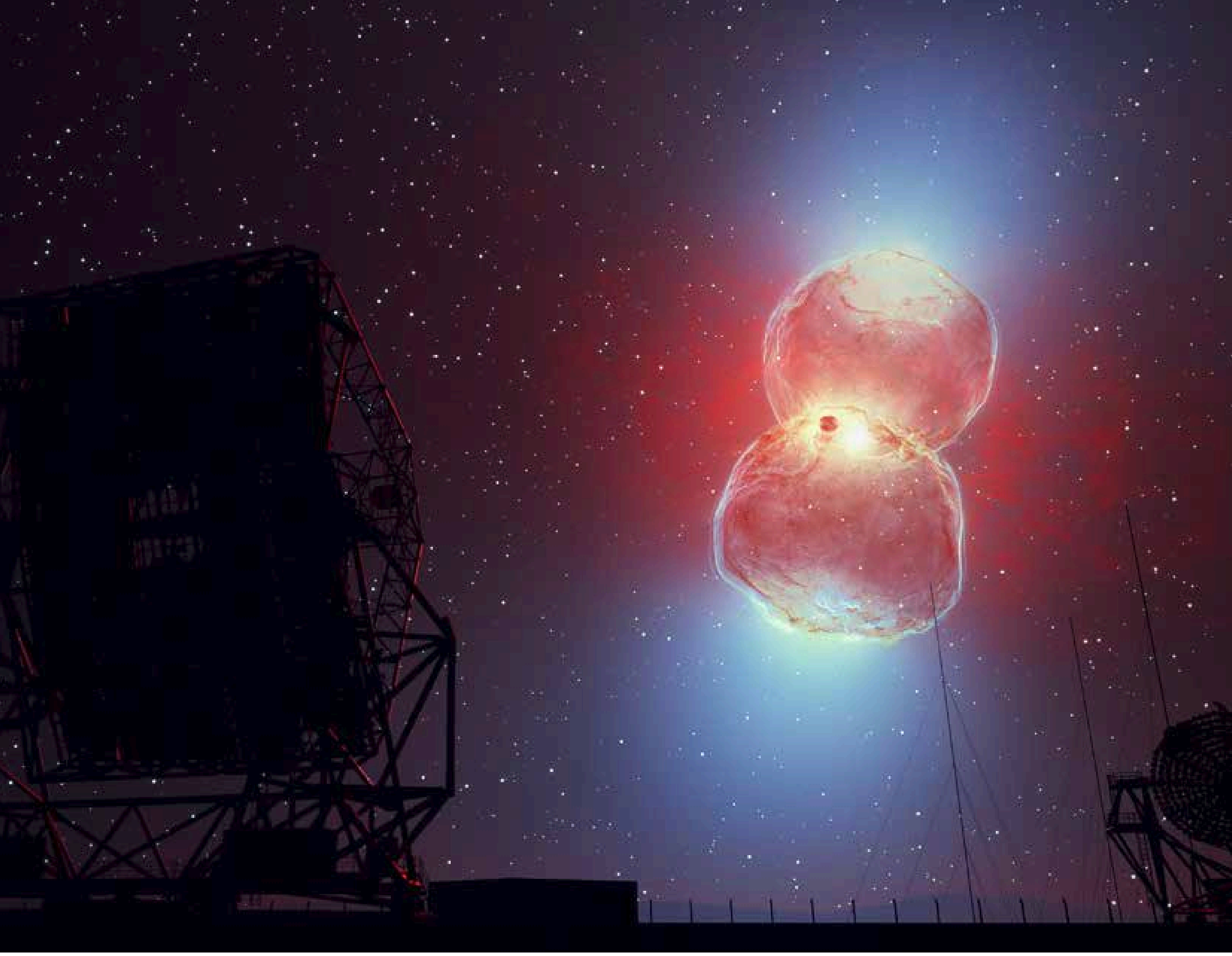

ASTROPARTICLE PHYSICS 2022.

Highlights and Annual Report

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

Cover
Artist's impression of the outburst of the nova RS Ophiuchi. As the fast shock waves expand, they form an hourglass shape in which gamma rays are produced. This gamma-ray emission is detected by the H.E.S.S. telescopes (shown in the foreground).

ASTROPARTICLE PHYSICS 2022.

Highlights and Annual Report

Artist's impression of the tidal disruption event AT2019fdr with its glistening "dust echo". The intense radiation from the debris disk around the black hole (centre) heats the dust until it begins to radiate brightly in the infrared. The time delay creates the dust echo.

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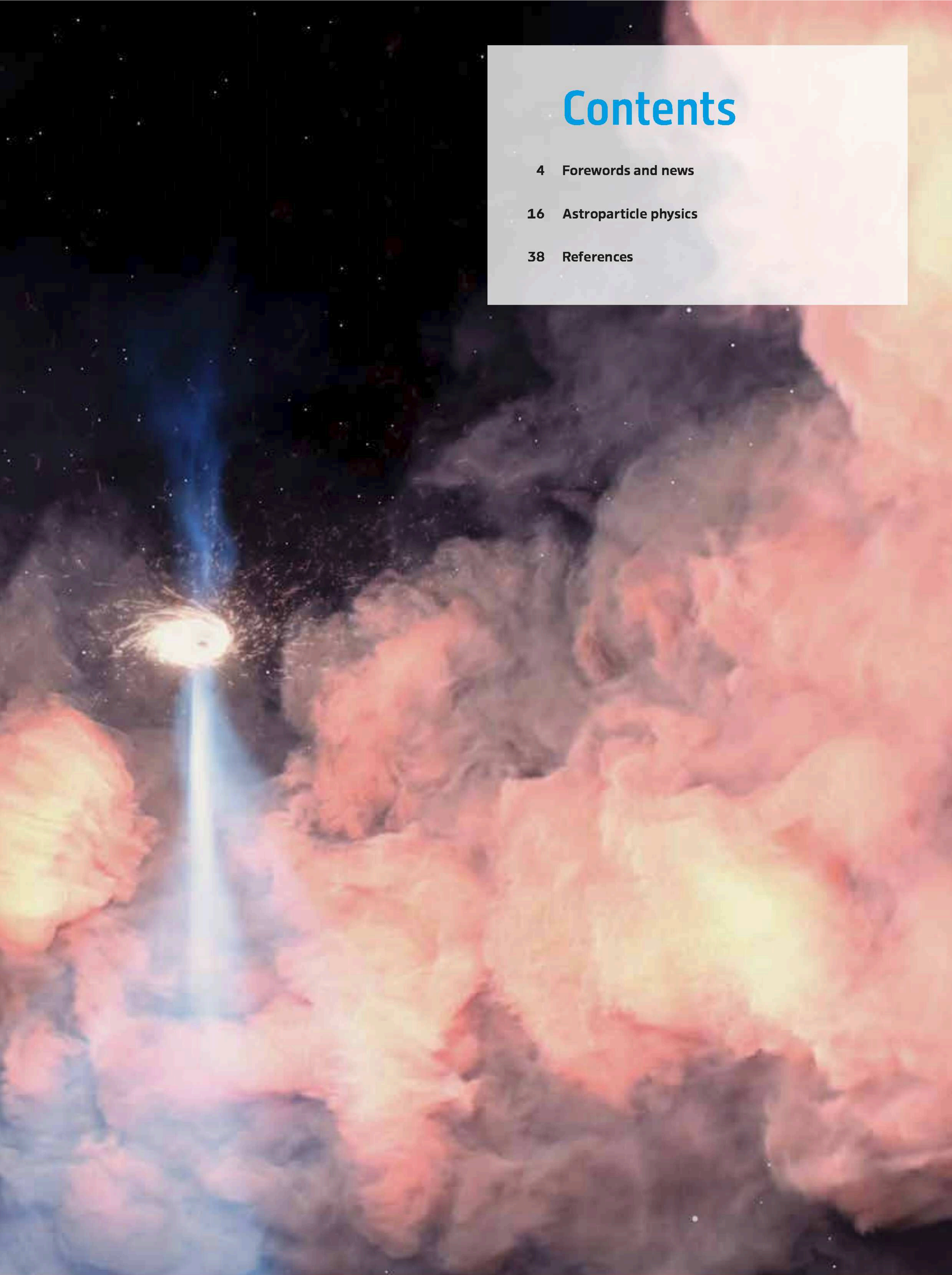


The year 2022 at DESY

Chairman's foreword

Dear Colleagues and Friends of DESY,

The DESY management has been working in crisis mode ever since the outbreak of the COVID-19 pandemic in March 2020. After the strains of the pandemic, the Russian war on Ukraine is now calling into question much of what we have hitherto taken for granted and posing enormous challenges. Our main concern remains the suffering people in Ukraine and the families who have fled the war with its dire human consequences.

