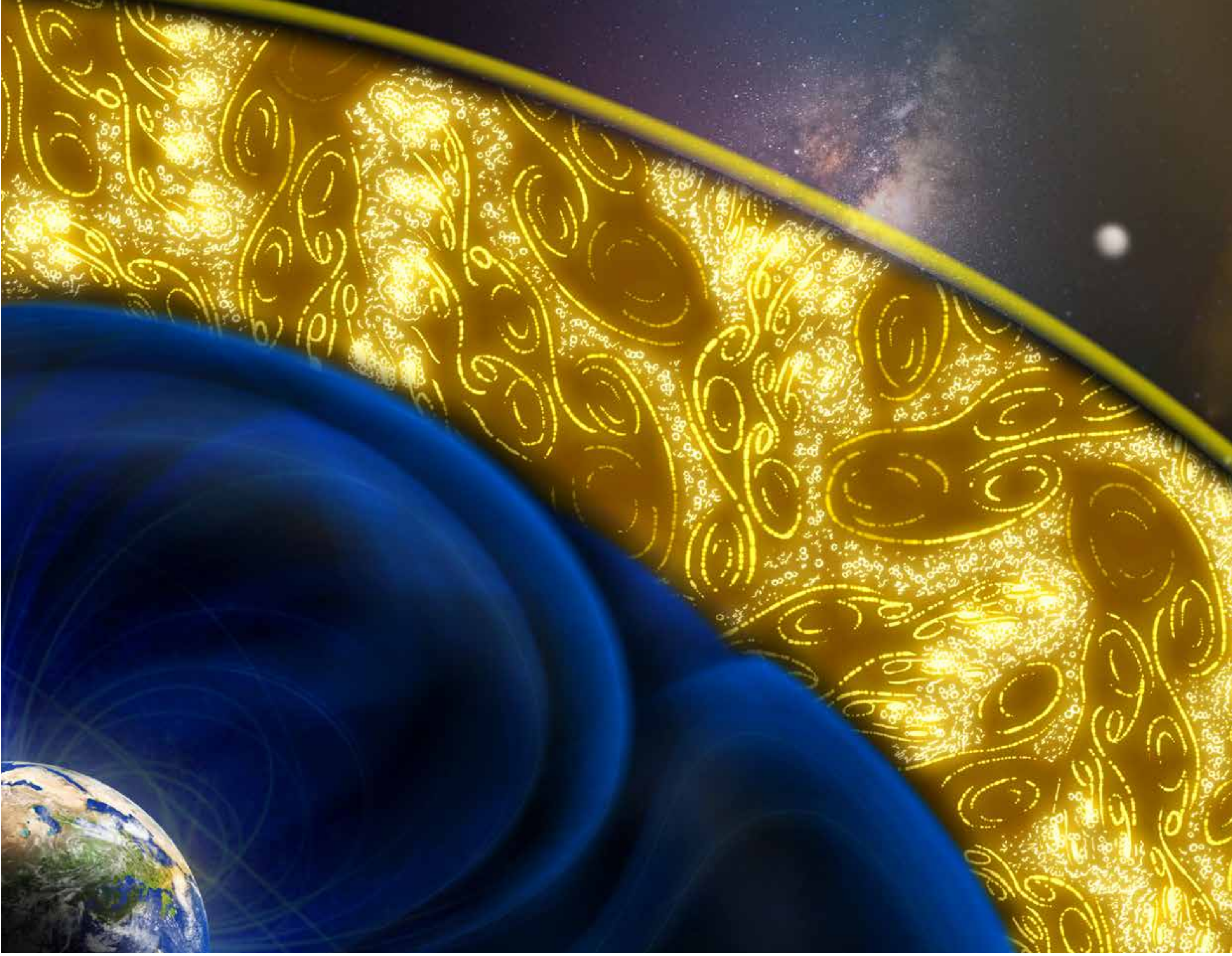


ASTROPARTICLE PHYSICS 2024.

Highlights and Annual Report

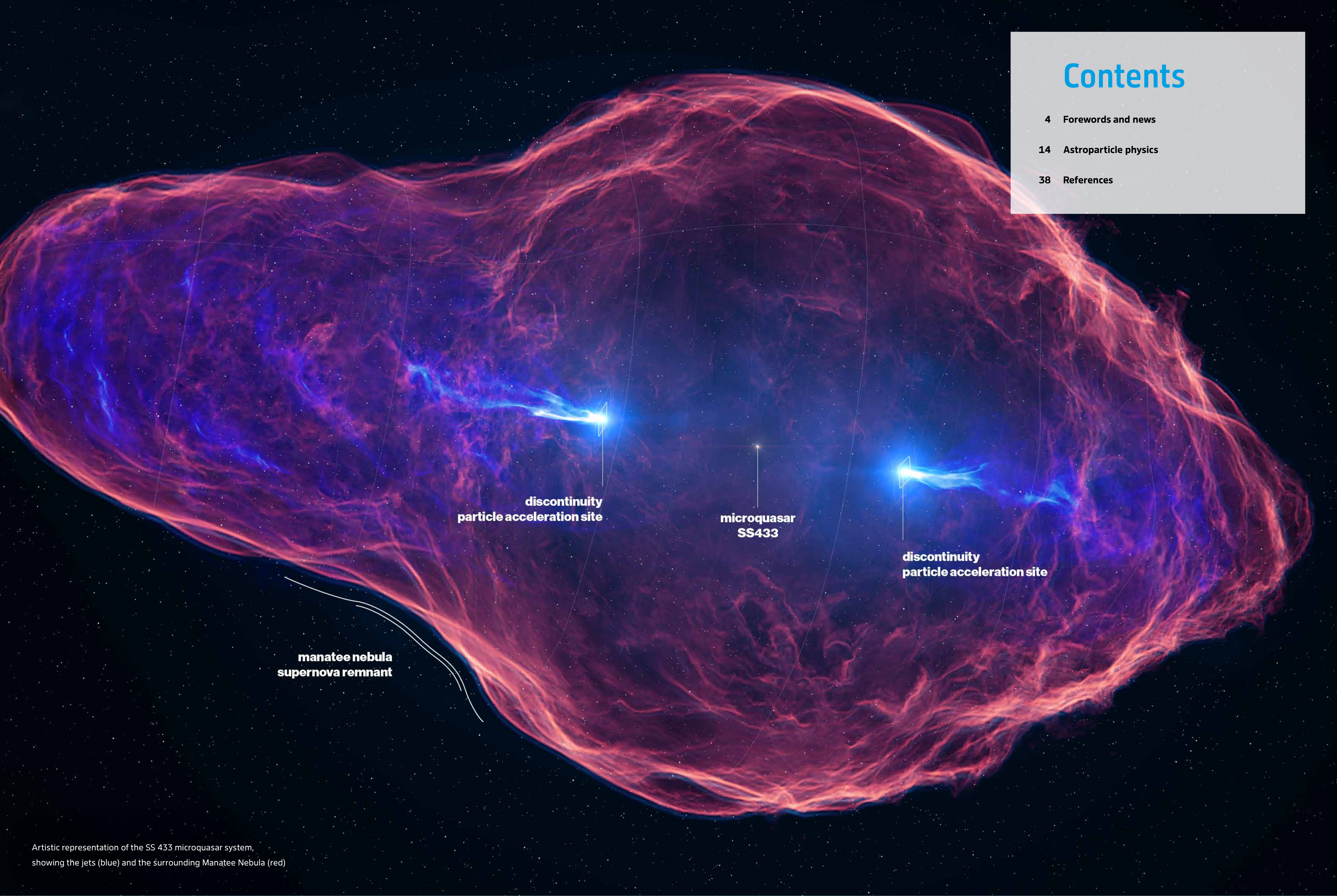
Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

ASTROPARTICLE PHYSICS 2024.

Highlights and Annual Report

Cover
Cartoon of turbulence eddies in Earth's magnetosheath from large to small scales, with increasing nonlinearity as indicated by the brightness.

Contents



Artistic representation of the SS 433 microquasar system, showing the jets (blue) and the surrounding Manatee Nebula (red)

The year 2024 at DESY

Chairman's foreword

Dear Colleagues and Friends of DESY,

In a time of significant challenges – financial constraints, geopolitical instabilities and heightened international competition – DESY faces a demanding landscape. Rising personnel costs, volatile energy prices and inflation-driven reductions in purchasing power put us under considerable pressure, and the priority is to lead DESY safely into the future.

At the heart of our strategy stands the ambitious PETRA IV upgrade project. The conversion of PETRA III into a state-of-the-art fourth-generation X-ray light source is essential not only for DESY's advancement but also for strengthening international research and securing Germany's technological sovereignty. As the world's most advanced and brilliant X-ray source, PETRA IV will enable unprecedented precision in studying materials and biological macromolecules, paving the way for pioneering innovations, such as AI-driven material design.

The DESY infrastructure focus also includes transformative projects. The new DESYUM visitor centre, whose construction is progressing according to plan, will soon be a public landmark and could become the iconic symbol of the Hamburg-Bahrenfeld campus. Through our Centre for Accelerator Science and Technology (CAST) and the DESY Innovation Factory, an integrated technology and start-up centre, we are expanding the "Bahrenfeld ecosystem" by linking research and innovation to drive technological and economic development.

This is my last foreword for an annual report as the chairman of the DESY Board of Directors, and I would like to take this opportunity to make a few personal remarks: It has been an honour to serve in this role. I would like to thank all DESY employees and our national and international partners for their trust over the past 15 years, and especially the Board members for their unique team spirit and constructive cooperation. Together, we have achieved numerous successes, including the remarkable construction of the European XFEL from 2009 to 2017, a masterpiece "made by DESY", the establishment of the Astroparticle Physics Division, the strategic expansion of nanoscience and laser plasma research and the successful operation of PETRA III, FLASH and the European XFEL as Hamburg's flagship photon sources. We are continuing a long tradition: Since the commissioning of its first particle accelerator in 1964, DESY has been one of the pioneers of research with synchrotron radiation worldwide.

Figure 1
Celebrating 60 years of research with synchrotron light at DESY: (from left) Robert Feidenhans'l, Poul Nissen, Edgar Weckert, Saša Bajt, Massimo Altarelli, Jerome Hastings, Jochen Schneider, Tetsuya Ishikawa, Laurent Chapon, Francesco Sette, Harald Reichert, Rolf Heuer and Helmut Dosch

I reflect with pride on the growth of the two DESY sites in Hamburg and Zeuthen together with our partners. The new interdisciplinary research centres – CFEL, CSSB and CXNS for photon science, the recently opened Science Data Management Centre (SDMC) for astroparticle physics, the ongoing projects mentioned above as well as the planned Wolfgang Pauli Centre for theoretical physics (WPC) and Centre for Molecular Water Science (CMWS) – are visionary initiatives that will contribute to strengthening Germany's research landscape as a whole and the innovation regions of Hamburg and Zeuthen in particular.

A highlight of my time at DESY has been the recruitment of renowned scientists. With the appointment of over 30 W3 professorships, including 15 women, and close collaborations with universities in Hamburg, Schleswig-Holstein, Berlin, Brandenburg and beyond, we have enhanced our scientific network and supported our university partners' excellence. Particularly noteworthy are the new members on the DESY Board of Directors in 2025: Beate Heinemann, Wim Leemans, Britta Redlich, Christian Stegmann and Arik Willner, bringing science, innovation and technology transfer expertise. With this exceptional team, DESY is well equipped to master future challenges.

When I will hand over the helm to Beate Heinemann in spring 2025, I will do so in a turbulent time not only for DESY. Research and social issues can no longer be addressed only on the national level. Sharing expertise and infrastructures and thereby strengthening international cooperations is becoming more important: Innovation is the key for our future. Therefore, the pending political decision for PETRA IV is crucial for DESY and our national and international partners and users, and I hope for swift action in the next period.

Figure 2
Visualisation of the DESY Centre for Accelerator Science and Technology (CAST), close to the PETRA III experimental hall "Max von Laue" (right)

Figure 3
The Science Data Management Centre (SDMC) building for the CTAO gamma-ray observatory on the DESY campus in Zeuthen

I extend my best wishes to all DESY staff, hoping you will continue to lead this remarkable research centre into a bright future. Thank you all and also our partners for constant support and excellent cooperation over the years. I wish DESY continued success and that essential extra bit of luck.

Yours

Helmut Dosch
Chairman of the DESY Board of Directors

Astroparticle physics at DESY

Director's foreword

Dear friends of DESY,

Despite the challenges that the world faced in 2024 and their numerous implications also for the world of science, the DESY Astroparticle Physics Division achieved key milestones during the year, which bring many of our projects closer to realisation.

In February, production of components started for the Medium-Sized Telescopes (MSTs) of the upcoming Cherenkov Telescope Array Observatory (CTAO) – a unique, world-class observatory for gamma-ray astronomy with over 60 telescopes to be installed at two sites in Chile and on the Canary Island of La Palma. DESY is responsible for the design and production of the MSTs. The start of production is an important step towards the observatory's first two prototype MSTs, which will be manufactured at DESY and prepared for installation at both observatory sites. DESY is also a major contributor to the Array Control and Data Acquisition (ACADA) system, which will manage the control, supervision and data handling of the telescopes and auxiliary instruments at the two CTAO sites. The completion and approval of the ACADA Critical Design Review were further significant milestones for CTAO in 2024.

In October, DESY and CTAO then celebrated the official opening of the new CTAO Science Data Management Centre (SDMC) building on the campus in Zeuthen, where the software and computing work of the observatory will be coordinated and CTAO's data products be made available to the worldwide community. Aligning with the regional importance of DESY in Zeuthen, this is the first time an international research project will be co-hosted on the Zeuthen campus, fostering top international research in Brandenburg and attracting scientists worldwide to work on our premises.

The Science Data Management Centre (SDMC) building for the upcoming CTAO gamma-ray observatory was officially opened on 14 October 2024.

