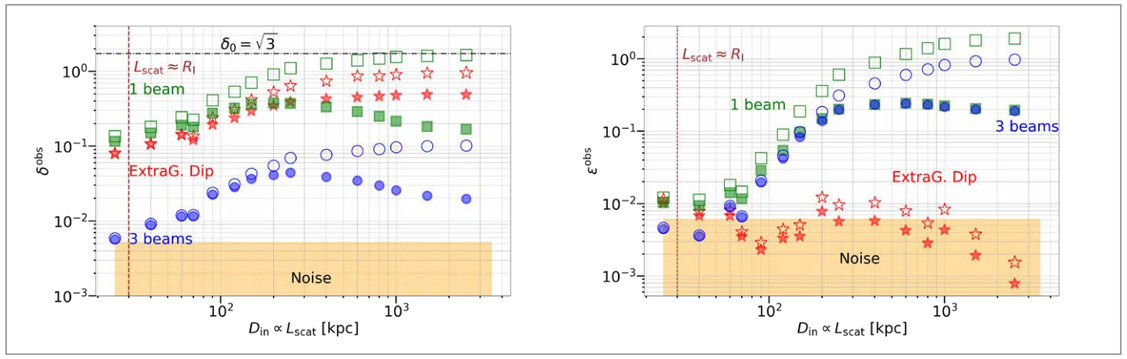


Figure 4
Dipole (left) and quadrupole (right) amplitude as a function of scattering length for three different source scenarios. From [3].

Cosmic-ray memory of Centaurus A's powerful past

The team calculated the skymaps of the cosmic rays' arrival distribution at the Milky Way (Fig. 3). The skymaps showed strong similarities with those observed, demonstrating that a clear imprint of the Council of Giants' extragalactic structure is picked up during the propagation of the cosmic rays through this structure. The results are consistent with the fact that Centaurus A was noticeably more active in the past and that the cosmic rays arriving from it today are a consequence of this past activity.

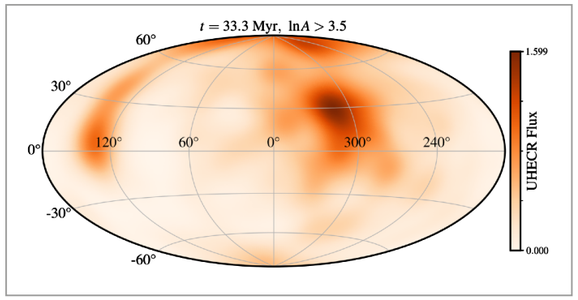


Figure 3
Simulated skymap of the arrival distribution of UHECRs emitted by Centaurus A after their propagation through the Council of Giants extragalactic structure, showing strong similarity with the observed UHECR skymap (Fig. 1). From [2].

The Milky Way's ability to suppress cosmic-ray memory

In addition to the effects on cosmic rays as they propagate through the Council of Giants and interact with the magnetic fields of its galaxy members, the Milky Way's own magnetic-field structure is expected to imprint itself on the cosmic rays that arrive at Earth.

Using a dedicated, separate set of simulations for the propagation of cosmic rays into the Milky Way, the level of suppression of small-scale structure in the lower-energy cosmic-ray skymaps was obtained [3]. Given that this suppression effect is energy-dependent, simulations were performed over a broad energy range. Figure 4 shows the energy dependence of the growth in the multipole (dipole and quadrupole) strength of the cosmic rays that arrive at Earth. Although only the dipole term has been detected so far, the more rapid growth of the quadrupole term suggests that this term should become detectable in the near future. Once detected, these multipole terms will offer a new probe of the Milky Way's magnetic-field structure.

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Artist's impression of very high-energy photons from a gamma-ray burst entering Earth's atmosphere and initiating air showers that are being recorded by the H.E.S.S. telescopes

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