This war now also affects research at DESY. Our current problems include the general uncontrolled price development on the energy market and in the construction sector, the enormous inflation trend and the shaky supply chains worldwide. All of these pose unprecedented challenges for the research centre that we have not known before on this scale in Europe and beyond.

In our current deliberations, we assume that we will have another three very difficult years ahead of us and will therefore have to implement massive cost-saving measures. These will include cuts in the operation of our major research infrastructures, if we do not receive financial relief, and painful personnel decisions. The DESY Directorate sees a particularly sensitive area here in the next generation of scientists and engineers, whom we must not abandon under any circumstances. However, we do not give up hope that the German government will also focus more strongly on saving the nation's future innovation potential. The current signals from politics to set up a rescue package also for science make us cautiously optimistic.

In a high-tech nation like Germany, research and innovation are the decisive – if not the only – levers to lead us out of the crisis and secure our long-term sovereignty in key technologies. Against the background of the most acute problems in energy supply, we must not forget that the main threat to our survival on this planet is man-made climate change, which we have to counter with new energy concepts. Nor must we lose sight of the constant threat of viral or bacterial pandemics. At DESY, we are all working at full speed to play our part in solving these complex challenges. This is also reflected in our strategy loop, which we are currently working on intensively – in addition to daily crisis management.

We have identified three pillars for the future development of DESY:

- The cross-divisional DESY Transformation Project (DTP), which is to prepare the future strategy of our "solution ecosystem" and which requires profound conceptual changes in how we organise research and innovation in the future
- The National Analytics Centre (NAC) with the facilities PETRA IV, FLASH2020+ and the Plasma Accelerator as well as an integrated data management structure as the core research infrastructures of DESY
- Increased focus in particle physics on medium-sized dark-matter projects on the DESY campus and exploration of new opportunities in astroparticle physics offered by the Science Data Management Centre (SDMC) of the Cherenkov Telescope Array Observatory (CTAO) and by the German Center for Astrophysics (DZA)

Sustainable concepts play a central role in all our planning. The Directorate has a clear vision for DESY's path to energy-saving and climate-friendly operation. In 2022, we published our first sustainability report, which will appear at regular intervals in the future.

Figure 1
The Hamburg Senate invited DESY to present the PETRA IV project at the Hamburg City Hall. From left to right: Nobel Laureate Stefan Hell, Hamburg Science Senator Katharina Fegebank and DESY Director Helmut Dosch.

In September 2022, we presented the PETRA IV project – the upgrade of our synchrotron radiation source PETRA III to a 3D X-ray microscope – to a broader public at a major event with representatives from science, politics and industry. I was very pleased that the project was also supported by Stefan Hell from the Max Planck Institutes in Göttingen and Heidelberg, a Nobel Laureate and one of the world's most renowned representatives of new microscopy concepts. On the evening of the event, he gave an impressive lecture in Hamburg's City Hall, demonstrating the innovative power that new types of high-performance microscopes can unleash.

Under the leadership of Harald Reichert and Riccardo Bartolini, the preparation of the PETRA IV project continues to make great progress. The technical design is essentially complete, and the team is currently working on the application for inclusion of the project in the German national roadmap for research infrastructures.

PETRA IV will be a key building block in the transformation process of DESY that we have been designing over the past few months. The major impact of the facility will not only be due to its technical design as an interdisciplinary "discovery and solution engine" that includes AI-assisted operations, a new access model and comprehensive involvement of the broad user community. Although these will increase the construction and operational costs of the facility, the expected socio-economic impact will outweigh this investment many times over. In view of the competing Chinese High Energy Photon Source (HEPS) project in Beijing, for instance, which is already at an advanced stage, we must not lose any valuable time now in implementing the PETRA IV project.

We have noted with great pleasure the positive decision of the German Federal Ministry of Education and Research (BMBF) to realise the German Center for Astrophysics (DZA), which was prominently promoted by the European Space Agency (ESA) and DESY. On the DESY side, Christian Stegmann, Director in charge of Astroparticle Physics, and Arik Willner, Delegate of the Directorate for Innovation, were instrumental in the application. This development is a new piece of the puzzle in our 2022/2023 strategy loop, which fits perfectly into DESY's aspiration to build an international beacon in astroparticle physics at its Zeuthen site.

We live in difficult times and so does our research centre. My special thanks therefore go to the DESY staff and all our national and international users and partners for their reliable support at all times. I hope this annual report will show you that, despite the current challenges that occupy us on a daily basis, we are keeping DESY on course for a bright future development!

Helmut Dosch
Chairman of the DESY Board of Directors

Astroparticle physics at DESY

Director's foreword

Dear friends of DESY,

After the challenges posed by the COVID-19 pandemic in the past years, 2022 promised to get off to a better start, with the slow easing of many of the restrictions that were necessary to handle this exceptional situation. However, the Russian war on Ukraine quickly reminded us how precarious our relative peace and stability in Europe really is. DESY reacted speedily to the aggression. The centre suspended all participation of Russian and Belarusian institutes in its scientific projects, while aiming to create prospects for scientists and people seeking refuge from the war, for instance by offering accommodation on its campuses in Hamburg and Zeuthen as well as funding and study programmes for Ukrainian scientists. I was also very impressed by the great efforts of many colleagues at DESY to help those in need.

In addition to the dreadful human toll, this war has changed many facets of the scientific landscape. With energy costs soaring, supply chains under strain and peaceful international cooperation no longer a given, we are being forced to rethink and remodel our scientific endeavour to ensure its long-term success and sustainability. To this end, we are currently revising our DESY 2030 strategy, with the update due to be presented in autumn 2023.

Despite all these challenges, 2022 was also a year full of highlights and scientific achievements, in which the DESY Astroparticle Physics division took major steps towards establishing DESY as a key international centre of astroparticle physics. Most notably, the foundation stone of the Science Data Management Centre (SDMC) for the upcoming Cherenkov Telescope Array Observatory (CTAO) was laid on the DESY campus in Zeuthen in March. The CTAO will be a unique, world-class observatory for gamma-ray astronomy, the first of its kind on Earth. With more than 60 telescopes built during the first construction phase at the two telescope sites in Chile and on the Canary Island of La Palma, the observatory will provide unprecedented insights into our universe. The SDMC at DESY in Zeuthen will be the scientific gateway to the CTAO for scientists from all over the world and further strengthen DESY's expertise and international standing in gamma-ray astronomy.

In September, a major decision with far-reaching impact on the astrophysics landscape in Germany was announced: The German Federal Ministry of Education and Research (BMBF) and the federal states of Saxony and Saxony-Anhalt selected the German Center for Astrophysics (DZA) as one of the winners of the competition

Figure 1
Groundbreaking ceremony for the CTAO SDMC on the DESY campus in Zeuthen. From left to right: CTAO gGmbH Managing Director Federico Ferrini, Volkmar Dietz, Head of Large Facilities and Basic Research at BMBF, DESY Director Helmut Dosch, Helmholtz President Otmar Wiestler, Brandenburg Science Minister Manja Schüle and Christian Stegmann.

"Knowledge Creates Perspectives for the Region". The DZA, a joint initiative of astronomy and astroparticle physics in Germany, will be a large-scale national research centre with international impact, located in the Lusatia region in Saxony. With the project office based in Zeuthen, DESY played a major role in preparing the DZA, and it will continue to support its establishment. As one of the applicants of the proposal, I am particularly proud that the project was selected for realisation, and I am convinced that the DZA will stay a strong partner of DESY and become a high-profile beacon for astroparticle physics as a growing research field in Germany and beyond.

Among the scientific highlights of the year was the observation by the IceCube collaboration of high-energy neutrinos emitted by the galaxy NGC 1068, also known as Messier 77 – a discovery that was published in the journal *Science* in November. This galaxy hosts an active galactic nucleus (AGN), a black hole surrounded by a disk of matter it accretes. The observation, made over a decade with the IceCube detector at the South Pole, links the origin of the neutrinos to the AGN activity, taking the IceCube collaboration one step closer to answering the century-old question of the origin of cosmic rays.