In August, a first batch of 128 light sensors left DESY in Zeuthen for the South Pole, where they will be installed as part of the current upgrade of the IceCube neutrino telescope. Together with German universities, DESY in Zeuthen developed one of the two sensor types for the upgrade: the multi-photomultiplier digital optical module (mDOM), 225 of which are being produced at DESY. Equipped with 24 photomultipliers each, the mDOMs have about twice the light-sensitive area of their predecessors in IceCube and allow intrinsic directional determination of the measured light. The first delivery safely arrived in Antarctica in December, where the mDOMs were tested again to ensure they survived the transport well, so that they will be ready for installation in December 2025. Installation work also continued 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 current IceCube Upgrade is an important step towards IceCube-Gen2, the future expansion of the neutrino telescope to a measurement volume of a full eight cubic kilometres. The technical design report for IceCube-Gen2 was completed in June 2024 with major contributions from DESY, and in October, a DESY-led proposal for the German participation in IceCube-Gen2 was submitted to the "National Prioritisation Procedure for Large-Scale Research Infrastructures" of the German Federal Ministry of Education and Research. In early July 2025, the research ministry announced the results of the review, and DESY is proud that both proposals it submitted – its next-generation synchrotron radiation source PETRA IV and the German participation in IceCube-Gen2 – were shortlisted as research infrastructures of national importance.

Another major event of the year was the official opening of the interim location of the German Center for Astrophysics (DZA) in the historic post office building on Postplatz in Görlitz. As a joint initiative of German astronomy and astroparticle physics, the DZA will push forward resource-saving digitalisation, develop new technologies, ensure transfer and create perspectives for the region of Lusatia in Saxony. The DZA is currently in the start-up phase, in which it is funded as a project before being established as a legally independent centre in 2026. Together with TU Dresden University of Technology, DESY plays a major role in the establishment of the DZA: As the organisation responsible for the project, DESY is partly in charge of financing the start-up phase and contributes its extensive experience from setting up other large-scale research projects.

DESY is also significantly involved in the realisation of the ULTRASAT space telescope, a satellite mission led by the Weizmann Institute of Science (WIS) and the Israel Space Agency (ISA). DESY is currently designing, building and testing the ultraviolet camera for ULTRASAT, which forms the centrepiece of the satellite. The production phase for the first version of the camera is in full swing.

The scientific output of the Astroparticle Physics Division in 2024 encompassed many highlights in a broad range of subjects, a selection of which we are pleased to present to you in this report. A significant step was made toward solving the last puzzle in magnetohydrodynamic turbulence theory by observing the weak-to-strong transition in space plasma turbulence surrounding Earth – a phenomenon that had long been predicted but never been observationally confirmed. A new analysis of IceCube data targeted heavy neutral leptons produced through their coupling to oscillated, atmospheric tau neutrinos. Data on solar bursts recorded by RNO-G as a by-product of neutrino observations proved to be an unexpected boon for solar physics. A theoretical analysis found that the observation of black hole binaries with higher-than-expected eccentricity or even stalling frequency could hint at a new particle that could be otherwise unobservable.

And the AM^3 software developed at DESY enabled theorists to propose an explanation for the radio and X-ray emissions in the jets of the tidal disruption event (TDE) AT 2022cmc, providing for the first time a universal and self-consistent interpretation of the X-ray light curves and spectra of all four jetted TDEs identified so far.

To further the public understanding of science and inspire young people in particular to take an interest in science, the Astroparticle Physics Division continued to actively promote young talent and outreach activities, for example through its school lab, a three-year cooperation agreement signed with the Brandenburg Ministry of Education, the organisation of the annual International Cosmic Day, which was attended by over 5900 young people from 24 countries, the traditional summer student programme, which featured the first DESY–Ukraine summer school, and several other events organised throughout the year.

I would like to extend my sincerest gratitude to our entire team and our partners in Germany and across the globe for their dedication and contributions to our shared successes in 2024. I look forward to continuing to collaborate with you to achieve great scientific results in the years to come.

Christian Stegmann

Christian Stegmann
Director in charge of Astroparticle Physics

News and events

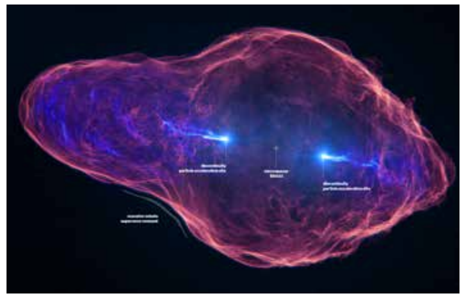
Highlights in 2024

January

Galactic microquasar SS 433 reveals a secret

The collaboration running the High Energy Stereoscopic System (H.E.S.S.) telescope in Namibia detected very high-energy gamma-rays above several teraelectron-volts coming from the jets of the micro-quasar SS 433 in our galaxy. With these observations, scientists from the Max Planck Institute for Nuclear Physics in Heidelberg and from DESY in Zeuthen led a dedicated study, which found that the emission from both jets depends on the location and varies as a function of energy. Relativistic particles are thus accelerated and transported along the plasma beams, meaning that the particles somehow receive an energy boost in the jets.

The results of the study, published in *Science*, enable a more precise localisation of the most energetic particles and bring us one step closer to understanding the mechanism behind this highly efficient acceleration.



Artistic representation of the SS 433 system, showing the jets (blue) and the surrounding Manatee Nebula (red)

February

Production of Medium-Sized Telescopes for CTAO begins

Components of the active mirror control for the CTAO medium-sized telescopes

Production of components began for the upcoming Cherenkov Telescope Array Observatory (CTAO) – a major milestone in the construction of the observatory's first two telescopes, which will be located on the Canary Island of La Palma and in the Atacama Desert in Chile. The Medium-Sized Telescopes within the array will require extremely sensitive mirror controls. To produce these systems, DESY has partnered with the University of California Santa Cruz (UCSC), which will build the active mirror control systems and bring them to series maturity.

DESY's contributions include the development of the electronics systems to series maturity, the production of the complete electronics and cabling, the development of control software and the commissioning of the finished systems.

The key to unlock our universe

The German Center for Astrophysics (DZA) officially opened its interim location in the historic post office building on Postplatz in Görlitz. During the inauguration ceremony, Federal Research Minister Bettina Stark-Watzinger and Saxony's Minister President Michael Kretschmer symbolically handed over the key to the DZA's designated Founding Director, Günther Hasinger, a professor at the TU Dresden University of Technology and leading scientist at DESY.

The offices in the historic post office building offer two floors of workspace for the centre's first approximately 100 staff members before the DZA will move to its final locations in Görlitz and in the district of Bautzen.

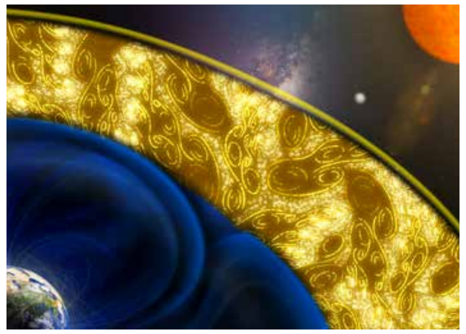
From left: Sebastian Gemkow, Science Minister of Saxony, Ursula Staudinger, Rector of TU Dresden, Michael Kretschmer, Saxony's Minister President, Bettina Stark-Watzinger, Federal Research Minister, Günther Hasinger, DZA Founding Director, and Octavian Ursu, Mayor of Görlitz

April

Turbulence in space plasma

Astrophysicists from the University of Potsdam and DESY made a significant step toward solving the last puzzle in magneto-hydrodynamic turbulence theory by observing the weak-to-strong transition in space plasma turbulence around Earth with newly developed multispacecraft analysis methods. This phenomenon had long been predicted but never been observationally confirmed.

The pioneering discovery, which was published in *Nature Astronomy*, substantially deepens our knowledge of ubiquitous turbulence. Its implications extend beyond the study of turbulence itself to particle transport and acceleration, magnetic reconnection, star formation and all other relevant physical processes from our Earth to the remote universe.



Artistic representation of turbulence eddies in Earth's magnetosheath from large to small scales, with increasing brightness indicating increasing non-linearity

Israeli high-school students visit DESY

A group of students from the Schwartz/Reisman Science Education Centers visited DESY.

A group of 23 highly talented 17- and 18-year-old Israeli students visited DESY in Hamburg for a week. The students came from the Israeli Schwartz/Reisman Science Education Centers, a unique platform for physics enthusiasts in Rehovot and other cities in Israel and an institution under the umbrella of the renowned Weizmann Institute of Science.

July

Summer student programme and Ukraine summer school begin at DESY

In summer, a total of 112 participants from 27 countries performed research on the Hamburg and Zeuthen campuses for seven weeks as part of DESY's summer student programme. This year's novelty: For the first time, a DESY–Ukraine summer school was held simultaneously, with 14 students coming from Ukraine. In view of the many positive responses from participants of the earlier DESY–Ukraine winter school, the organisers around Olaf Behnke had decided to offer even more places for Ukrainian students this year.

The 2024 summer students at the DESY campus in Hamburg...

... and in Zeuthen

With their 24 light sensors, the mDOMs for IceCube can detect light from all directions.

August

First sensors for IceCube Upgrade on their way to Antarctica

The upgrade of the IceCube neutrino telescope reached an important milestone with the shipment of the first 128 sensors built at DESY to Antarctica. The IceCube detector consists of more than 5000 light sensors on 86 cables melted into the ice of the South Pole at a depth of up to 2500 m. In the Antarctic summer 2025/2026, the international IceCube collaboration will install the IceCube Upgrade: Seven new cables with more than 700 sensors will be placed close to each other in the centre of the detector. Together with German universities, DESY in Zeuthen developed one of the two sensor types for the upgrade: the multi-photomultiplier digital optical module (mDOM). More than 400 mDOMs are being manufactured at DESY and at Michigan State University in the USA. After several years of development and two years of construction, the first delivery of 128 mDOMs was shipped from Zeuthen to Antarctica in mid-August, where it arrived in December.

mDOMs for the IceCube Upgrade being assembled under cleanroom conditions at DESY in Zeuthen

September

Cooperation agreement with Brandenburg Ministry of Education

The collaboration between the Brandenburg Ministry of Education, Youth and Sport and the DESY school lab in Zeuthen, which focuses on making high-quality content on physical phenomena widely accessible to teaching staff and students, was formalised with a three-year cooperation agreement. As part of the cooperation, online experiment courses and 40 asynchronous teaching units on the topic of air pressure and vacuum were developed for the nationwide platform "Digitale Drehtür". The self-study programme is aimed at pupils in grades 5 to 8 and teaches basic content and phenomena relating to air pressure and vacuum in ten interactive courses with a total of 40 lessons.

New European project for multimessenger astronomy

ACME team members during the kick-off meeting in mid-September in Paris

In mid-September, a kick-off meeting in Paris marked the start of ACME – the Astrophysics Centre for Multimessenger Studies in Europe. ACME is funded by the European Union with 15 million euros and coordinated by the Centre national de la recherche scientifique (CNRS) in France. Its aim is to promote Europe-wide cooperation between research institutes in astroparticle physics and astronomy. Scientists from across Europe will be able to share large-scale equipment and instruments, exchange data and expertise and advance multimessenger astronomy. The European cooperation consists of 40 leading institutes in astroparticle physics and astronomy from a total of 14 countries.

New hub for high-energy astrophysics

DESY and the Cherenkov Telescope Array Observatory (CTAO) celebrated the official opening of the new CTAO Science Data Management Centre (SDMC) building on the DESY campus in Zeuthen. The event brought together key figures from the international CTAO community, political representatives, regional partners as well as DESY and CTAO staff members to celebrate an important milestone in the further exploration of the high-energy processes in the universe. As a shareholder of the CTAO gGmbH and one of the CTAO's hosting partners, DESY provides the building of the SDMC, where the software and computing work of the observatory will be coordinated, making CTAO's data products available to the worldwide community.

The Science Data Management Centre building for CTAO on the DESY campus in Zeuthen

November

Discovery of extremely voracious black hole from shortly after the Big Bang

Using the James Webb Space Telescope (JWST), a team led by the International Gemini Observatory/NSF NOIRLab, DESY and TU Dresden found a fast-growing supermassive black hole from a very early phase of the universe shortly after the Big Bang. Named LID-568, it raises fundamental questions about our current understanding of supermassive black holes. As the researchers reported in *Nature Astronomy*, they found a striking cluster of objects that are bright in the X-ray range but almost invisible in the optical and infrared ranges. Using the JWST's spectroscopic instruments, the scientists realised that what they were seeing was a new population of supermassive black holes from the early universe, shrouded in dust. One of these objects, a tiny speck observed as it was some 1.5 billion years after the Big Bang, stood out in particular due to its intense X-ray emission and its unusually high consumption of matter (accretion rate), which is unprecedented at this scale.

Breaking ground for new technology and start-up centre at DESY

A combined total of over 8500 m^2 of workspace for the new DESY Innovation Factory will be created in three years of construction at two locations: the main site on the DESY campus in Hamburg and a second close by in the Altona Innovation Park. Complex laboratories, offices and open working environments will be built to foster the flow and transfer of knowledge and technology from research to industry and society.

Breaking ground for the DESY Innovation Factory (from left): Helmut Dosch (DESY), Volkmar Dietz (Federal Ministry for Education and Research), Melanie Leonhard (Hamburg Senator for Economics), Eva Gümbel (Hamburg State Councillor for Science), Arik Willner and Hansjörg Wiese (both DESY)

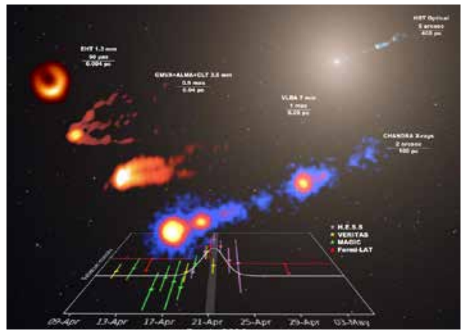
Cosmic particles connect young minds across the globe

On 26 November, the annual International Cosmic Day (ICD) took place for the 13th time, organised by DESY in Zeuthen. The ICD is dedicated to the unnoticed cosmic particles that flood our universe and constantly surround us on Earth. In 2024, it brought together 100 groups at schools, universities and research institutions across 24 countries, inspiring students to learn about cosmic particles, conduct experiments and exchange their findings in 14 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.

December

Powerful jet unleashes rare gamma-ray flare

The international multi-instrument Event Horizon Telescope (EHT) collaboration revealed observations of a spectacular gamma-ray flare from the powerful relativistic jet emanating from the centre of the galaxy M87 with the broadest wavelength range ever collected, potentially leading to a better understanding of how and where particles are accelerated in these kinds of jets. Also known as Virgo A or NGC 4486, M87 is the brightest object in the Virgo cluster of galaxies. It came to fame in April 2019 after EHT scientists released the first image of the supermassive black hole M87* in its centre. Led by the EHT multiwavelength group, a study published in *Astronomy and Astrophysics* presented the data from the second EHT observational campaign conducted in April 2018, involving over 25 terrestrial and orbital telescopes. The authors reported the first observation of a high-energy gamma-ray flare in over a decade from the black hole M87*. The data set will enable scientists from around the world to further test their theoretical models to explain the radiation and the physical environment near the black hole.



Light curve of the gamma-ray flare (bottom) and collection of quasi-simulated images of the M87 jet (top) at various scales obtained in radio and X-ray wavelengths during the 2018 EHT observational campaign. The instrument, wavelength observation range and scale are shown at the top left of each image.

Prizes and awards

Humboldt Research Award for Jacco Vink
Jacco Vink, an associate professor at the University of Amsterdam, the Netherlands, working in the field of high-energy astrophysics, received a Humboldt Research Award by the Alexander von Humboldt Foundation. As part of the award, Jacco Vink will come to work in the Gamma Astronomy group at DESY in Zeuthen in 2025. The Humboldt Research Awards are granted to internationally leading researchers of all disciplines from abroad in recognition of their academic record to date.

Humboldt Research Fellowship for Damiano Fiorillo
Damiano Fiorillo, formerly at the Niels Bohr Institute in Copenhagen, Denmark, was awarded a Humboldt Research Fellowship by the Alexander von Humboldt Foundation for his postdoctoral work in the Astroparticle Physics Theory group at DESY in Zeuthen from September 2024 to early 2026. Through the Humboldt Research Fellowship, the Foundation sponsors researchers with above-average qualifications from across the globe in their research work in Germany.

IceCube Impact Award for Massimiliano Lincetto
Massimiliano Lincetto, a postdoctoral researcher in the Multi-Messenger group at DESY in Zeuthen, was honoured with the IceCube Impact Award for his exceptional support and improvements to two real-time software projects, SkyMist and Skymap Scanner. The IceCube Impact Awards recognise broad and significant contributions to the IceCube neutrino telescope that would not normally be acknowledged through its publications.

IceCube Group Impact Award for Richard Naab (and Erik Ganster)
Richard Naab, a former doctoral researcher in the Neutrino Astronomy group at DESY in Zeuthen, and Erik Ganster from RWTH Aachen, Germany, won the IceCube Group Impact Award for their leadership in enabling and supporting a wider use of the NNMFit analysis software tool in the IceCube collaboration.

Simon Swordy Outstanding Contribution Award for Tobias Kleiner
Tobias Kleiner, a postdoctoral researcher in the Gamma Astronomy group at DESY in Zeuthen, received the Simon Swordy Outstanding Contribution Award from the VERITAS collaboration for major contributions to the VERITAS gamma-ray observatory during his graduate work, where he pioneered the first implementation of a Gammapy-based extended source analysis for VERITAS.

DESY Award for Exceptional Achievements for Adelheid Sommer
Adelheid Sommer, head of the school lab at DESY in Zeuthen, was honoured with the DESY Award for Exceptional Achievements in the category "Social Commitment and Outreach" for her outstanding commitment to promoting young talent, especially for networking with partners from politics, schools in the region and extracurricular learning centres.

DESY Award for Exceptional Achievements for Katharina Henjes-Kunst
Katharina Henjes-Kunst from DESY in Zeuthen, the overall project manager of the German Center for Astrophysics (DZA), received the DESY Award for Exceptional Achievements in the category "Science Management" for her extraordinary achievements particularly in promoting the scientific landscape in Germany and strengthening DESY's reputation in eastern Germany.

DESY International Fellowship Award – Wilfried Wurth Award for Giulia Illuminati
Giulia Illuminati, a researcher at INFN Bologna, Italy, who specialises in high-energy neutrino astrophysics, won the DESY International Fellowship Award – Wilfried Wurth Award. As part of the award, she will come to work in the Neutrino Astronomy group at DESY in Zeuthen in 2025.

Best trainees of the year – Vanessa Kunze and Til Kaeber
DESY trainees in various professions are among the most successful in their year. At DESY in Zeuthen, Til Étienne Kaeber was honoured as the best electronics technician for devices and systems, and industrial mechanic Vanessa Kunze as one of the best of her year by the Cottbus Chamber of Industry and Commerce. The Hamburg Chamber of Commerce also honoured a total of 64 young talents, including two trainees from DESY in Hamburg.

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 carried out. 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.

Artist's impression of the RS Ophiuchi binary star system, which is comprised of a white dwarf (background) and a red giant that orbit each other. Material from the red giant is continually accreted by the companion star.

Experiments, theory, projects and infrastructures

The Sun as seen with RNO-G

Calibration meets novel solar science

The Sun has recently hit its activity maximum, bringing us beautiful auroras even all the way south to DESY in Zeuthen. With every outburst, the Sun shines brightly also in radio waves, making it directly visible to the sensitive neutrino triggers of the Radio Neutrino Observatory Greenland (RNO-G) on top of the Greenlandic ice sheet. RNO-G thus records all solar bursts simply in the background: with an unprecedented timing resolution, unlike regular solar observatories, and, thanks to its remote location, mostly undisturbed by human interference. Led by a DESY postdoctoral researcher, the RNO-G collaboration has shown that these somewhat unexpected data provide an opportunity for solar physics as well as a very reliable calibration source for RNO-G.

Although it is our closest star, the Sun and its inner workings are not fully understood. Every 11 years, the Sun exhibits an activity maximum in its behaviour, which is visible in the number of dark sunspots, its magnetic field and the number of outbursts. During these outbursts, the Sun emits charged particles. Each time they hit Earth and interact with its geomagnetic field, they lead to colourful auroras – the most real-life experience of astroparticle physics. Why the Sun undergoes this periodicity, which has been observed for hundreds of years, and what precisely happens within the Sun remains unknown as yet. What is known is that the outbursts are never the same, but often come with measurable radio emission. Networks of solar observatories around the globe (e.g. [3]) monitor the Sun and provide data, mostly in the form of dynamic spectra. These show the received power per frequency as a function of time, with a granularity of typically seconds. The spectra exhibit a large variability, lasting from only a few minutes to hours. The variations are thought to stem from plasma physics processes on the solar surface and in its atmosphere, ranging from storms with many eruptions to single coronal mass ejections. Given the available data, the field is faced with a chicken-and-egg problem. Plasma physics processes should also take place on much shorter time scales, but what is the use of modelling these processes in detail for the Sun if there is no data to compare the modelling results with?

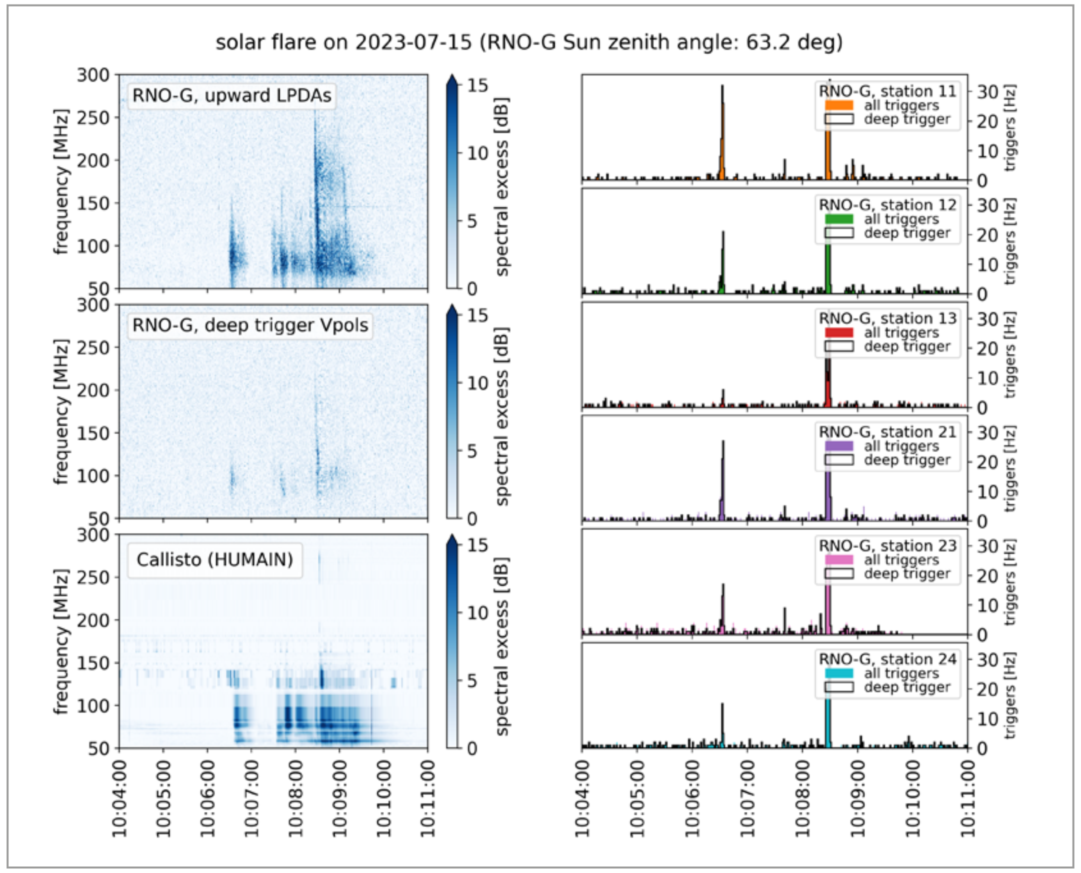


Figure 1
Solar burst recorded with RNO-G. Shown are dynamic spectra (left) from the upward-facing antennas of RNO-G (top), the antennas dedicated to neutrino triggering (middle) and a standard solar observatory (bottom). Each entry of the histograms on the right corresponds to almost 1 µs of data at full 2.4 GHz timing resolution. More data is available at [2].

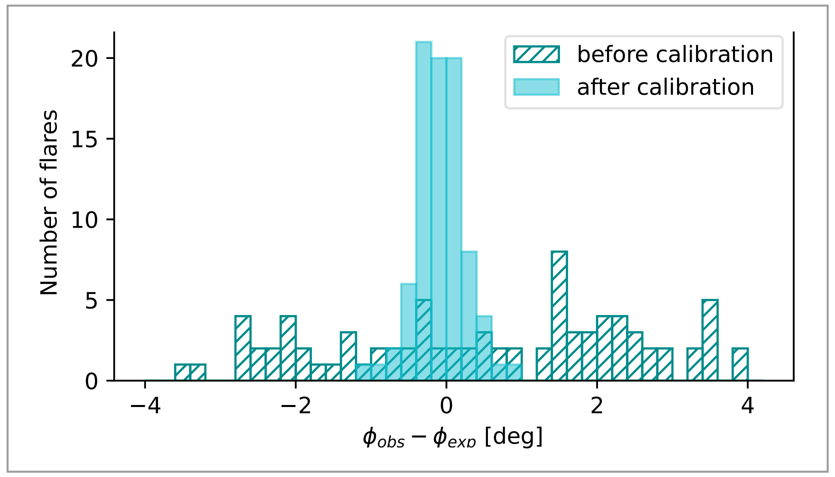


Figure 2
Effect of the calibration of RNO-G using the Sun. By correcting the nominal antenna positions by less than 10 cm each (solid histogram), the Sun could be reconstructed to its known location. The Sun has an intrinsic diameter of about 1 degree. From [1].

Using RNO-G for the Sun
RNO-G seeks to detect neutrinos by measuring radio pulses of nanosecond duration that follow the interactions of a neutrino in the ice. DESY has been playing a leading role in the construction and commissioning of the observatory, which is expected to continue for the coming years. Because of the very different science case, RNO-G uses the same radio frequency range as solar observatories, but records with a much higher timing resolution based on a 2.4 GHz sampling rate. RNO-G thus records the detailed time structure of all radio emission – not continuously, but only when a signal passes a threshold. As shown in Fig. 1, this leads to much finer-grained data of the solar bursts occurring over Greenland. In particular, the upward-facing antennas that have been added to RNO-G for background characterisation (top left) demonstrate their power and usefulness in these observations.

The data taken with RNO-G reveal nanosecond-scale structure in the radio waves stemming from the solar bursts. As RNO-G is fully solar-powered, it is taking data whenever the Sun is visible to the experiment with an up-time of nearly 100% during these times. This leads to a quasi-complete data set of solar bursts with unprecedented timing resolution, simply as a by-product of the neutrino observations. The radio signals from the Sun are very different from the expected neutrino signals, meaning that they are not a problematic background but simply data available to serendipitous discovery. The collaboration has made them public for all follow-up science, together with the first RNO-G solar paper, led by a DESY postdoc [1].

Using the Sun for RNO-G
While getting in touch with solar physicists to interpret the data is still an ongoing process, these data are also intrinsically useful for RNO-G. For every station, three holes of 100 m depth have to be drilled with heaving equipment so that the antennas for RNO-G can be placed in the ice, where the neutrino interactions take place. To achieve the design goal of being able to point a neutrino to its astrophysical origin, the antenna positions have to be known to centimetre precision – a quite challenging task once the antennas are placed in the ice, leading to a significant calibration effort. Here, the Sun at its known location in the far field of RNO-G plays an important role – for free.

With every outburst, the Sun acts as a calibration source at a known position, with many arrival directions sampled that are visible with all RNO-G stations. In the RNO-G solar paper [1], the collaboration was able to show that small corrections of the antenna positions of tens of centimetres make it possible to reconstruct the solar position to a resolution of less than 1 degree. This is shown in Fig. 2 for the azimuthal angle, demonstrating that the technique can be used to correct for unknown rotations and shifts of the stations that occurred during drilling and installation.

As the Sun has an extent of 1 degree on the sky, the limit of what is possible using this method is thus already being reached. However, given that reconstructing the neutrino arrival direction is currently subject to even larger uncertainties, the technique already ensures sufficiently correct global positioning to make RNO-G ready for its first neutrino detection. With such an astrophysical calibration, RNO-G will be able to most accurately point the multimessenger community to potential follow-up observations.