Exploring new ideas, DESY was also involved in an analysis of galactic "PeVatrons" – cosmic-ray factories that accelerate particles to petaelectronvolt (PeV) energies – which were recently discovered by the LHAASO observatory in China and prompted a rethink of the mechanism by which high-energy particles are produced in our galaxy. The study reveals the extreme nature of young, energetic pulsars, which could potentially be the machines powering these ultrahigh-energy cosmic accelerators. These are just two examples of the exciting scientific results presented in this highlight brochure, which reflect the vibrant and dynamic nature of the field of astroparticle physics in helping to explain the wonders of our universe.

The scientific excellence of DESY once again impressed Manja Schüle, Science Minister of the federal state of Brandenburg, who, after making her inaugural visit to DESY in Zeuthen in September 2021, visited the DESY campus in Hamburg in April 2022. She lauded DESY as one of the world's leading centres for research on and with particle accelerators, emphasising that "it shapes the future with outstanding science and research".

I am also very proud that the Helmholtz–Weizmann International Research School on Multimessenger Astronomy, in which DESY is strongly involved, was rated very positively by the Helmholtz Committee at the mid-term evaluation in December 2022. The committee praised the good structure and cooperation with the partners, the efforts to ensure unbiased recruitment and the concern for the well-being of the PhD students. All partners are motivated to extend the School after the end of the third-party funding period in 2025.

At the regional level, DESY convinced the jury of a competition launched by the Dahme-Spreewald district and other partners, who selected DESY as Company of the Year 2022 of the district in the new category "Public Administration". Here, DESY was judged less on its science than on aspects such as its values and corporate culture, its human resources strategy, its sustainability, its impact on society and its commitment to promoting young scientists.

More than ever, the past months with the pandemic and the war in Ukraine have shown how important cosmopolitanism, internationality, diversity and joint action are for all of us. These are among the core values of DESY – and they form the basis for successful research and scientific cooperation across the globe.

I would like to thank all our staff and our partners in Germany and around the world who share these values and join us peacefully in our efforts to expand the frontiers of science.

Christian Stegmann
Director in charge of Astroparticle Physics

News and events

Highlights in 2022

March

Groundbreaking ceremony for CTAO Science Data Management Centre

The Science Data Management Centre (SDMC) of the international gamma-ray Cherenkov Telescope Array Observatory (CTAO) is to be located at DESY in Zeuthen. On 2 March, Manja Schüle, Science Minister of the German federal state of Brandenburg, and Volkmar Dietz, Head of the Sub-Department Large Facilities and Basic Research at the German Federal Ministry of Education and Research (BMBF), joined Federico Ferrini, Managing Director of the CTAO gGmbH, Otmar Wiestler, President of the Helmholtz Association, and DESY Director Helmut Dosch to lay the foundation stone for the SDMC on the Zeuthen campus.

With more than 60 gamma-ray telescopes of various sizes built during the first construction phase at two telescope sites in the northern and southern hemispheres, the CTAO will enable unique astronomical observations and yield unprecedented insights into the universe. The SDMC will be the scientific gateway to the observatory.

Groundbreaking ceremony for the CTAO SDMC on the DESY campus in Zeuthen. From left to right: Federico Ferrini, Volkmar Dietz, Helmut Dosch, Otmar Wiestler, Manja Schüle and Christian Stegmann.

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

Cosmic particle accelerator at its limit

Using the High Energy Stereoscopic System (H.E.S.S.) gamma-ray observatory in Namibia, an international team including researchers from DESY was able to track a cosmic particle accelerator in greater detail than ever before. The H.E.S.S. observations showed for the first time the course of an acceleration process in a stellar event called a nova, which comprises powerful eruptions on the surface of a white dwarf. A nova creates a shock wave that tears through the surrounding medium, pulling particles with it and accelerating them to extreme energies. Surprisingly, the nova RS Ophiuchi seems to cause particles to accelerate at speeds reaching the theoretical limit, corresponding to ideal conditions.

According to Ruslan Konno, one of the lead authors of the study and a doctoral candidate at DESY in Zeuthen, "the observation that the theoretical limit for particle acceleration can actually be reached in genuine cosmic shock waves has enormous implications for astrophysics. It suggests that the acceleration process could be just as efficient in their much more extreme relatives, supernovae." The research was published in the journal *Science*.

Slava Ukraini!

Ever since the Russian invasion of Ukraine, DESY staff members have been very willing to help Ukrainian refugees. DESY employees got involved in many ways, e.g. by helping with administrative matters, doing shopping for the International Office, organising trips to nearby clothing or cell phone shops, providing laptops for school classes, doing translation work or simply offering space and time for talking. DESY employees also helped financially by contributing money to the GoFundMe pot, from which many needed things and activities are being financed.

Snapshots from the drive to Przemyśl on the Ukrainian border

In early March 2022, Stefan Klepser, Stefan Ohm and Pavlo Plotko even drove 2000 kilometres from DESY in Zeuthen to the Polish–Ukrainian border town of Przemyśl to deliver parcels with protective waistcoats, helmets and first-aid kit, then fetch two relatives of a Ukrainian employee and bring them to the DESY hostel in Zeuthen. On their way back through Lublin in Poland, they picked up three more refugees – mother, child and cat – and drove them to Berlin-Kreuzberg. "I was very impressed by the solidarity of the people we met on the way," said Stefan Klepser upon their arrival at DESY. "When the need arises, we will get back on the road. A group of volunteers at DESY has set up a chat group to be ready to go at any time."

April

Students of Research School for Multimessenger Astronomy visit Israel

In April and May, four students of the International Helmholtz–Weizmann Research School for Multimessenger Astronomy spent several weeks in Israel, both in Rehovot at the Weizmann Institute of Science (WIS) and in Neot Smadar in the Negev Desert to conduct observations with the Large Array Survey Telescope (LAST). At WIS, the students took part in meetings and discussions and learned about the telescopes and the analysis pipeline developed to handle the high rate of LAST data. The observatory itself, which is currently under construction, is located about 260 kilometres south of Rehovot and will be a part of the Weizmann Astrophysical Observatory (WAO). The students were able to support the progress of the project, install polarisation filters on one of the mounts and conduct observations during a few cloudless nights.

The Research School for Multimessenger Astronomy was launched in 2019 by WIS, the Humboldt University of Berlin, the University of Potsdam and DESY. It is funded by the Helmholtz Association.

A telescope of the LAST setup

May

GNN Dissertation Prize for Steffen Hallmann

Steffen Hallmann, who is currently working as a post-doctoral researcher at DESY on the neutrino experiments RNO-G and IceCube-Gen2, was awarded the Global Neutrino Network (GNN) Dissertation Prize at the 2022 IceCube Collaboration Meeting in Brussels for his PhD thesis “Sensitivity to atmospheric tau-neutrino appearance and all-flavour search for neutrinos from the Fermi Bubbles with the deep-sea telescopes KM3NeT/ORCA and ANTARES”. The GNN awards the prize to recent graduates who “have written an outstanding thesis and contributed significantly to the project”.

International IceCube Masterclass 2022

On 23 May, scientists from DESY took part for the sixth time in the international IceCube Masterclass – the first to be held in person again at DESY in Zeuthen after the COVID-19 pandemic. The IceCube Masterclass is a one-day event where high-school students learn more about astrophysics through lectures and hands-on analysis of data from the IceCube neutrino observatory at the South Pole. The day’s schedule includes opportunities to discuss results with IceCube researchers and ask them questions about life of a physicist.

In total, 24 students from different schools participated in the event at DESY in Zeuthen. As an innovation, the online format developed during the pandemic – with shorter lectures and more focused content – was successfully adopted for the face-to-face event.

Students and their supervisors at the IceCube Masterclass at DESY in Zeuthen

May

First Diversity Day at DESY

Celebrating the first Diversity Day at DESY. From left to right: DESY Astroparticle Physics Director Christian Stegmann with staff members Summer Blot and Lia Lang.

After signing the Diversity Charter in 2021, DESY celebrated its first Diversity Day on 31 May 2022 – a nationwide day of action launched by the "Charta der Vielfalt" association. DESY Astroparticle Physics Director Christian Stegmann kicked off the event in Zeuthen by raising the rainbow flag, sending a sign of support to the queer and diverse community at DESY. The ceremony was attended by about 50 people on site.