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ACADA – Array Control and Data Acquisition system for CTAO

Managing the control, supervision and data handling of the CTAO telescopes and instruments

The Cherenkov Telescope Array Observatory (CTAO) is nearing its construction and operation phases, generating excitement about its scientific potential. As the first open, proposal-driven observatory of its kind, CTAO will provide public access to high-level gamma-ray science data and software. It aims to expand the number of known gamma-ray sources by up to 1000. CTAO will offer insights into many fascinating astrophysical questions, such as the origin of cosmic particles and the nature of extreme astrophysical environments. At the heart of CTAO operations is the Array Control and Data Acquisition system, or ACADA for short. ACADA will manage the control, supervision and data handling of telescopes and auxiliary instruments at the two CTAO sites.

Controlling arrays of CTAO telescopes

The ACADA system will ensure efficient observation planning and execution while processing the multi-Gb/s data streams generated by the Cherenkov cameras. One of the key features of ACADA is the Science Alert Generation Pipeline, a real-time system that automatically identifies potential science alerts as data are collected. These alerts, along with incoming ones from external observatories, will be processed by the Transients Handler system. The latter will be able to prompt the Short-term Scheduler to adjust the observation plan within seconds.

Such dynamics require a robust and responsive software framework, able to effectively control instruments and optimise scientific output. The ACADA software is designed to facilitate these requirements. It is built on the Alma Common Software (ACS) framework, developed using C++, Java, Python and JavaScript. Combined with the rapid movement of the CTAO telescopes, this positions the observatory as a powerful tool for investigating fast, high-impact astronomical transients. Examples include observations of gamma-ray bursts and the follow-up of gravitational wave alerts.

The ACADA project

The development of ACADA to this stage has involved about 40 experts from 10 institutes, across six countries and over five years of effort. DESY is a major contributor to ACADA, leading work packages dedicated to the Central Control and the Resource Manager, the Human–Machine Interface as well as the Configuration Database. DESY also provides extensive support for the computing infrastructure of CTAO. In addition, DESY collaborates on the development of the Transients Handler system, which is led by the University of Potsdam, Germany.

First testing and integration campaign with a CTAO telescope

The first official release of ACADA, REL1, was completed in July 2023 and successfully integrated with the first prototype of CTAO's Large-Sized Telescope, LST-1. Over the course of two weeks in September and October 2023, teams of scientists and engineers visited the CTAO-North site on the island of La Palma, Spain, to carry out first integration tests with LST-1 (Fig. 1). These tests were key to evaluating the performance of the software on a single telescope, an essential step before scaling it up for the full array.

Following nearly two years of preparation in collaboration with the LST team, the integration campaign and its successful results represented a major achievement in the development of ACADA. The project now advances towards integrating ACADA with the full telescope array, with work under way towards the second software release in 2025.

Figure 1
Scientists and engineers from DESY and collaborating institutes, conducting integration tests with the first prototype of CTAO's Large-Sized Telescope, LST-1.

Figure 2
Participants of the Critical Design Review for the ACADA system

ACADA completes Critical Design Review

The year 2024 also saw the completion of the Critical Design Review for the ACADA system. The review panel included internal and external experts from the European Southern Observatory (ESO), the European Organization for Nuclear Research (CERN), the Thirty Meter Telescope Observatory (TMT) and the European Space Agency (ESA) (Fig. 2). The panel evaluated the work done so far as well as the designs and plans for continued development of ACADA. The completion and approval of the ACADA Critical Design Review were another significant milestone for CTAO.

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Radio and X-ray emissions from TDEs with luminous relativistic jets

Bridging the TDE accretion history and jet evolution with multiwavelength observations in the time domain

Tidal disruption events (TDEs) occur when a star is torn apart by the tidal forces of a supermassive black hole, resulting in a transient that can last from months to years. To date, four TDEs have been identified as exhibiting luminous jets accompanied by rapidly declining non-thermal X-ray emission. A recent theoretical investigation by researchers at DESY demonstrated that a two-component jet scenario can explain the radio and X-ray observations of the jetted TDE AT 2022cmc, utilising the AM³ software developed at DESY. This work provides for the first time a universal and self-consistent interpretation of the X-ray light curves and spectra of all four jetted TDEs by modelling the jets propagating through an external density medium.

Jetted TDEs in a netshell

TDEs are astronomical phenomena that occur when a star is torn apart by the tidal forces of a supermassive black hole as the star orbits in close proximity to it. The subsequent accretion activities, fuelled by the bound mass of the star, can generate a luminous transient spanning a broad electromagnetic spectrum, including radio, optical, ultraviolet, X-ray and gamma-ray bands. Promising sites for multiwavelength emissions include the accretion disk, gas debris, sub-relativistic winds and relativistic jets.

Among the expanding catalogue of recorded TDEs, four TDEs, including Swift J1644+57 [1, 2], Swift J2058+05 [3], Swift J1112-8238 [4] and AT 2022cmc [5], have been classified as jetted TDEs. These jetted TDEs display promising signatures of relativistic outflows, including fast-decaying light curves and non-thermal flux intensities in X-ray bands, alongside bright, long-lived radio emission. It has been thought that the radio emission is explained by synchrotron emission of electrons accelerated at external forward shocks, as the jet propagates into the circumnuclear medium and becomes decelerated. As for the X-ray emission from jetted TDEs, interpreting it within the same emission zone as the radio emission is challenging, which implies that the radio and X-ray emissions are produced in two distinct zones.

Relativistic jet structure and dynamics

Motivated by the distinct signatures of radio/sub-millimetre and X-ray signals, such as their light curves, their variability time scales and their spectral shapes, researchers from the DESY Astroparticle Physics Theory group have presented a multizone model that incorporates a fast relativistic jet (narrow outflow, denoted as "fast jet") and a slow relativistic jet (wide outflow, denoted as "slow jet"). This model is capable of simultaneously explaining the X-ray and radio spectral energy distributions and light curves [6].

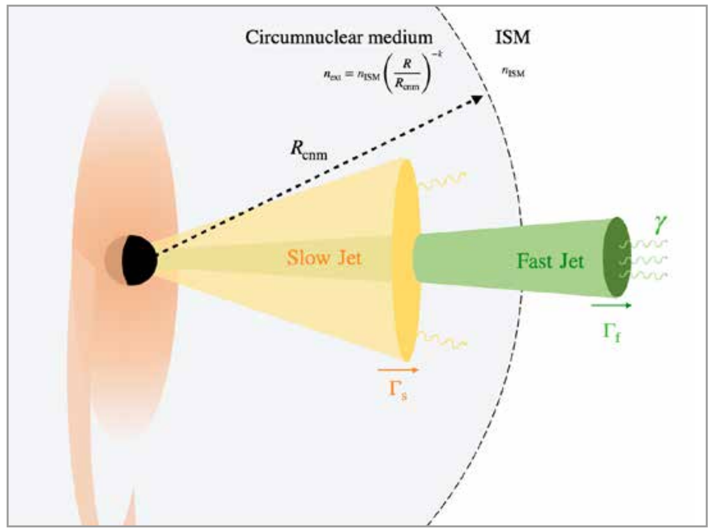

Figure 1
Schematic picture of the structured jet model, showing a fast jet propagating in the interstellar medium (ISM) and a slow jet propagating in the circumnuclear medium. From [6].

Figure 1 illustrates the configuration of the multizone model, depicting an accretion disk, a fast jet and a slow jet propagating in the ambient gaseous environment, which is characterised by connecting the circumnuclear medium (e.g. [7]) and the interstellar medium. For completeness, time-dependent mass and power injections into the jet are considered when deriving the differential equations of jet dynamics, noting that the mass accretion rate after the disruption of the star is time-dependent and could last from months to years. Moreover, the energy and mass transfers between the jet forward shock (FS), which accelerates the ambient gas, and the reverse shock (RS), which decelerate the ejecta, are also taken into account in this study. Unlike treatments in the context of gamma-ray burst (GRB) afterglows (e.g. [8]), the continuously powered jet could significantly alter the X-ray light curves.

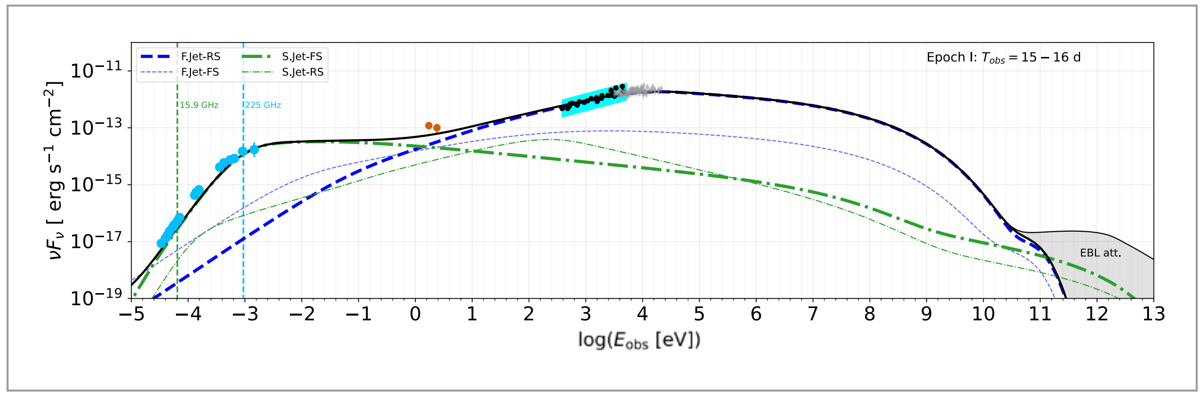

Figure 2
Spectral fitting for AT 2022cmc, illustrating the SY/IC spectra of the fast/slow-jet forward (F.Jet/S.Jet-FS) and reverse (F.Jet/S.Jet-RS) shocks. The orange points indicate the energy fluxes in optical bands, which are considered as upper limits. From [6].

Interpretation of radio and X-ray observations

Given the dynamics of the slow and fast jets, time-dependent multiwavelength emissions from the forward and reverse shocks are self-consistently calculated leveraging the Astrophysical Multi-Messenger Modeling (AM³) software [9] developed at DESY. Similar to GRBs, parameter sets for FS and RS regions are introduced to parametrise the fractions of internal energy density that are converted to non-thermal electrons and turbulent magnetic fields. Synchrotron and inverse Compton emissions from relativistic electrons are used to explain the multiwavelength observations.

Figure 2 shows the fitting to the AT 2022cmc spectral energy distribution in a selected epoch, 15–16 days after the disruption of the star. In the fast-jet (denoted as "F.Jet") scenario, the thin and thick blue dashed curves depict the combined synchrotron and inverse Compton (denoted as "SY/IC") emissions from the FS and RS regions. The figure demonstrates that the RS fast-cooling synchrotron spectra are consistent with the observed X-ray data, whereas the slow-jet FS region explains the radio data.

Figure 3 illustrates the fitting to the measured X-ray and radio/sub-millimetre light curves. The results indicate that emissions from the fast-jet reverse shock could account for the fast-decaying X-ray light curve. Remarkably, the jet break steepening (dashed red line) due to the jet deceleration naturally explains the late-stage X-ray upper limits (red triangles). The slow-jet forward-shock model can explain the 225 GHz and 15.5 GHz light curves very well after 15 days, whereas the early-time radio signal could be contaminated from other radiation processes.

Summary

The comprehensive modelling of the structured jet, involving the forward and reverse shock, related to TDEs provides a useful physical framework for interpreting the time-dependent multi-wavelength observations of all four jetted TDEs [10] and of TDEs that will be detected in the future. Furthermore, this work also offers a prototype to investigate the physical conditions of mass accretion, the ambient gas density profile and the outflows, through spectral and light curve fitting.

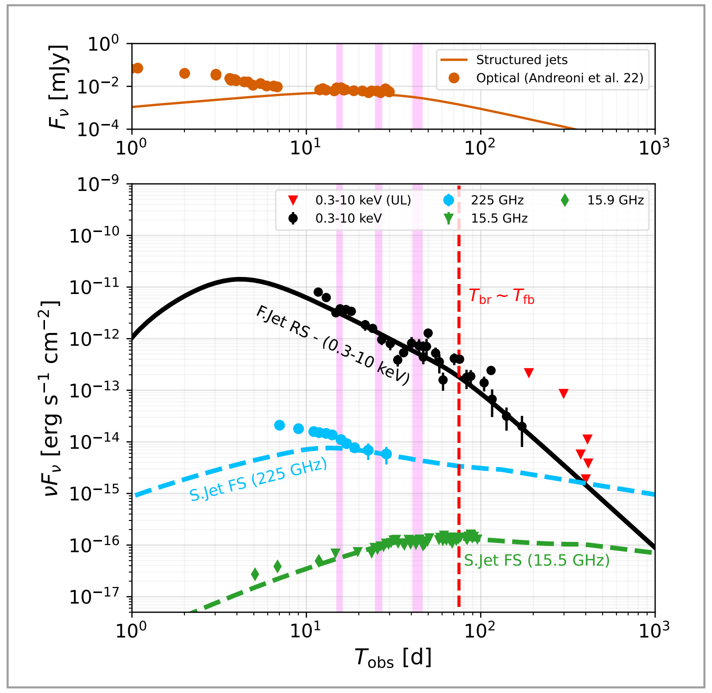

Figure 3
Fitting of non-thermal X-ray and radio light curves of AT 2022cmc with fast-jet reverse-shock region (F.Jet RS) and slow-jet forward-shock region (S.Jet FS). From [6].

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Turbulent properties in space plasma

Revealing the nature of space magnetohydrodynamic turbulence and its self-organised weak-to-strong transition

Plasma turbulence transfers energy across a wide range of scales, creating a chaotic superposition of multiscale fluctuations. However, limited satellite sampling hinders the direct measurement of magnetohydrodynamic (MHD) turbulence, complicating the *in-situ* validation of turbulence theories. A team led by the DESY Plasma Astrophysics group and the University of Potsdam has developed a novel multispacecraft mode decomposition method to reveal turbulent properties in space plasma. The researchers presented the first observational evidence of an Alfvénic transition from weak to strong turbulence as energy cascades to smaller scales. The findings show that compressible turbulence is primarily shaped by large-scale forcing and small-scale damping. Understanding Alfvénic self-organisation and compressible-mode damping is key to fully capturing the energy cascade in MHD turbulence.

Observational evidence for Alfvénic weak-to-strong transition

The theory of anisotropic MHD turbulence has been used to successfully describe natural phenomena in plasma systems, ranging from clusters of galaxies and the interstellar medium to accretion disks or the heliosphere. According to the modern theory of compressible MHD turbulence, small-amplitude fluctuations can be decomposed into three linear eigenmodes: incompressible Alfvén modes as well as compressible slow and fast modes. One of the most crucial predictions of the theory is an Alfvénic transition from weak to strong turbulence when energy cascades from large to small scales, which has not been observationally confirmed. Confirming MHD turbulence theory in spacecraft observations is exceptionally challenging because 3D sampling of turbulence is not available. To address this issue, the team developed a novel multi-spacecraft mode decomposition method to obtain 3D energy distributions of magnetic field and velocity, allowing direct comparisons between observations and theory.

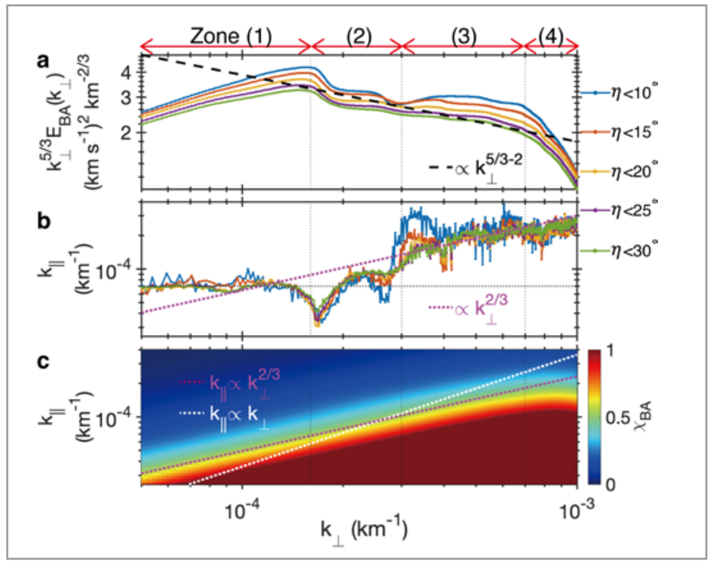

Figure 1
Perpendicular wavenumber dependence of the compensated spectra, parallel wavenumber and non-linearity parameter

The researchers presented the first observational evidence for the presence of this transition using data from the four Cluster spacecraft [1]. First, they observe a shift in the wavenumber distribution of magnetic energy from a purely perpendicular cascade to a scale-dependent Goldreich–Sridhar cascade [2] (Fig. 1 and 3a). Second, a sharp change in the spectral slope of the energy spectral density from wave-like (-2) to Kolmogorov-like (-5/3) is apparent evidence for a transition of turbulence regimes (Fig. 1). Third, the non-linearity parameter exhibits Goldreich–Sridhar scaling [2] with respect to wavenumber (Fig. 1). Fourth, turbulent fluctuations start to deviate from the dispersion relation of linear Alfvén wave when below the Alfvénic transition scale (Fig. 2).

The observational confirmation of such a transition completes the final puzzle in MHD turbulence theory: the transition from linear wave-like fluctuations to strong turbulence during the energy cascade. This self-organised process is a cornerstone of modern MHD turbulence theory, effectively connecting weak and strong turbulence systems. The results reveal the universal presence of strong turbulence on small scales, accompanied by weak turbulent fluctuations on large scales. Moreover, the non-linear interactions of MHD turbulence play a critical role in mediating the energy cascade by broadening both the cascade directions and the fluctuating frequencies. The Alfvénic weak-to-strong transition may be fundamental to various astrophysical environments, such as star formation, energetic particle transport, turbulent dynamos and solar corona or solar wind heating.

Compressible MHD turbulence modulated by collisionless damping

Using the novel multispacecraft mode decomposition method, the wavenumber distributions of the energy density were obtained for the three MHD eigenmodes (Fig. 3) [1, 3]. Compared to the isotropic dotted curves, the energy spectrum of Alfvén modes is prominently distributed along the $k_\perp$ direction, suggesting a more rapid cascade in the perpendicular direction. In the strong-turbulence regime, the energy spectrum of Alfvén modes aligns well with the theoretical model for strong turbulence:

$$I_A(k_\perp, k_\parallel) \propto k_\perp^{-\frac{7}{3}} \exp\left(-\frac{L_0^{1/3}|k_\parallel|}{M_{A,turb}^{4/3}\, k_\perp^{\frac{2}{3}}}\right)$$

(Fig. 3), where $k_\perp$ and $k_\parallel$ are wavenumbers perpendicular and parallel to the background magnetic field (B_0), L_0 is the injection scale of turbulence and $M_{A,turb}$ is the turbulent Mach number.

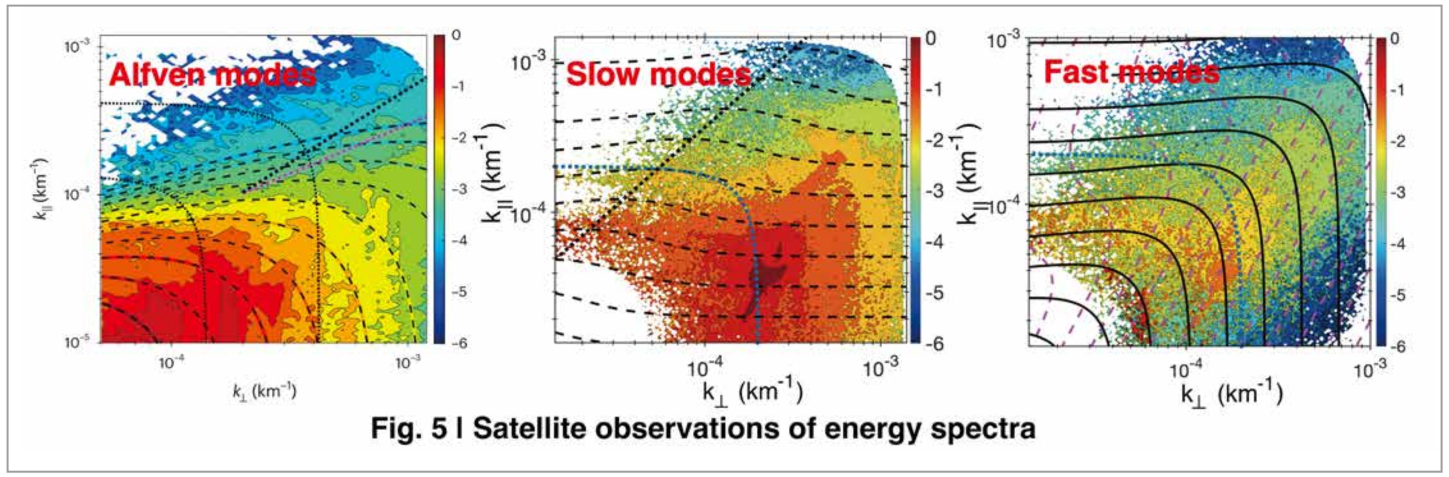

Figure 3
Wavenumber distributions of the normalised energy density $\hat{D}(k_\perp, k_\parallel)$. Left: Alfvén modes. The dashed curves mark the theoretical energy spectra of strong turbulence. Centre: Slow modes. The dashed curves mark the damping rate of slow modes. Right: Fast modes. The purple dashed curves mark the damping rate, the solid curves the cascading rate of fast modes. In the three parts of the figure, the dotted curves mark isotropic contours.

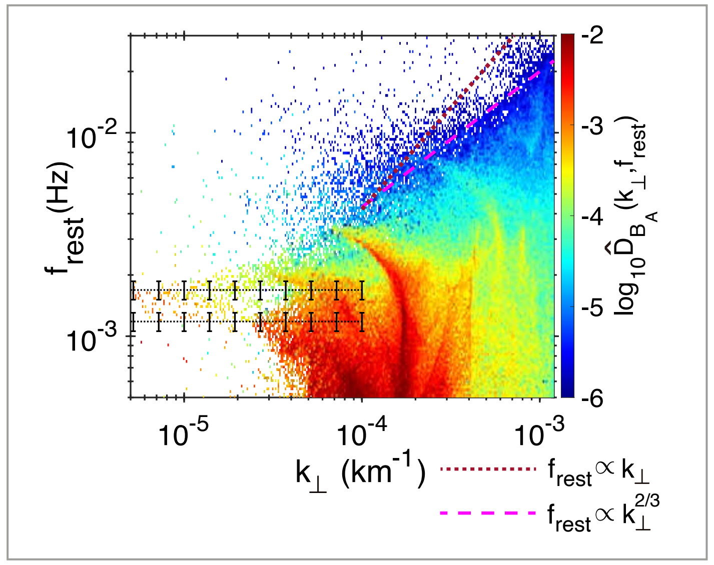

Figure 2
$k_\perp$ versus f_{rest} distributions of Alfvénic magnetic energy in the plasma flow frame. The horizontal dotted lines represent theoretical Alfvén frequencies $f_A = |k_\parallel V_A|/(2\pi)$, where $k_\parallel = 7\times10^{-5}$ km in zone (1) of Fig. 1b.

Unlike incompressible Alfvénic turbulence, compressible turbulence is subject to damping processes during the inertial-range energy cascade, which remain not completely understood. Collisionless damping (CD) leads to the rapid dissipation of plasma waves through wave–particle interactions, such as gyroresonance, transit time damping or Landau resonance. A comprehensive understanding of how damping influences compressible turbulence is essential for accurately characterising turbulence in real plasma environments.

In compressible plasma, both the composition of MHD eigenmodes and the effects of CD significantly influence the energy cascade and statistical properties of turbulence. The observations demonstrate that wavenumber distributions of slow modes are elongated perpendicular to B_0, with minor modulation by CD. In contrast, fast modes are subject to more significant CD modulation. Above the CD truncation scale, fast modes exhibit a scale-independent but slight anisotropy. Below the CD truncation scale, however, their anisotropy increases with the decreasing scale [3].

These results provide the first observational confirmation of a central theoretical prediction: Plasma turbulence is primarily shaped by forcing on large scales and damping on small scales within the MHD regime. The results improve the general understanding of how CD shapes the cascade of compressible turbulence, with implications for energy transfer, particle transport and particle energisation in space and astrophysical plasmas.

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Searching for heavy neutral leptons at the South Pole

New analysis of IceCube DeepCore data constrains coupling between tau neutrinos and heavy neutral leptons

The IceCube DeepCore neutrino detector at the South Pole has captured GeV-scale atmospheric neutrino interactions for over a decade, providing a rich data set for precision measurements of neutrino oscillations and searches for physics beyond the Standard Model of particle physics. A new analysis led by researchers at DESY and Harvard University targets heavy neutral leptons (HNLs) with masses around 1 GeV that are produced through their coupling to oscillated atmospheric tau neutrinos. Dedicated simulations were developed to study HNL production and decay in the detector. The results set new constraints on the HNL mixing parameter $|U_{\tau 4}|^2$ and establish a foundation for future searches.

Introduction

Since the discovery of neutrino oscillations, which proved that neutrinos are massive, researchers have been trying to uncover the mechanism responsible for neutrino mass generation. One interesting theoretical framework posits the existence of heavy right-handed neutrinos, or heavy neutral leptons (HNLs), which have small Yukawa couplings to left-handed neutrinos and the Higgs boson of the Standard Model (SM). In this way, neutrino masses arise after electroweak symmetry breaking, similar to other SM fermions [1]. The mass of the HNLs and their coupling strength to SM particles are free parameters that can be constrained experimentally.

As right-handed neutral particles, HNLs are not directly observable. However, they can be indirectly detected through their mixing with SM electron, muon and tau neutrinos, parametrised by $|U_{e4}|^2$, $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$, respectively. Numerous searches across a wide range of experiments – including at particle accelerators and in nuclear decays – have placed strong limits on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ for HNL masses between 10^{-3} – 10^2 GeV. In contrast, constraints on $|U_{\tau 4}|^2$ are comparatively weaker [1]. A promising opportunity to probe this largely unexplored sector arises from the substantial flux of atmospheric tau neutrinos detected by IceCube DeepCore.

Heavy neutral leptons in IceCube

IceCube DeepCore detects thousands of atmospheric neutrinos each year. By mapping the flavour composition of the neutrino flux as a function of energy and arrival direction, the experiment enables precise measurements of neutrino oscillations [2]. The dominant effect is the mixing between muon and tau neutrinos, resulting in the appearance of a substantial upward-going tau neutrino flux with multi-GeV energies.

This flux enables a novel search for HNLs produced via tau neutrino up-scattering. Here, a tau neutrino interacts with a nucleon inside or near the detector to produce an HNL. If both the production and the decay of the HNL occur inside the detector, it can leave a distinct signature: a pair of low-energy cascades separated by several metres, depending on the HNL mass and mixing strength $|U_{\tau 4}|^2$ [3].

To model these rare events in IceCube DeepCore, a dedicated Monte Carlo simulation was developed in collaboration with researchers at Harvard University in the USA [4, 5, 6]. The simulation incorporates HNL production cross sections, decay processes and a detailed detector response. Three data samples were simulated for HNL masses of 0.3, 0.6 and 1.0 GeV. Figure 1 (right) shows an event display for a GeV-scale HNL production and decay inside the detector, illustrating the double-cascade signature. For comparison, examples of typical single-cascade and track topologies arising from SM atmospheric neutrino backgrounds are also shown.

Convolutional neural networks were used to reconstruct the energy, arrival direction and topology of signal and background events. Simulation studies found that most HNL events resemble single cascades, since one of the two cascades is often outside of the detector volume or contains too little visible energy to be detected by IceCube DeepCore's sparse instrumentation [6]. In addition, the dedicated double-cascade selection was dominated by atmospheric neutrino backgrounds and was therefore not used in the analysis.

Figure 2 shows the expected rate of HNL interactions as a function of $|U_{\tau 4}|^2$ for each HNL mass. The rates differ because heavier masses enable access to different decay channels and impact the decay length, leading to different event kinematics and detection efficiency.

Results

Ten years of IceCube DeepCore data were analysed to search for HNLs. The dedicated simulations for each HNL mass hypothesis (0.3, 0.6 and 1.0 GeV) were used to model the expected signals.