To gather input from all DESY employees, the organisation team hosted a diversity lunch in the Zeuthen canteen and an online coffee bar to present diversity and inclusion initiatives at DESY. Throughout the day, statements from DESY employees about their personal understanding of diversity and inclusion were shown on various social media channels and on the campus screens. This first official Diversity Day celebration cemented DESY's commitment to diversity and inclusion and set the stage for more activities in the years to come.

The intense radiation from the debris disk around the black hole (centre) heats the dust until it begins to radiate brightly in the infrared. The time delay creates the dust echo.

June

"Dust echo" reveals cosmic catastrophe

In a galaxy in the constellation Hercules, a gigantic black hole tore apart a giant star. The tidal disruption event (TDE) was studied with several observatories at different wavelengths, from radio waves to gamma rays, as an international team led by DESY reported in the journal *Physical Review Letters*. The TDE occurred in a galaxy 4.4 billion light years away, in the centre of which resides a black hole 35 million times the mass of our sun. A giant sun ventured too close and was torn to pieces by the tidal forces of the black hole, forming an accretion disk around it. As the stellar debris circled the black hole faster and faster, it heated up and started to glow brightly, in what may have been the most luminous transient cosmic phenomenon ever observed.

The cosmic catastrophe also produced a glistening "dust echo" in the infrared range, which was observed about a year after the original eruption. In addition, the IceCube observatory caught a high-energy neutrino that could have come from the TDE. Such multimessenger observations enable new insights into cosmic events. "With electromagnetic radiation, we look at the surface of an object," explained co-author Marek Kowalski, who leads neutrino astronomy at DESY. "Neutrinos reach us unhindered from the interior."

APPEC Town Meeting organised by DESY

On 9 and 10 June, the Astroparticle Physics European Consortium (APPEC) held its Town Meeting in Berlin to discuss the mid-term review of the European Astroparticle Physics Strategy 2017–2026. The aim of the Town Meeting was to receive final feedback from the community on the implementation process of the strategy in light of the international context and on new developments in astroparticle physics and neighbouring fields that could lead to further evolution of the strategic recommendations. The event, which was organised by DESY, was attended by about 100 scientists. The publication of the updated strategy is expected for autumn 2023.

Participants of the APPEC Town Meeting in Berlin

July

H.E.S.S. Prize awarded to Sylvia Zhu

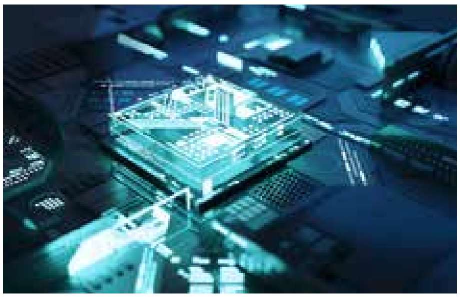
Sylvia Zhu, a post-doctoral researcher at DESY, was awarded the H.E.S.S. Prize for her contribution to efficient operations of the H.E.S.S. gamma-ray telescope system in Namibia, the diligent and careful oversight of its data acquisition system (DAQ), coordination of the H.E.S.S. gamma-ray burst (GRB) team as well as numerous science communication and outreach activities.

Sylvia Zhu has acted as DAQ lead since 2019 and significantly contributed to the upgrade of the system in 2019/2020. She was the main contact for shift personnel in troubleshooting problems – a particularly important task during the challenging COVID-19 pandemic when only remote support was possible. As GRB coordinator, she shaped the GRB science programme and its multiwavelength activities. Her continued strong commitment to science communication and outreach efforts elevated the visibility of H.E.S.S. and, in particular, its early-career scientists.

DESY joins IBM Quantum Network

DESY and IBM entered an agreement on quantum computing that welcomed DESY as a member of the IBM Quantum Network. As a future hub in the network, DESY seeks to exploit the opportunities of the new technology to solve scientific problems much more efficiently on quantum computers in the future and even potentially tackle challenges that are not accessible to classical computers. IBM hopes that DESY will identify new and important fields of application for this emerging technology.

IBM will grant the newly founded Centre for Quantum Technologies and Applications (CQTA) at DESY access to the company's quantum computers through licenses. The CQTA will thus open up the opportunity for scientists and engineers from DESY, but also from other academic institutions and industry to familiarise themselves with quantum computers and develop novel, efficient quantum algorithms for targeted applications. In addition, the CQTA will offer a comprehensive training and education programme to make a new generation of scientists and engineers in Germany "quantum ready" on the way to world leadership in quantum computing.



Strategy update: DESY gets fit for the future

With a first meeting on 4 July, DESY started a comprehensive update of its DESY 2030 strategy, setting the course for a successful future at the forefront of research. The goals fixed in the DESY 2030 strategy in 2018 needed to be sharpened to incorporate current challenges – such as advancing climate change, the new threat to society from pandemics and the digital transformation – even more strongly and visibly into future planning. The strategy update is to be presented in autumn 2023. For DESY, this will form the basis for the scientific planning and application for the fifth round of the Helmholtz Association's programme-oriented funding (PoF V).

Image of the centre of our galaxy in radio waves taken by the MeerKAT radio telescope, showing supernova remnants, compact star-forming regions and filaments of unknown origin. With the technologies being developed for radio astronomy at the DZA, it will be possible to see galaxies in even better resolution in the future.

August

Summer student season

In 2022, the summer students were finally back on campus. After cancellation in 2020 and one year of very restricted hybrid summer student programme in 2021, a total of 84 students from around the world took part in the 2022 DESY summer student course either in person or remotely. The students spent almost eight weeks working on research projects with DESY supervisors from different areas, including particle and astroparticle physics, photon science and accelerator physics. They could choose from around 90 research topics from many walks of DESY science in Hamburg, Zeuthen and at European XFEL. Lectures were part of the programme as well, but as per input by previous summer students, who wanted to work more on their projects, the number of lectures was reduced to three per week, leaving more room for proper research.

The Zeuthen summer students by the lake

September

German Center for Astrophysics to be built in Lusatia

The German Center for Astrophysics (DZA) will be located in the Lusatia region in the German federal state of Saxony. Together with the Center for the Transformation of Chemistry, the DZA proposal won the competition “Knowledge Creates Perspectives for the Region” of the German Federal Ministry of Education and Research and the federal states of Saxony and Saxony-Anhalt. DESY played a key role in preparing the initiative: The project office was based at DESY and Astroparticle Physics Director Christian Stegmann was one of the DZA’s applicants.

The DZA is a joint initiative of astronomy and astroparticle physics in Germany. The new research centre will have two sites: In Görlitz, it will bring together the data streams of astronomical observatories around the globe and develop new technologies in cooperation with industry and technology centres in Saxony and worldwide. In the district of Bautzen, an underground laboratory is planned in the granite of Lusatia, a place of great seismological tranquillity. The funding provides for a three-year setup phase before the centre can be formally founded. Afterwards, annual funding of around 170 million euros is foreseen. The DZA will employ more than 1000 people.

October

Volker Soergel (1931–2022)

DESY mourns the death of Volker Soergel, long-time Chairman of the DESY Board of Directors and pioneer of the united DESY with its locations in Hamburg and Zeuthen. Soergel passed away on 5 October at the age of 91. He was one of the great visionaries of the research centre and key in shaping DESY as it is known today.

Under his 12-year leadership, following the end of the German Democratic Republic (GDR), the Institute for High Energy Physics (IfH) of the Academy of Sciences of the GDR in Zeuthen was successfully merged with DESY on 1 January 1992. It thus became the DESY site in Zeuthen with its unique research profile centring on astroparticle physics with a focus on gamma-ray and neutrino astronomy, parallel computing for theoretical particle physics as well as the development and construction of electron sources for X-ray lasers.

November

DESY is Company of the Year 2022 of the Dahme-Spreewald District

DESY in Zeuthen was selected as the best public institution in the Dahme-Spreewald district. It won the competition, which was launched by the district together with Wirtschaftsförderungsgesellschaft Dahme-Spreewald mbH and other partners at the beginning of 2022, in the new category "Public Administration".

In August, DESY had presented itself to the jury of experts from administration and business during an on-site visit. The focus was not only on DESY's research successes and goals, but more particularly on the values and work culture with which these goals are being achieved. Corporate culture, human resources strategy, innovative action and sustainability were just as important aspects as examples of DESY's impact on society and its commitment to promoting young scientists.