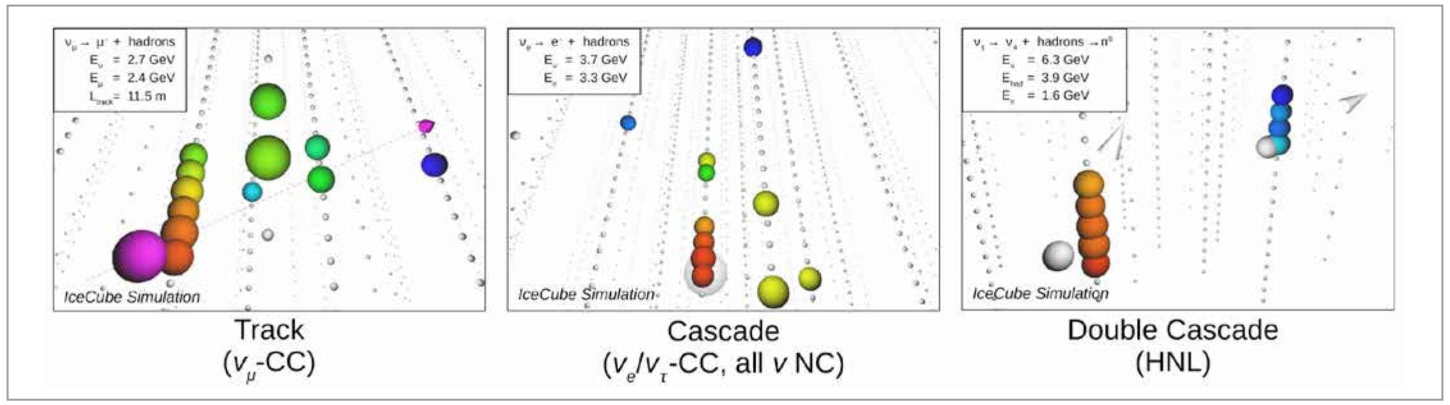

Figure 1
Event topologies in IceCube DeepCore. Coloured spheres show optical modules that have detected light. Left: Track produced mostly by charged-current muon neutrino interactions. Centre: Single cascade produced by charged-current interactions of electron and tau neutrinos or by neutral current interactions of all flavours. Right: Double cascade from the production and decay of an HNL in the detector.

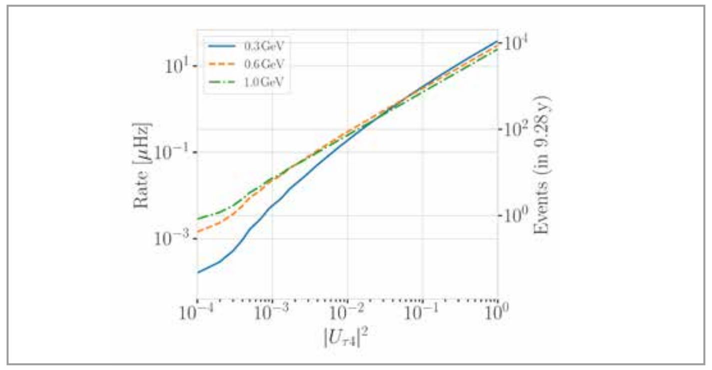

Figure 2
Expected HNL rates (left axis) and number of events (right axis), assuming 9.28 years of detector lifetime, as a function of $|U_{\tau 4}|^2$ for each of the three simulated masses after applying all event selection criteria [6]

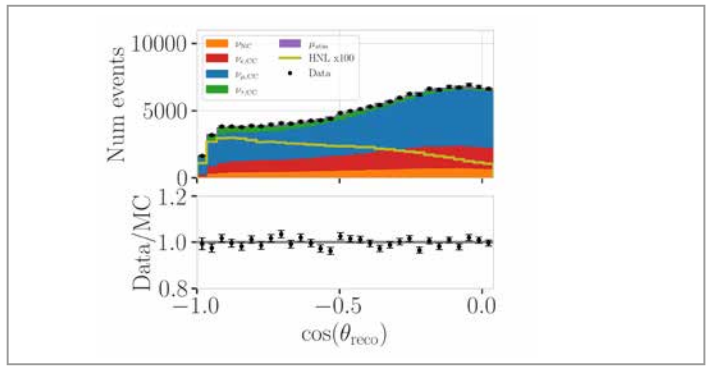

Figure 3
Reconstructed zenith angle distribution of the data (black points) compared to the best fit simulation shown as stacked histograms reflecting the different interaction types. The HNL signal is scaled up by a factor of 100 for visibility and assumes m_{HNL} = 0.6 GeV and $|U_{\tau 4}|^2$ = 0.08 [6].

Figure 3 shows the reconstructed arrival direction for the SM neutrino backgrounds compared to an HNL signal. The signal is predominantly expected in the up-going region, corresponding to the maximum appearance probability for oscillated atmospheric tau neutrinos.

A fit to the data was performed to estimate the strength of $|U_{\tau 4}|^2$ for each mass. The fit accounted for systematic uncertainties in atmospheric neutrino fluxes, cross sections and detector calibration, incorporating a novel statistical method developed by early-career researchers at DESY [4].

No significant HNL signal was observed, and corresponding upper limits on $|U_{\tau 4}|^2$ were set. More information, including quantitative results for each mass hypothesis, can be found in [6, 7]. This first dedicated search for HNLs with IceCube DeepCore has laid a strong foundation for future analyses, demonstrating the feasibility of probing HNL models and identifying experimental challenges to be addressed in upcoming efforts.

Looking towards the future

A key challenge in this analysis was the separation of the distinct double-cascade signature expected from HNLs from the large background of atmospheric muon neutrino interactions. The sparse spacing of optical modules in IceCube DeepCore, coupled with uncertainties in detector efficiency and properties of the glacial ice, led to significant rates of background events misidentified as double cascades.

The IceCube Upgrade [9], expected to begin operations in 2026, will address these challenges directly. Seven new boreholes will host more densely packed instrumentation, including novel optical modules with more than twice the effective area for photon detection as well as dedicated light sources for precision calibration. These enhancements will significantly improve event reconstruction capabilities, opening new opportunities for rare-event searches, such as HNLs. Preparatory work is already under way to estimate the potential gains in signal-to-background separation with the upgraded detector.

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New sensors for IceCube Upgrade in final stage of preparation

Production, testing and shipment towards deployment at the South Pole

The IceCube Upgrade project will improve the performance of the currently operating IceCube neutrino observatory by deploying ~700 new modules in a dense pattern in the ice of the South Pole. Around 400 of them are modules with 24 photomultipliers, designed by DESY together with other German institutions. DESY has developed an efficient production and testing procedure, which was then transferred to Michigan State University in the USA. Over the past few years, production and testing have been conducted intensively at both sites. A first shipment of 128 modules has already been delivered to the South Pole, and the rest will be shipped in mid-2025 after a careful selection process based on the test results. The deployment of all the modules is scheduled for the Antarctic summer 2025/2026.

IceCube Upgrade

Preparation for the new sensors for the IceCube Upgrade has entered the final stage before their planned deployment at the South Pole in the Antarctic summer 2025/2026. The IceCube Upgrade is the extension of the current IceCube experiment with new sensors installed in the core region of the detector [1].

As the world's leading neutrino observatory, IceCube has significantly advanced our knowledge of both astroparticle physics and neutrino physics since it went into operation in 2010. The detector consists of 86 strings, each with 60 light sensors (digital optical modules, DOMs), reaching down to a depth of 2500 m below the ice surface. The strings are roughly 100 m apart from neighbouring ones, and the DOMs of each string are vertically spaced at intervals of 17 m.

For the upcoming IceCube Upgrade, new sensors will be deployed in a dense pattern. It will consist of seven strings located horizontally within a diameter of 100 m. Each string has 100 sensors with a vertical spacing of only 3 m. The goal of the IceCube Upgrade is to increase the sensitivity to relatively low-energy neutrinos down to GeV energies as well as to better understand the properties of the ice using densely populated calibration devices.

mDOM design, production and testing

The new sensors were designed to meet the scientific performance of the IceCube Upgrade. More than 400 of them are multi-PMT digital optical modules (mDOMs) with 24 three-inch photomultiplier tubes (PMTs) oriented in different directions in each module (Fig. 1) [2]. They have nearly isotropic photon acceptance and a direction-averaged detection efficiency that is more than twice as high as that of the DOMs used for IceCube. DESY has been leading the mDOM development and production in cooperation with other German universities and institutions.

In recent years, mDOMs have been intensively produced at DESY in Zeuthen and Michigan State University (MSU) in the USA (Fig. 2). Despite the precise work required to assemble various devices including PMTs, cables and electronic boards in a relatively small sphere of ~30 cm, manufacturing was as fast as about five mDOMs per week thanks to the matured skills of the team. As of May 2025, only around 10 mDOMs out of the target number of 235 including spare ones remained to be produced.

At DESY, the mDOMs underwent a series of tests after production [3]. This was done in two test setups. One is a climate chamber in which basic functionalities of the PMTs and calibration devices are examined and monitored for a few weeks at two different temperatures of -40°C and -20°C. The other is an optical setup in which precise measurements are performed on the PMTs with controlled amounts of light using a laser. The DESY team has developed dedicated software to automate and parallelise the tests. More than 20 mDOMs per month can be currently tested without requiring much human intervention, except for transportation between the setups.

Figure 1
mDOM sustained with metal ropes

The test results were compiled in one summary file for each mDOM for review. As part of the review process, multiple experts carefully monitored the plots and judged the acceptability of the mDOM for deployment based on predefined criteria. Web-based interactive plots were also developed to facilitate the review. Once availability was confirmed, the mDOMs underwent a mechanical harness load test before finally being declared ready for shipment. The fraction of mDOMs with critical issues has been less than 5%.

Figure 2
mDOM production site near DESY in Zeuthen

Status of shipment and deployment plan

The first 128 mDOMs were shipped from DESY in Zeuthen in August and arrived at the South Pole in December 2024 (Fig. 3). After arrival, final acceptance tests were performed to confirm the availability of the mDOMs together with other types of sensors and calibration devices.

Figure 3
Upgrade sensors delivered to the South Pole, including the first 128 mDOMs

All the 128 mDOMs have successfully passed the tests and are now ready for deployment. The rest of the mDOMs will be shipped in July/August 2025 from DESY and MSU.

The deployment of all seven strings equipped with mDOMs in the glacial ice of the South Pole is planned to take place from December 2025 to January 2026.

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Black hole superradiance in binary systems

Eccentric black hole binaries could point to new fundamental particle

Researchers from the DESY Astroparticle Theory group have found that observing black hole binaries with a higher-than-expected orbital eccentricity could hint at the existence of an unknown fundamental particle. Ultralight particles, much lower in mass than any known particle, are well-motivated dark matter candidates and could produce measurable effects on gravitational wave signals. The team from DESY and Universität Hamburg has shown that such ultralight particles can also leave an imprint in the distribution of orbital eccentricities of black holes orbiting each other.

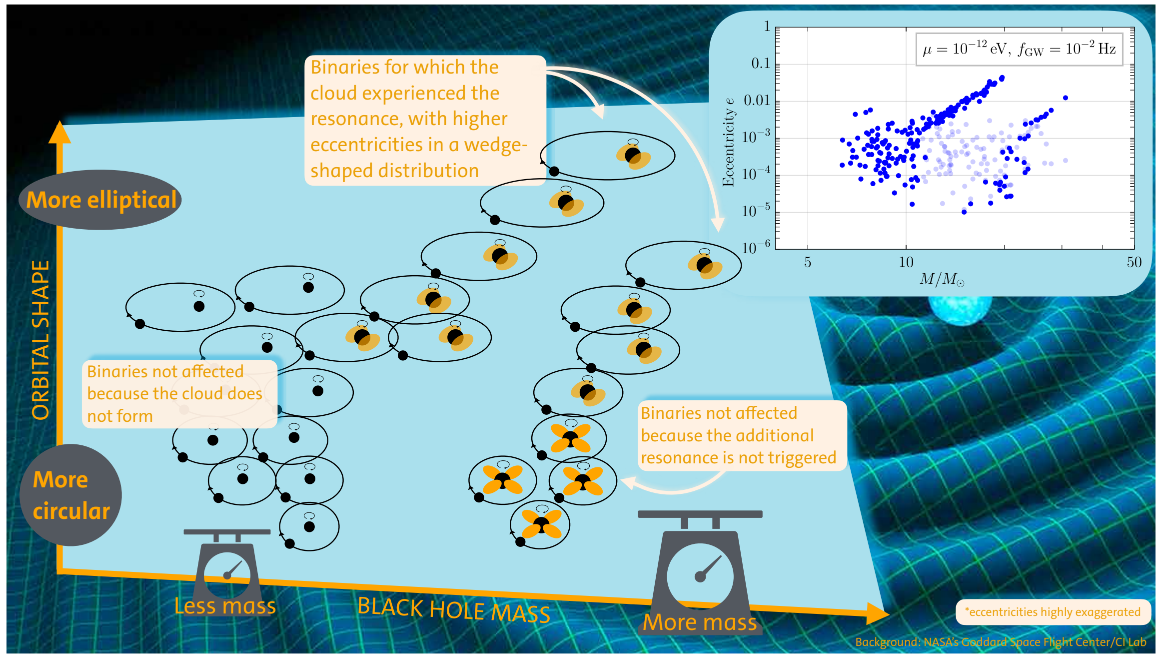

Figure 1
Diagram of orbital shape (eccentricity) vs. black hole mass for black hole binaries. Binaries in the top-right corner can exhibit higher eccentricities due to resonance with a cloud of ultralight particles. The inset shows the published plot, with a wedge-shaped pattern of eccentricities (dark blue dots) in contrast to the same population of black holes without a cloud (pale blue dots).

Theory predicts that fundamental scalar particles can be produced from the rotational energy of a black hole and then accumulate in its environment in the form of a dense cloud. The team demonstrated that, in a black hole binary in which one of the black holes is surrounded by such a cloud, due to the tidal forces from the binary companion, the eccentricity of the binary's orbit – a measure of how elongated it is – can increase. The shape of the binary's orbit thus carries a signature, readily accessible with the next generation of gravitational wave detectors, that could provide tantalising evidence for such a new fundamental particle in nature.

Ultralight particles have been intensively investigated in elementary particle physics. The most prominent of these hypothetical particles is the axion, proposed to solve the so-called strong CP problem in quantum chromodynamics (QCD). It was also identified as a valid candidate for the elusive dark matter, the unidentified form of matter that shows its influence only through gravitational interactions in astrophysics and cosmology. String theory also supports the existence of many different light bosonic particles, usually called axion-like particles (ALPs).