From left to right: DESY Astroparticle Physics Director Christian Stegmann, Zeuthen Mayor Sven Herzberger and Ulrike Behrens, Head of DESY Communications in Zeuthen

H.E.S.S. Prize awarded to Tim Lukas Holch

Tim Holch, a post-doctoral researcher at DESY, was awarded the H.E.S.S. Prize for his many contributions to different elements of H.E.S.S. operations and data analysis. From the start of his PhD project within H.E.S.S., Tim Holch was an essential member of the data acquisition team. In this capacity, he implemented remote observing with the H.E.S.S. telescopes from a control room at DESY in Zeuthen, safeguarding operations in the challenging times of the COVID-19 pandemic. He was the key person in tracking data transfer to Europe.

In addition to his contributions to H.E.S.S. operations, Tim Holch participated in efforts to improve the understanding of the instrument response and data quality and contributed to validating Monte Carlo simulations from the individual components to the entire array against the data.

International Cosmic Day

The 11th International Cosmic Day (ICD), which is dedicated to the unnoticed cosmic particles that flood our universe and constantly surround us on Earth, took place on 22 November. On the occasion of the ICD, schools, universities and research institutions in over 20 countries enable young people all over the world to learn more about these particles from the cosmos, explore them and exchange the newly acquired knowledge in video conferences. Supported and guided by scientists and teachers, the students deal with exciting questions in astroparticle physics, carry out measurements of cosmic muons and network all over the world.

In 2022, DESY in Zeuthen initiated and coordinated the ICD for the 11th time with a team of scientists, students and event experts. More than 6800 young people attended the event in more than 90 groups.

Coordinating the International Cosmic Day at DESY in Zeuthen

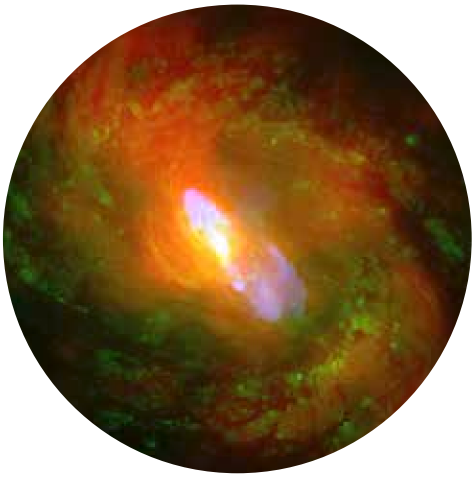
November

Review of CTAO medium-sized telescopes

The Critical Design and Manufacturing Review of the Medium-Sized Telescope Structure (MST-STR) for the CTAO gamma-ray observatory was conducted in November in Berlin-Adlershof. The review is a decisive step forward to start production of the telescopes for the observatory.

The MST-STR team led by DESY provided detailed design and manufacturing documentation for review by the expert panel, which consisted of scientists and engineer from areas ranging from electronics and mechanics through software and IT setup to project management. The review resulted in many detailed requests and comments to the MST-STR team. In a herculean effort, all these points were addressed in writing before the review event in November. Points considered still open or in need of further discussion were addressed in an in-person meeting between the MST-STR team and the panel.

Prototype of the MST-STR for the CTAO



Multicolour image of the galaxy NGC 1068

Neutrinos provide unique insight into active galaxy

Reanalysing a decade's worth of data from the IceCube neutrino observatory at the South Pole, an international team including researchers from DESY found an excess of high-energy neutrinos emitted by the active galaxy NGC 1068, or Messier 77. The galaxy is powered by a supermassive black hole, obscured by cosmic dust, which makes observation of the galactic core difficult. The IceCube discovery, which was published in the journal *Science*, provides a unique glimpse into the galaxy's active core.

IceCube discovered that the universe is glowing brightly in neutrinos as early as 2013. The origin of this cosmic neutrino flux has been a mystery ever since. A few years later, the experiment linked several high-energy neutrinos with a blazar flare and two tidal disruption events, i.e. violent transient phenomena at the centre of galaxies. Unlike these events, which are active for only a short time, NGC 1068 emits a continuous flow of neutrinos that can explain about one hundredth of the total cosmic neutrino flux. While providing one key piece of the puzzle, the NGC 1068 observation thus suggests there are many more sources of astrophysical neutrinos out there waiting to be discovered.

December

Mid-term evaluation of the Multimessenger School

The Helmholtz–Weizmann International Research School on Multimessenger Astronomy was assessed very positively by the Helmholtz Committee at the mid-term evaluation in December 2022. As strengths of the School, the panel identified its good structure and cooperation with the partners, efforts to ensure unbiased recruitment and care for the well-being of the doctoral researchers. All partners are motivated to extend the School after the end of the third-party funding period in 2025.

HELMHOLTZ WEIZMANN RESEARCH SCHOOL
MULTIMESSENGER ASTRONOMY

Election of DESY physicists as representatives of KAT

The Committee for Astroparticle Physics (KAT) represents German scientists working in astroparticle physics at German universities, Helmholtz centres and Max Planck institutes. The KAT aims to bring together the different research directions, to discuss current developments and to advocate the interests of the scientific community, including strategic aspects. The KAT represents the common goals and interests to the outside world.

David Berge (gamma-ray astronomy), Marek Kowalski (high-energy neutrino astrophysics) and Walter Winter (theory) from DESY were elected as new representatives or vice-representatives for the current term of office lasting until 2025.

Astroparticle Physics Morning Show

In the first ever “AP Morning Show”, hosts Anna Nelles and Stefan Ohm welcomed colleagues from DESY in Hamburg and Zeuthen virtually to the campus in Zeuthen and gave them a tour of the Astroparticle Physics division. A mixture of interviews, films, Q&A sessions and commercials gave the audience a lively and exciting insight into the research topics of astroparticle physics at DESY.

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 white-dwarf and red-giant binary system following the nova outburst. Material ejected from the surface of the white dwarf generates shock waves that rapidly expand, forming an hourglass shape. Particles are accelerated at these shock fronts, which collide with the dense wind of the red giant star to produce very-high-energy gamma-ray photons.

Experiments, theory, projects and infrastructures

Strong evidence for the first persistent source of cosmic neutrinos

Neutrinos from the Seyfert galaxy NGC 1068

The IceCube neutrino telescope at the South Pole has been operating in its final configuration for more than a decade. DESY astroparticle physicists have been involved in this endeavour even longer, playing key roles in the design and construction of the instrument and in its scientific harvest. One of the telescope's main goals is to determine the sources of high-energy cosmic neutrinos. In 2022, the IceCube collaboration announced the observation of an excess of neutrino events pointing to the nearby Seyfert galaxy NGC 1068 as a likely source of such neutrinos.

Until today, IceCube has collected hundreds of thousands of high-energy neutrinos (E > 100 GeV). Only a small fraction of these neutrinos is of cosmic origin. Nevertheless, the IceCube collaboration was able to measure the cosmic neutrino flux for the first time as early as 2013 [1].

This initial discovery led to the next stage of the puzzle: The distribution of the cosmic neutrinos in the sky was compatible with a predominantly extragalactic origin, but no individual sources could be identified. In 2017 and 2019, correlations of the arrival directions and times of high-energy neutrinos with a blazar flare [2] and two tidal disruption events [3, 4] provided evidence that cosmic neutrinos are produced in violent transient events in the vicinity of the supermassive black holes at the centre of galaxies (see previous *DESY Astroparticle Physics* reports). However, such transients can only account for a small fraction of the observed neutrinos. So the search for high-energy neutrino sources continued.

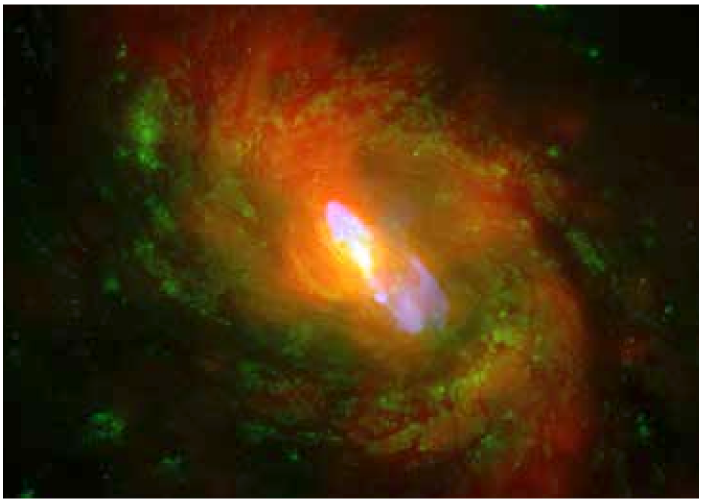


Figure 1
Multicolour image of the Seyfert galaxy NGC 1068 (red: infrared, green: optical, blue: X-rays)

In 2022, after analysing a decade of IceCube high-energy neutrino data that had been uniformly reprocessed and calibrated, and using improved statistical methods, the IceCube collaboration announced the observation of a localised excess of neutrino events in the sky consistent with the position of the enigmatic nearby Seyfert galaxy NGC 1068 [5] (Fig. 1).