For ALPs, their large wavelength corresponding to their small mass allows for a process dubbed black hole superradiance around astrophysical black holes: A particle wave can come close to the rotating event horizon and bounce off it in such a way that it gets amplified, carrying away some of the black hole's rotational energy. This is the wave equivalent of the so-called Penrose process, in which a particle entering the ergoregion of a rotating black hole can extract energy from it. Bound to the black hole by gravity, superradiance happens in a repeated fashion, resulting in a dense cloud of ALPs surrounding the black hole. Since the configuration of this cloud only allows for discrete energy levels, much like the states of an electron in an atom, this object has been dubbed a gravitational atom. The team points out that this would be independent of this ALP being dark matter, it would just need to generally exist in nature.

When the gravitational atom is orbited by a second object, for example another black hole, the orbital companion induces tidal forces. Because of the discrete energy levels of the cloud, there can be resonance effects when the orbital frequency matches the energy gap between the cloud's energy levels, similar to excitations of actual atoms by light at particular wavelengths.

The black holes in a binary spiral in closer together over time as they lose energy through the emission of gravitational waves. Because of this, the orbital frequency gradually increases, and at certain points, it can hit one of the resonance frequencies of the cloud. During such a resonant Landau–Zener transition, the cloud is not only transformed into a state that is re-absorbed by the black hole, but it loses or gains energy and angular momentum, which is transferred to or from the orbit, respectively. It is already known that the energy transferred into the orbit during such a transition can counterbalance the loss of energy in gravitational waves, meaning that the inspiral of the two black holes stalls for some time. These are called floating transitions.

In their work, the researchers considered, for the first time, orbits with non-zero eccentricity. Due to the more complex motion celestial objects have on elliptical orbits, which can be expressed as an infinite sum of eccentricity-suppressed overtones, the binary–cloud system allows for additional resonances at different orbital frequencies from the resonance of circular orbits. If such an additional resonance is also of the floating type, a different interplay between energy and angular momentum transfers can then lead to the effect that, while the orbit is stalling, the eccentricity of the orbit increases.

Such a floating transition with increasing eccentricity could, for some parameters, also be observed directly by gravitational wave observatories. However, while the cloud is gone afterwards, the effect of the transition – a larger eccentricity – remains imprinted on the orbit. During the following continued inspiral, the eccentricity naturally decreases slowly, which is why almost circular orbits are usually expected at high orbital frequency. This means that observing an unusually high eccentricity at a late stage of the inspiral could be a sign that one of the black holes once carried a cloud of ultralight particles!

As a proof of concept, the team studied the history of resonances of a typical low-mass population of black hole binaries formed in isolation. If a single new particle exists, black holes with slightly different masses could all carry a cloud, while the resonance effect would happen at slightly different orbital frequencies due to the different characteristic size ratios of the particle and the black holes. Comparing all of those binaries at a particular reference frequency, the effect of the cloud and the tidal resonance could be imprinted as a peculiar feature in the distribution of eccentricities: The higher-mass black holes would have experienced the resonance at a slightly higher frequency, leading to a higher remnant eccentricity at a later time. Therefore, the distribution of eccentricities in the whole population would have a skewed feature, like a wedge (Fig. 1).

If ALPs are only coupled via gravity, their experimental investigation would basically be impossible in the foreseeable future. This research is the newest in a series of papers that tries to open backdoors towards their observation. For the currently planned next generation of gravitational wave detectors, such as LISA and Deci-hertz, it will be possible to observe binaries long before they merge, during their inspiral phase. The observation of binaries with higher-than-expected eccentricity (or even stalling frequency) could possibly hint at a new particle in nature that could be otherwise unobservable.

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New hub for CTAO

Towards construction of the Medium-Sized Telescope structure of CTAO

The Cherenkov Telescope Array Observatory (CTAO) is an international observatory for very high-energy gamma-ray astronomy, featuring telescope arrays located in the Atacama Desert in Chile and on the Canary Island of La Palma, Spain. The launch of the Science Data Management Centre (SDMC) marks a significant milestone in the development of CTAO. Alongside the production of the first two pathfinder Medium-Sized Telescopes (MSTs), these efforts represent a major step forward in the observatory's construction. DESY in Zeuthen plays a central role in this progress, as it hosts the SDMC and leads the design of the MSTs.

Inauguration of the CTAO SDMC

On 14 October 2024, the international community gathered to celebrate the inauguration of the CTAO SDMC on the DESY campus in Zeuthen. As one of the four central facilities of the observatory, the SDMC building houses the CTAO computing department, DESY offices and a newly opened canteen (Fig. 1). The event marked a milestone for the Zeuthen campus, as it now hosts an international research project for the first time – strengthening the German Federal State of Brandenburg's position in global scientific research and drawing scientists from around the world to collaborate on site.

Medium-Sized Telescopes

The MSTs of CTAO play a crucial role in detecting gamma rays in the energy range from 100 GeV to several tens of TeV. The telescope structure, developed under the leadership of DESY, features a 12 m diameter reflector composed of 86 hexagonal mirror segments, each measuring 1.2 m across. When gamma rays interact with Earth's atmosphere, they produce faint Cherenkov light through electromagnetic cascades. This light is collected by the reflector and focused onto the camera. The camera designs differ between CTAO's northern and southern sites, with NectarCAM used in the north and FlashCam in the south. Both camera types feature a wide 8-degree field of view and use photomultiplier tubes to detect the faint bluish Cherenkov light – capturing the final traces of the high-energy gamma rays emitted by cosmic sources.

Project status and plan

A prototype of the MST structure was built and successfully operated for eight years in Berlin, serving as a crucial testbed for the development of the final design. The full CTAO observatory, in its initial Alpha baseline configuration, will include 23 MSTs. The prototyping phase focused on validating the performance of individual components while simultaneously refining the design to ensure cost efficiency and easy of reproduction.

Figure 1
The SDMC building of CTAO at DESY in Zeuthen

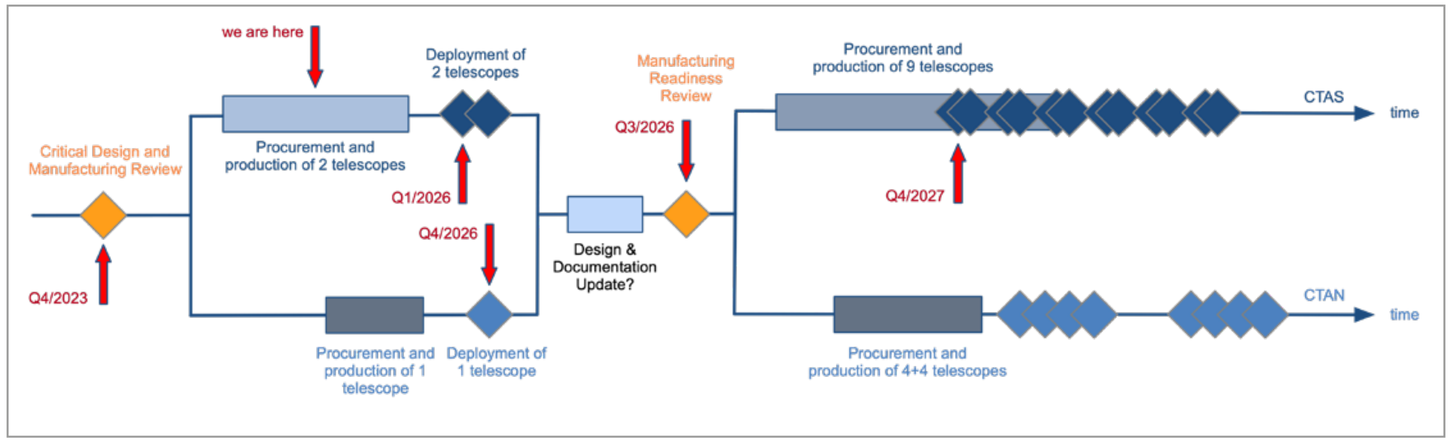

Figure 2
High-level project timeline representing the transition from prototyping to preproduction

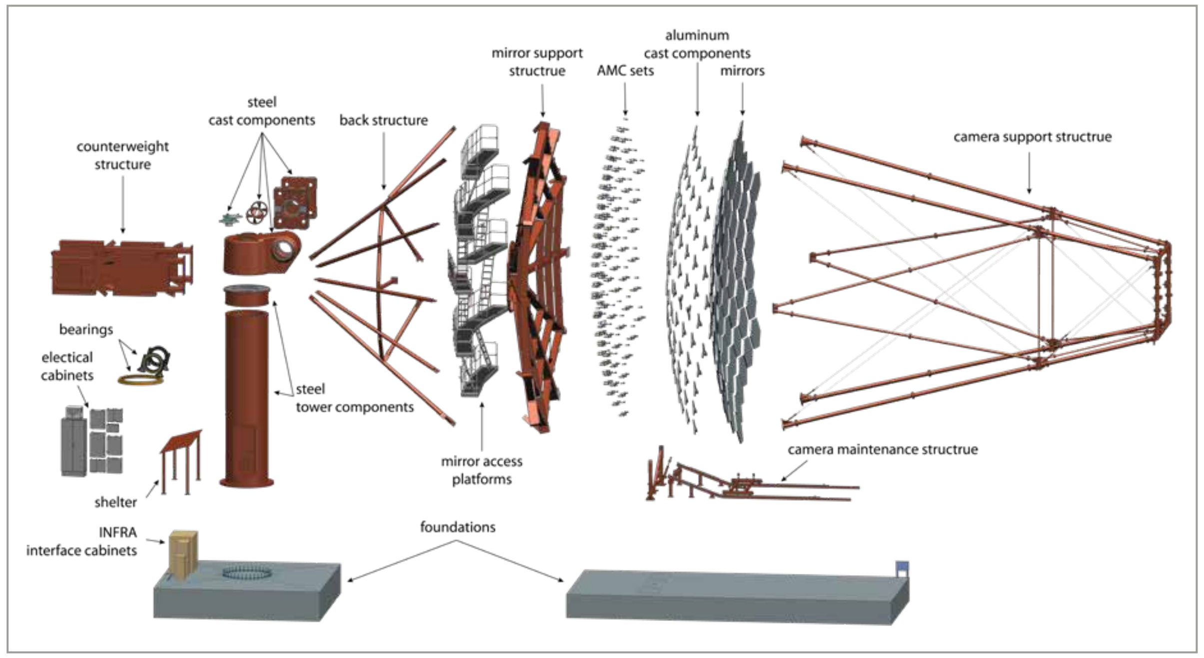

Figure 3
Organisation of MST parts into lots according to their type of production

Figure 2 illustrates the current project timeline. The Critical Design and Manufacturing Review of the telescope structure was successfully completed in 2023, marking a major milestone. Production of the first two pathfinder telescopes is currently in progress, with deployment at the southern observatory site planned for early 2026. Preparations are also under way for procuring a third pathfinder to be installed at the northern site. Following the assessment of manufacturing processes and pathfinder performance during the Manufacturing Readiness Review, scheduled for the second half of 2026, full-scale production and deployment of the remaining 21 telescopes will begin. Serial deployment of the telescopes is expected to commence by the end of 2027.

Telescope procurement and production

Figure 3 illustrates the organisation of the telescope components into lots, grouped by production type. This arrangement is designed to minimise the administrative overhead by reducing the number of tenders while also aligning component groups with specific industrial manufacturing processes to facilitate participation of specialised companies.

Most components are intended to be shipped directly from their manufacturing sites to the observatory locations, using a combination of standard and open-top containers of various sizes tailored to specific transport requirements.

Pre-assembly of the telescope positioner will take place in a dedicated facility near DESY in Zeuthen. This step is intended to simplify the on-site assembly process. The key components designated for pre-assembly include both tower shells (with azimuth drive elements), cast parts such as the head (with elevation drive elements) as well as all electrical cabinets, cables and commercially available items required for pre-assembly. Once pre-assembled and tested, these units will be shipped to the observatory site for final installation.

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Campus development in Zeuthen

Towards a modern, open campus

For over 30 years, the Zeuthen campus has been an essential part of DESY. With its scientific focus on astroparticle physics involving high-energy neutrinos and gamma rays, the site has developed a distinctive, forward-looking and internationally visible research profile in recent years. This highly positive scientific development and the new tasks ahead have been key drivers in the ongoing development of the campus. The goal has been to create an environment that visibly reflects, also in architectural terms, the role that the Zeuthen campus already plays in science today.

Master plan

The implementation of the DESY 2030 strategy process and the construction of the Science Data Management Centre (SDMC) for the Cherenkov Telescope Array Observatory (CTAO) formed the basis for a new master plan for the Zeuthen campus. In particular, the construction of the SDMC, funded by federal and state sources, marked a major milestone on the way to transforming the site into an international hub for astroparticle physics.

In summary, the DESY 2030 strategy process as well as the Green DESY, Mobility and Open Campus development goals, together with the results of the feasibility study and the stipulations of the land-use plan, defined the following key requirements for the future campus planning:

- Enhancement of the main entrance on Platanenallee
- Clear access structures for external visitors and creation of a central campus hub
- Careful integration of new buildings with existing structures and green spaces
- Full use of the development potential for new buildings near the western entrance on Platanenallee and to the east near the sailing club
- Maximum preservation of existing trees
- Optimal use of the waterfront area, particularly for breaks and recreation
- Use of the green space in front of the old villa and along the Dahme river as a recreational area free of buildings
- Zoning of the campus: public and representative facilities in the north and east, aligned with the redesigned central plaza; concentration of primarily scientific and technical buildings in the southwest of the campus

These requirements led to a series of strategic measures, with a key milestone reached in October 2024 with the opening of the new building for the CTAO SDMC and the new canteen. Further steps included the renovation of the seminar room area, which was largely completed by the end of 2024, as well as ongoing renovations and expansions in the laboratory building, where new communication areas are scheduled for completion in 2025.

New building on the campus

In the long term, up to 400 people will be employed on the campus. The required space (approximately 1200 m^2) was provided through the new building, in which 66 additional workplaces were created. In addition, around 500 m^2 were allocated to the construction of a new canteen to meet the increased demand on campus.

The new building complements the DESY campus in Zeuthen as a representative ensemble (Fig. 1). In the spirit of an open campus, the canteen and assembly room on the ground floor are publicly accessible. The two upper floors, which are visually set apart from the base floor in terms of design, provide additional workplaces as well as lounge and communication areas.

Figure 1
The new building for the CTAO SDMC and the new canteen

Figure 2
The DESY campus in Zeuthen with the newly designed central plaza

On 14 October 2024, DESY and CTAO officially opened the new SDMC building. Important personalities of the international CTAO community, political representatives, regional partners as well as DESY and CTAO employees gathered in Zeuthen to celebrate this major milestone for the further exploration of high-energy processes in the universe.

Central green space

The new building creates a tangible connection between the newly designed campus plaza and the waterfront. Its placement has resulted in the formation of a central green space, named "Campus-Anger", which offers an enhanced quality of stay and serves as a place of communication (Fig. 2). The building blends harmoniously into its surroundings. Most of the trees on the construction site have been preserved, and seating and gathering areas have been created around them. This central plaza acts as a natural hub, guiding both staff members and guests to the various parts of the campus.

Campus expansion – seminar room level

In 1995, a former hall was converted with seminar rooms added on the upper floor. In view of the expansion of the campus, their capacity was no longer sufficient. Two new flexible event spaces were created by extending the rooftop terrace, and the aging roof was renovated at the same time (Fig. 3). The seminar rooms were equipped with a newly designed ventilation system, and fire safety standards were also updated. As part of these upgrades, the foyer was redesigned to meet the requirements of a modern conference centre.

Campus expansion – laboratory building extension

The laboratory building has long been the heart of the campus, housing most of the offices for scientists and engineers. However, its layout no longer met the demands of efficient, future-oriented work, and it lacked a central entrance area. Long, dark corridors

Figure 3
The former rooftop terrace was transformed into a new seminar room and a second foyer.

with cellular offices branching off on both sides hindered the kind of low-threshold communication that is essential for collaborative group work.

Daylight in the corridors, a redesigned entrance area and new communication zones are now contributing to a friendlier atmosphere. Fire protection and the modernisation of the sanitary facilities were also addressed as part of the renovation. The laboratory building thus forms the counterpart to the new SDMC building – vis à vis on the Campus-Anger, the new hub of the campus.

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A beacon for astrophysics: The German Center for Astrophysics (DZA)

An integrated approach of research, technology development and digitalisation – anchored in Lusatia, connected with the world

The German Center for Astrophysics (DZA) is being established as a new large-scale research centre with international appeal and regional responsibility. Located in Lusatia in Saxony, it will focus on forward-looking topics such as gravitational wave research, radio astronomy, multimessenger astrophysics, data science and technology development. Together with TU Dresden University of Technology, DESY is playing a central role in setting up the DZA: As the organisation responsible for the project, DESY is partly responsible for funding the start-up phase and is contributing its extensive experience from setting up other large-scale research projects.

A centre with a vision

The DZA combines excellent basic research with technological innovation and digitalisation. With its establishment in Görlitz, a national centre for astrophysics is being created for the first time in eastern Germany. It will be closely networked with regional industry, major international projects such as the Square Kilometre Array Observatory (SKAO) or the Einstein Telescope and leading research institutions such as DESY.

Figure 1
The DZA's temporary accommodation on Postplatz in Görlitz

The setup phase began in April 2023 and is scheduled for completion in 2026. The DZA will then be able to operate independently. As a centre for astrophysics, digitalisation and technology development with cutting-edge research, it will be a driver of innovation in Lusatia, supporting the region in the border triangle of Germany, Poland and the Czech Republic in its transition following the coal phase-out.

Scientific focus

The DZA focuses on multimessenger astrophysics with an emphasis on radio astronomy, gravitational waves and time domain astronomy. Together with the Max Planck Institute for Radio Astronomy in Bonn, Germany, two SKAO-compatible antennas (MeerKAT+) are being realised, one of them in Botswana. At the same time, a test array for the DSA-2000 project of Caltech, USA, is being set up in Lusatia. In cooperation with Caltech, the data archive of the Zwicky Transient Facility (ZTF) will also be transferred to the DZA. Thanks to the success of the DZA, Lusatia is currently also being investigated as a possible location for the Einstein Telescope.

Technology development and DESY contributions

Research operations at the Center for Technology Development (ZTE) in Görlitz started as early as 2024, with pilot projects on silicon mirrors, detector technologies and radio receivers under way – in some cases in close cooperation with industry. DESY is making decisive contributions to the development of technologies for gravitational wave detectors and the design of the Low Seismic Lab (LSL).

Research data and green computing

Over 20 PB of storage capacity and field-programmable gate array (FPGA) test systems were installed at TU Dresden with the support of the university's Center for Interdisciplinary Digital Sciences (CIDS). The DZA uses this infrastructure for data from the MeerKAT radio telescope, among other things, and is planning a German Gaia data centre with the European Space Agency (ESA). The high-performance computer Capella was expanded in close cooperation with the DZA – it is ranked top 5 worldwide in terms of energy efficiency ("green computing").

Figure 4
The rapidly growing team: DZA employees in spring 2025

Figure 2
Setting up the DZA laboratories

Figure 3
Announcement of the purchase of the future DZA campus by the Free State of Saxony, August 2024

Science communication and transformation

With over 600 events, a transformation research area that is unique in Europe and collaborations with Poland and the Czech Republic, the DZA is strengthening its regional roots. The success of the first planetarium tour "Universe on Tour" in 2023 in Hoyerswerda and three major conferences in Görlitz in 2025 emphasise its strong external impact.

The DZA plays a central role in the structural change in Lusatia following the coal phase-out. A separate department for transformation research specifically analyses the impact of the DZA on the region, society and the scientific system.

Next steps

The DZA is currently being founded as a non-profit limited company to ensure its organisational independence; at the same time, the start-up phase project is being evaluated by the funding bodies.

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Promoting young talent at DESY in Zeuthen

From initial curiosity to international research experience

Supporting young people is a core priority at DESY. The promotion of young talents at DESY goes beyond preparing future professionals – young people are seen as active contributors to a dynamic scientific community. Whether curious pupils visiting the laboratory, apprentices training in technical or administrative professions, or international summer students joining research groups – DESY provides an environment that is challenging, supportive and inspiring at all levels. Hands-on learning opportunities, personalised supervision and international networking create a unique educational setting that is ideal for creative minds who want to shape the future of science.

New impulses for STEM education

A key milestone in supporting young talents in 2024 was the signing of a cooperation agreement between DESY and the Ministry of Education, Youth and Sport of the German Federal State of Brandenburg (Fig. 1). The three-year agreement aims to develop innovative STEM education programmes with a focus on digital formats and tailored support. With its more than 20 years of experience in running its school lab, its numerous training schemes for teachers and its bespoke programmes for interested groups, DESY is an ideal partner in this respect.

Figure 1
Brandenburg's Minister of Education, Youth and Sport Steffen Freiberg (left) learns about the programme "Digitale Drehtür" from Adelheid Sommer and Christian Stegmann (DESY).

As part of the collaboration, an interactive self-learning programme was created for pupils in grades 5 to 8. Across 10 interactive courses with 40 individual lessons, the programme introduces basic concepts and phenomena related to air pressure and vacuum. The materials are accessible through the nationwide platform "Digitale Drehtür" and directly through DESY's online lab "Air, air pressure and vacuum", enabling flexible and interest-driven exploration of physical phenomena – anytime, anywhere.

The initiative shows what modern education can look like: digital, inclusive and with a direct connection to real research. Further joint projects are already being planned [1, 2].

"Zukunftstag" – Career exploration day for girls and boys

Career orientation at DESY is more than just an information event – it reflects a long-term commitment. On this year's "Zukunftstag" in April 2024, the campus in Zeuthen welcomed 40 pupils, mentored by 32 dedicated staff volunteers. In 12 different departments – ranging from workshops and IT to administration and scientific research – pupils were able to get involved directly, ask questions and gain hands-on experience (Fig. 2). Each visit was individually tailored, offering a particularly authentic insight into the broad variety of careers at DESY. The feedback was overwhelmingly positive. Enthusiastic young guests and motivated employees made the day a lively example of successful promotion of young talents.

Figure 2
Pupils discover the function of a cloud chamber during a guided tour on astroparticle physics.

Figure 3
The yearly International Cosmic Day enables students to explore the mysteries of cosmic particles.

Figure 4
Trainer and apprentice in the mechanical training workshop

International Cosmic Day – science without borders

A highlight of DESY's science outreach calendar is the yearly International Cosmic Day (ICD), which was held for the 13th time in 2024 (Fig. 3). The global event brought together 100 groups from schools, universities and research institutions across 24 countries. More than 5900 young people spent the day exploring the mysteries of cosmic particles, with a focus on muons that reach Earth from space. Using simple yet effective detectors, the participants carried out their own measurements, analysed their data and presented their findings in 14 international video conferences. For those unable to conduct onsite experiments, DESY's Cosmic@Web platform offered access to data from long-term experiments as well as online analysis tools, enabling remote collaboration in much the same way scientists work today.

The ICD is more than a science event – it vividly illustrates how global cooperation in science works: open, curious and collaborative. The pupils experience themselves as part of an international community, united in the pursuit of knowledge. Astroparticle physics thus becomes a gateway to the world of science [3].

Vocational training at DESY in Zeuthen

DESY sets standards not only in research but also in vocational training. At the Zeuthen site, apprentices are trained in several recognised professions: industrial mechanics (precision engineering), electronics for devices and systems, IT and office management (Fig. 4). Apprentices benefit from close support by a dedicated training team and work in an inspiring environment with a direct connection to scientific research. Collegiality, appreciation and personal development are core values in the training process.

In 2024, as a particular highlight, two apprentices – one in electronics and one in industrial mechanics – were honoured by the Cottbus Chamber of Industry and Commerce (IHK) as top graduates of their year. During the awarding ceremony, the IHK President emphasised the growing appeal of vocational qualifications and the importance of lifelong learning – a principle actively embraced at DESY.

Summer student programme

Each summer, DESY welcomes a new cohort of summer students from all over the world. In 2024, a total of 112 students from 27 countries spent over seven weeks conducting research at the Hamburg and Zeuthen sites. A special feature this year was the first-ever DESY–Ukraine summer school, with 14 participants from Ukraine. Alongside a lecture series, the core of the programme lies in integrating the students into the DESY research groups. Here, they gain practical experience in real scientific investigations, data analysis, theoretical work and experiments while building professional networks that may be key to their future careers.

Engagement with a vision

The wide range of initiatives to promote young talent at DESY in Zeuthen shows that scientific excellence begins with sparking curiosity and enthusiasm for research early on. Through digital STEM education, first-hand professional insights and opportunities for international collaboration, DESY offers young people a platform to explore, discover and grow. Beyond individual support, the focus is also on a shared vision: to empower a new generation of scientifically and socially engaged professionals – ready to cross boundaries and actively shape the future.

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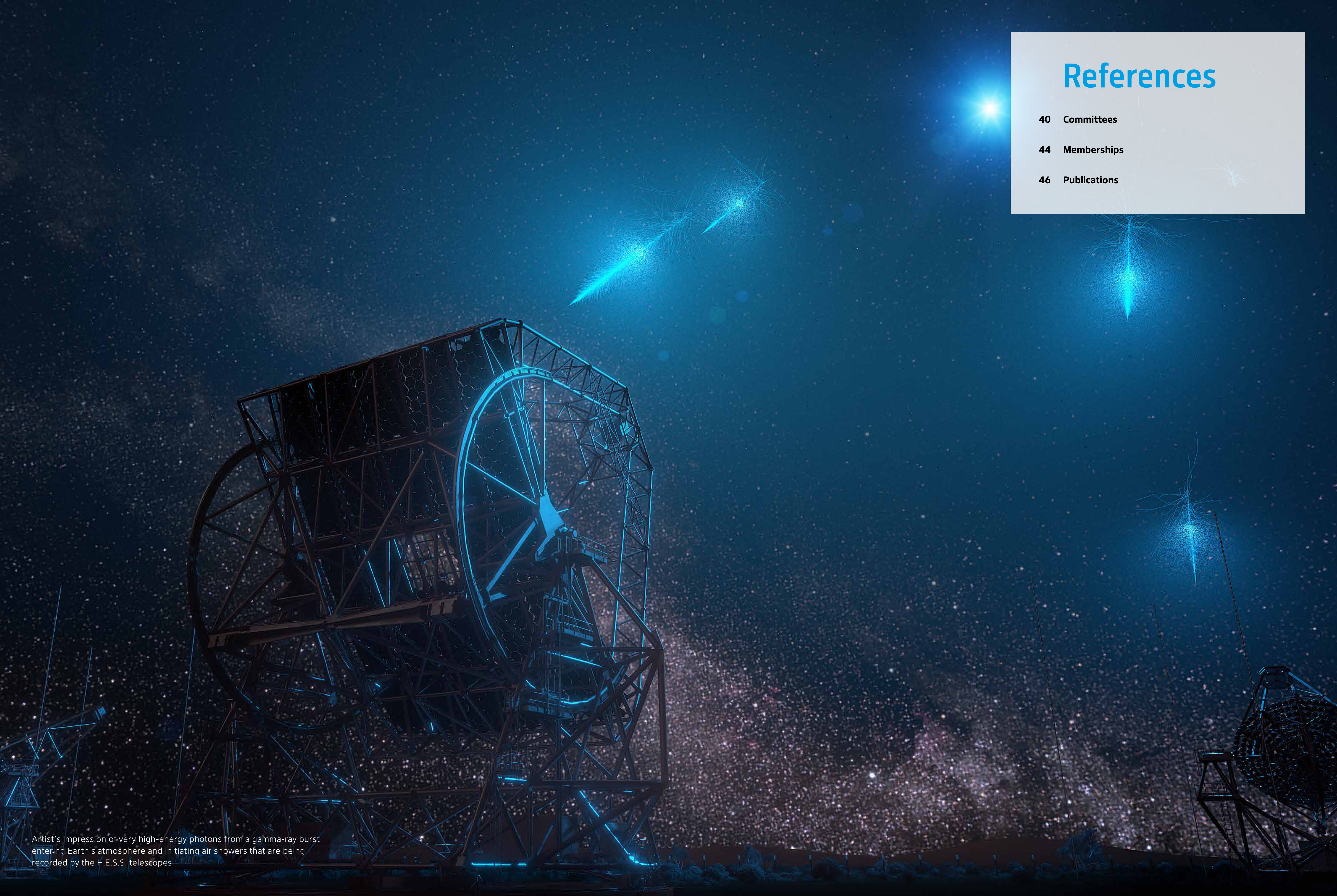

Artist's impression of very high-energy photons from a gamma-ray burst entering Earth's atmosphere and initiating air showers that are being recorded by the H.E.S.S. telescopes

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Committees

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Thesis

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