After accounting for multiple hypothesis testing ("look-elsewhere effect"), the significance of the excess was determined to be equivalent to 4.2 standard deviations. In total, 79 +22/-20 neutrinos above the expectations from atmospheric backgrounds were observed in an energy range between 1.5 TeV and 15 TeV. Figure 2 shows the excess and the background as a function of the angular distance from the direction of NGC 1068.

NGC 1068, at a distance of about 50 million light years, is a galaxy that hosts an active galactic nucleus (AGN), i.e. a black hole of 10 million solar masses, surrounded by a disk of matter it accretes. This disk, which has a radius of less than a light day, radiates so brightly from optical to X-ray wavelengths that it outshines the Milky Way many times over. However, most of this radiation is absorbed in the clouds of gas and dust surrounding the nucleus, leading to a classification of NGC 1068 as an "obscured AGN" and making observations of the core difficult. The galaxy is also characterised as a star burst galaxy due to its many regions of intense star formation activity scattered around its centre.

NGC 1068 is a known gamma-ray source that has been observed at GeV energies by the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope, but has evaded detection by ground-based Cherenkov telescopes at very high energies so far.

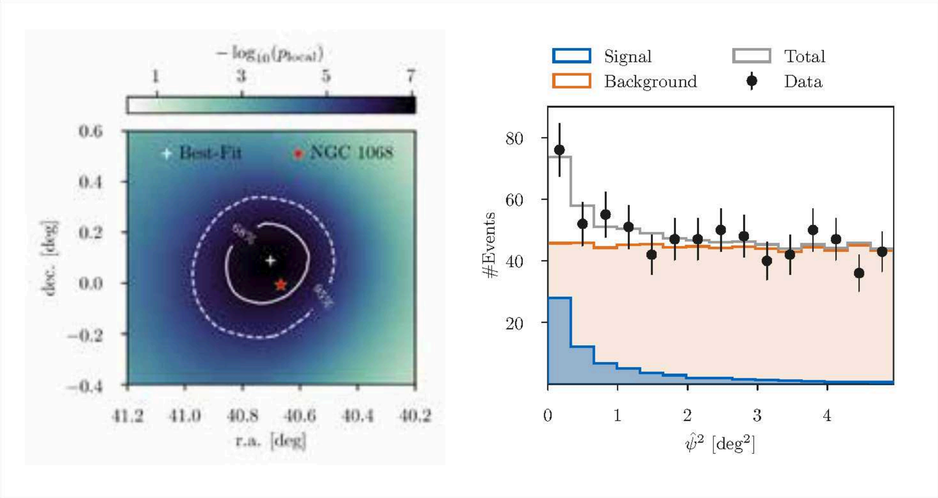


Figure 2
Left: Observed statistical excess and constraints on the position of the source of the statistical excess in relation to the known position of NGC 1068. Right: Excess of events observed as a function of the squared angular distance from NGC 1068. Expectations for the signal and the background are indicated.

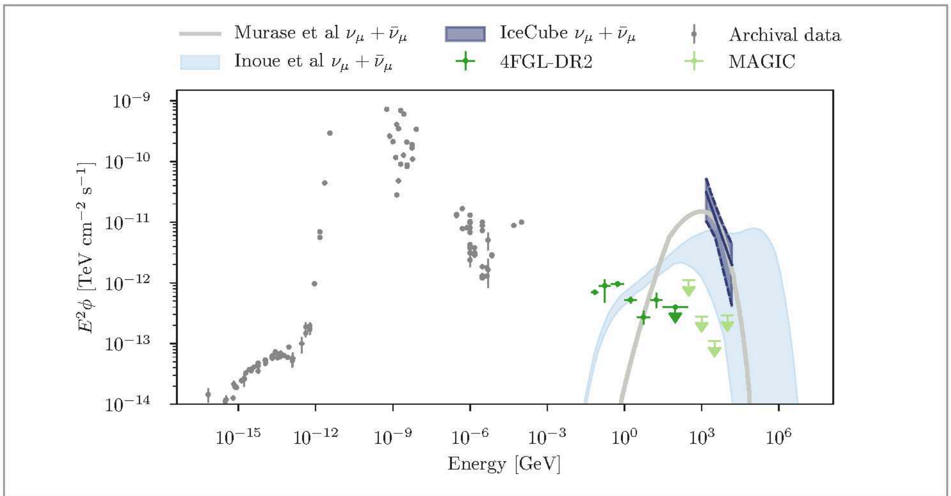


Figure 3
Multimessenger view of the energy spectrum of the emission from NGC 1068. Green crosses and arrows indicate gamma-ray observations by Fermi LAT and MAGIC, grey dots summarise archival measurements from radio to X-ray wavelengths. The dark-blue band indicates the neutrino flux derived from IceCube observations, while the light-blue region and the grey curve indicate model predictions for the neutrino emission from this source.

This gamma-ray emission is commonly attributed to the star formation activity, rather than the AGN at the core, due to its correlation with the galaxy's star formation rate [6]. In NGC 1068, several stars are born every year, a hundred times more than in our own galaxy. Such a high "birth rate" of stars leads to a similarly high "death rate", and the emitted gamma rays bear witness to cosmic rays accelerated in the shock waves of many supernova explosions.

One of the most intriguing features of the neutrino signal now observed by IceCube is that the neutrino luminosity of this source is several times higher than the gamma-ray luminosity (Fig. 3). This is only possible if gamma rays are absorbed, as is expected near the core, but not in the star-forming regions of the galaxy. This observation places the origin of the neutrinos close to the black hole and links them to the AGN activity rather than the star formation activity of NGC 1068. It is also consistent with earlier findings that a substantial fraction of the cosmic neutrinos needs to come from such obscured sources [7].

With NGC 1068, the IceCube collaboration has found the tip of the iceberg, promising routine observation of neutrino sources with the next generation of instruments, such as the planned IceCube-Gen2. The obscured nature of the source emphasises the important contributions of neutrinos as messengers for understanding particle acceleration around supermassive black holes. Neutrino astronomy has finally turned from a dream into a reality.

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Deep observations of the gamma-ray low state of M87 with H.E.S.S.

Constraining the cosmic-ray pressure in Virgo A

The galaxy Messier 87, or M87, is located at the centre of the Virgo Cluster, 16.5 Mpc away from Earth. It emits electromagnetic radiation across the entire spectrum and exhibits high variability. While its gamma-ray flaring states have been extensively studied [1], only its gamma-ray low-state emission provides insight into the acceleration of cosmic-ray protons, their interaction with the local plasma and their role in heating the cluster [2]. A team of scientists led by DESY used observations of M87 made with the High Energy Stereoscopic System (H.E.S.S.) in Namibia from 2004 to 2021 to constrain the size of the gamma-ray emission in M87's low state. As a result, the team was able to also constrain the pressure exerted and the total energy accelerated in cosmic-ray protons in the inner region of the cluster over its entire lifetime [3].

Introduction

M87 is a radio galaxy at the heart of the Virgo Cluster. Its supermassive black hole (SMBH) accretes matter and launches a jet of relativistic particles, which extends up to several kiloparsecs. X-ray measurements reveal features in the jet known as knots, where particles can be accelerated up to TeV energies. However, pinpointing the exact location of the TeV gamma-ray emission from M87 with imaging Cherenkov telescopes (IACTs), which are limited to an angular resolution of ~0.05° at 1 eV, is challenging.

The Event Horizon Telescope (EHT) collaboration conducted simultaneous observations of M87 in 2017, using IACTs to study its broad-band spectrum. M87 was in a historically low state at the time, and the detected TeV gamma-ray emission did not match the spectral distribution expected from a single-zone model in the core region (of less than 10 times the SMBH size). The discrepancy indicated that the emission could be from further away than previously thought.

The gamma-ray emission from the low state of M87 may originate in the inner Virgo Cluster, where cosmic-ray electrons with TeV energies accelerated in the central active galactic nucleus (AGN) rapidly lose energy through synchrotron and inverse Compton emissions before reaching large distances (~kpc). Cosmic-ray protons must also be accelerated in the central AGN. Unlike electrons, they accumulate and fill the inner cluster throughout its lifetime. Hadronic interactions of the cosmic-ray protons with the dense (~0.1 cm^{-3}) intra-cluster medium create pions, and the neutral pions decay to gamma rays, leading to an extended diffuse gamma-ray signal around M87.

Analysis and results

In the study presented here, we used 194 hours of observations of M87 with H.E.S.S. to probe the aforementioned diffuse emission scenario from Virgo A, as the M87 radio source is called. First, we used a Bayesian block analysis to statistically identify the flux levels of the source in the monthly binned light curve. We defined the low-emission state as the blocks below the average flux, the intermediate state as the blocks up to 30% above the average flux and the high states as the remaining blocks. This definition minimises the contribution of flaring activities to the low-state data set. Figure 1 shows the results.

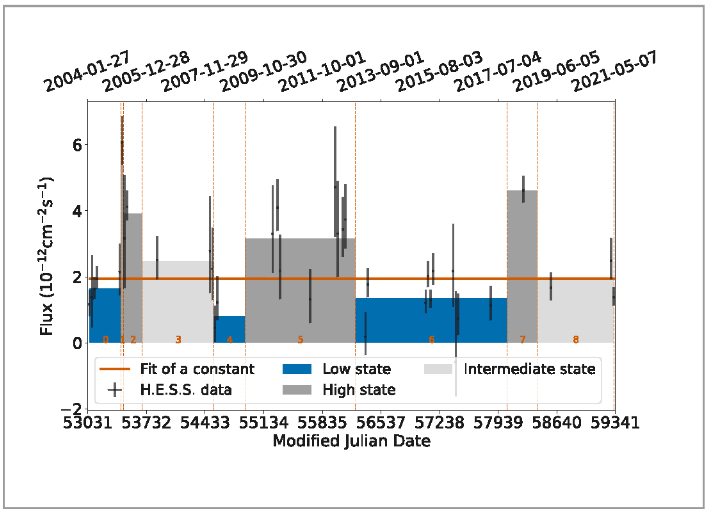

Figure 1

Monthly binned M87 gamma-ray light curve above 300 GeV, along with Bayesian blocks, defined source states and overall flux average. From [3].

Due to the causality argument, an extended signal greater than approximately kiloparsec scale is allowed only in non-flaring emission states. To investigate this scenario, we fitted the morphology of the low-state data set using two models: a point-like model and a rotationally symmetric 2D Gaussian model. The point-like model represents the gamma-ray emission from the core region of Virgo A, which includes the jet and knots not resolvable with current-generation IACTs. The Gaussian model represents potential extended emission, which is further explored in the next section.

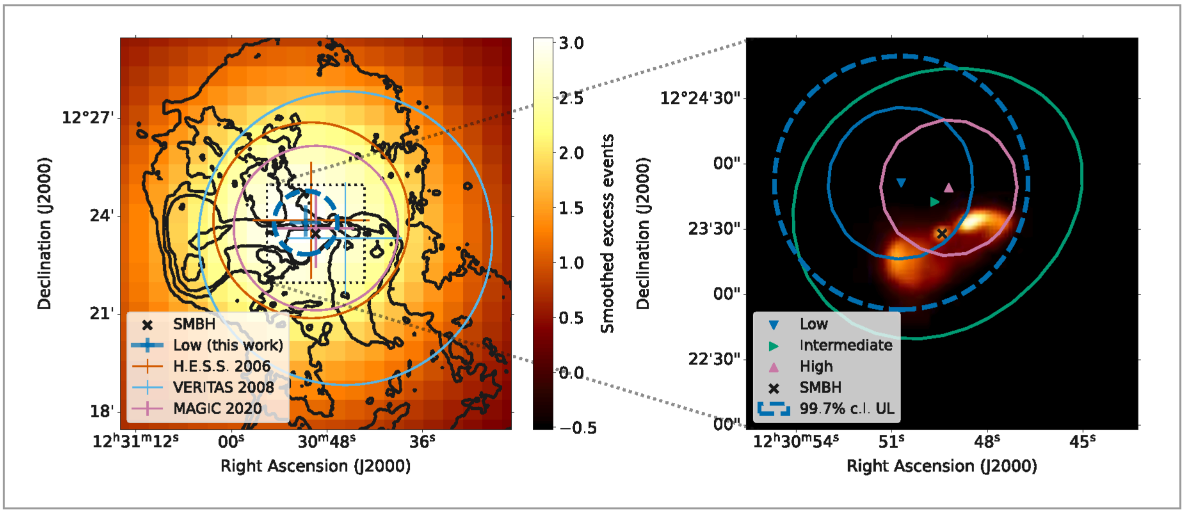

Figure 2
Left: Excess counts of the H.E.S.S. analysis and radio contours of the Karl G. Jansky Very Large Array (VLA) 90 cm radio telescope in New Mexico [5] showing the radio lobes of M87. The dashed blue circle indicates the upper limit derived in this work. Right: Best-fit position of the source states with 3 σ statistical uncertainties shown with the VLA 21 cm radio emission in colours [6]. From [3].

Our fit statistics showed no preference for the Gaussian model. Therefore, we derived the upper limit on the size of the Gaussian extension to be 0.016° (~4.6 kpc) at a 99.7% confidence level. This result is twice as constraining as the latest published results, as illustrated in Fig. 2. For the first time, we excluded the radio lobes as the primary component of the low-state gamma-ray emission of M87, including the statistical uncertainties of the best-fit position. However, the X-ray knots and the kiloparsec-long jet remain possible candidates, as shown in the summary sketch of Fig. 3.

Discussion

Our analysis did not find any evidence for extended gamma-ray emission in the low state of M87. However, the upper limit on the extension can be used to constrain models that predict such emissions. To test a scenario in which the radio lobes of M87 are populated by cosmic-ray protons in addition to synchrotron-emitting electrons, we defined a hybrid model composed of a point-like model and a template for the diffuse emission that mimics the radio lobes. The morphology fit of the hybrid model showed that the diffuse component may contribute up to a maximum of 45% of the total gamma-ray flux of the low state of M87 at a 99.7% confidence level. We used this information to derive upper limits on the cosmic-ray pressure and the total energy in cosmic rays allowed by the results of the morphology fit, assuming that cosmic-ray protons are distributed as a power law in energy with a typical spectral index of 2.1. Our results showed that the maximum energy stored in cosmic rays in the inner 20 kpc of the Virgo Cluster is $\lesssim 5 \times 10^{58}$ erg, which is on the same order of magnitude as the total energy expected from a theoretical model of shocks produced from outbursts in M87.

In a second scenario, we considered the AGN feedback model from [2] and derived the expected gamma-ray diffuse emission from it. The model proposes a heating mechanism through cosmic rays and is motivated by the unusually low star formation rate found in cool-core clusters such as the Virgo Cluster. We fitted a hybrid model composed of the template for the diffuse emission in addition to a point-like component and found that such a diffuse component may contribute up to a maximum of 55% to the gamma-ray low state of M87. The energy output in cosmic rays was also found to be $\lesssim 5 \times 10^{58}$ erg.

Although the origin of the gamma-ray emission from the low state of M87 remains a mystery, we have made progress in understanding it. Further DESY-led publications are in preparation, and we hope they will shed light on the nature of this most exciting source in the night sky.

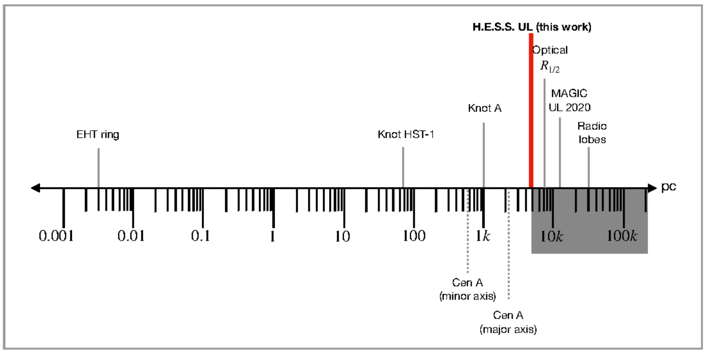

Figure 3
Sketch of the known features in M87 in perspective with the results of this work. For comparison, the measured extension of the jet in the radio galaxy Centaurus A is also shown [7]. From [3].

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Research that fascinates

Communicating astroparticle physics

In astroparticle physics, researchers investigate high-energy processes in the universe. A key mission is also to share the findings with the public. To this end, DESY uses various formats for different target groups: from making cosmic processes visible and audible to the interested public, through one-day events for young people, to innovative information events for colleagues at DESY.

Making cosmic particle accelerators visible and audible
For several years, DESY has been collaborating with the award-winning Science Communication Lab in Kiel, Germany. Initially, the DESY Astroparticle Physics division teamed up with the animation artists to develop a web-based microsite and animation that aimed to make the first astrophysical multimessenger event – the active galactic nucleus TXS 0506+056 – more accessible. The interactive storytelling webpage and key visuals page were created for a special press release and gained worldwide attention.

Over the years, the cooperation with Science Communication Lab has grown stronger and featured works showcasing significant astroparticle physics and astrophysics discoveries, ranging from stellar binary systems and nova eruptions to tidal disruption events or gamma-ray bursts.

The creations go beyond simple animations and also explore the audible. Two cosmic particle accelerators – the massive binary star Eta Carinae and the exploding star that resulted in the gamma-ray burst GRB 190829A – were brought to life in this way. In the case of Eta Carinae, the computer-generated images were close to reality, as the measured orbital, stellar and wind parameters were used for this purpose. The particle acceleration in the jet of GRB 190829A was also animated to an unprecedented level of detail [1]. The internationally acclaimed multimedia artist Carsten Nicolai, who uses the pseudonym Alva Noto for his musical works, composed the soundtracks exclusively for the animations. The aim of the multimedia projects is to make the discoveries more accessible to the general public and to present scientific results and their connection to reality from an artistic perspective.

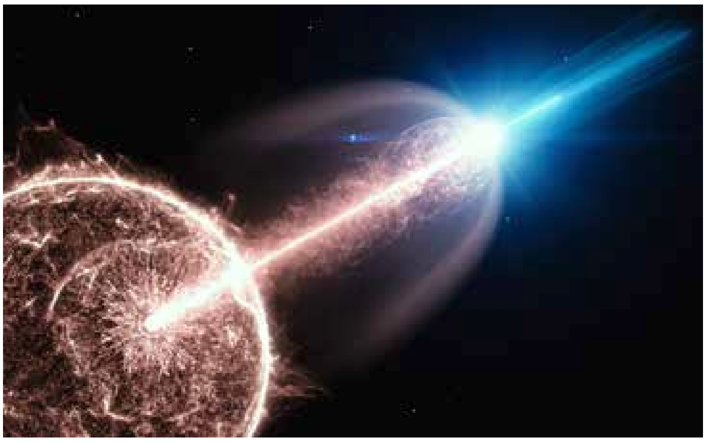

Figure 1
Artist's impression of the relativistic jet of a gamma-ray burst (GRB), breaking out of a collapsing star and emitting very-high-energy photons

Figure 1 shows one of the still images created on the occasion of the discovery of very-high-energy gamma-ray emission from GRB 190829A with the H.E.S.S. telescopes, illustrating the concept of the cooperation with Science Communication Lab. The scientific animations produced over the years regularly reach large audiences [2], even beyond the initial scientific announcements, registering hundreds of thousands of viewers on YouTube or Instagram, for instance. The animations are often reused by popular science accounts such as ExploreAstro [3] or used for short scientific information videos with e. g. popular scientists such as Harald Lesch [4].

Together with Science Communication Lab, DESY researchers are currently developing a dedicated website on multimessenger astroparticle physics that will serve as a science communication framework for different target audiences, from the general public to interested scientists. The website is planned to be launched in 2023.

International Cosmic Day – connecting young people worldwide
In 2022, DESY initiated and coordinated the International Cosmic Day (ICD) for the 11th time. The ICD2022 took place on 22 November.

Figure 2
Video call hosted at the ICD headquarters at DESY

Figure 3
Anna Nelles and Stefan Ohm hosting the first AP Morning Show

The day is dedicated to the unnoticed cosmic particles that flood our universe and constantly surround us on Earth. On this one day of the year, students have the opportunity to become a part of the scientific community. On ICD2022, participants conducted experiments and attended lectures in more than 90 groups at schools, universities and research institutes in over 20 countries around the globe. Students listened to scientists discuss their research and to other students present their results. The young people took on the role of researchers for a day and experienced first-hand how science works.

A special guest and supporter of ICD2022 was Rebecca Smethurst, astrophysicist at Oxford University, who is known on YouTube as Dr Becky. Another special feature was an online masterclass for Ukrainian students in Ukrainian, which was held in cooperation with the organisation Astrosandboxers and with young scientists at DESY in Zeuthen.

DESY provided material and organised the communication between the groups. In the 12 video calls that took place throughout the day, DESY researchers presented the IceCube neutrino telescope and moderated discussions between a total of 51 groups (Fig. 2). The team, consisting of scientists, students and event experts, again came up with some new highlights: activities for anyone who wanted to spontaneously join in on the day, including a quiz on astroparticle physics and drawing and selfie competitions on social media. Those who did not live near a venue could also participate without conducting their own experiments. The Cosmic@Web website provided data from long-term experiments and tools for evaluation.

The ICD is an initiative of DESY in cooperation with the International Particle Physics Outreach Group (IPPOG) and many national networks and partners.

The AP Morning Show – achievement breakfast of the Astroparticle Physics division

What do scientists research in the most remote places in the world? What do they talk about over breakfast? And what actually happens on the construction site and in the production halls at DESY in Zeuthen?

In the first ever AP Morning Show, hosts Anna Nelles and Stefan Ohm revealed the answers to these questions. The astroparticle physics team welcomed colleagues from DESY in Hamburg and Zeuthen virtually to the campus in Zeuthen and gave them a tour of the Astroparticle Physics division. A mixture of interviews, films, question-and-answer sessions and commercials gave the audience a lively and exciting insight into the research topics of astroparticle physics at DESY.

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International Cosmic Day: https://icd.desy.de
Global Cosmic Rays Portal: https://globalcosmics.org
Cosmic@Web: http://cosmicatweb.desy.de

New frontiers in precision gravity

From gravitational scattering to binary inspirals

As gigantic as the forces during a merger of two massive cosmological objects are – think of black holes or neutron stars with masses up to 200 times that of the sun – they only lead to the tiniest ripples in space-time when they reach Earth. Nevertheless, since the first detection of a gravitational wave (GW) in 2015, a network of high-precision detectors consisting of LIGO in the USA, Virgo in Italy and KAGRA in Japan has identified 90 events within their data that stem from such binary inspiralling systems somewhere in our universe. Finding a GW signal and extracting information – which allows us to learn about the objects in our cosmos, their interactions, their origin and about gravity itself – is highly non-trivial and requires precise theoretical models, pushing the frontiers of precision gravity. DESY theorists are strongly involved in efforts to develop such models.

Future GW detectors

Site preparations for the Einstein Telescope (ET), an underground GW observatory planned in Europe, are in full swing. Both ET and the Cosmic Explorer (CE), a planned US-based sibling of ET, will pursue a tenfold increase in sensitivity compared to current second-generation observatories. This future network of detectors will be completed by the space-based Laser Interferometer Space Antenna (LISA), which will cover a slightly lower frequency range. The data collected by the network will enable population studies of the invisible inhabitants of space, providing insights into the inner structure and mechanisms of neutron stars and (supermassive) black holes and into the beginning and evolution of our universe.

While we are awaiting the final decision on the location – including proposed sites in Germany – and the exact design of ET, theorists are already gearing up for the challenges that its unprecedented sensitivity will bring. Accurately modelling the coalescence of two massive bodies that interact gravitationally is difficult, not only because of the complicated non-linear structure of general relativity, but also due to the nature of such an event itself. Starting from a configuration of two distant and often slow-moving objects, the system evolves through a brutal merger into a single ringing body.

Computational tools from high-energy particle physics

The computational setup for the analytical study of the gravitational two-body problem, developed by the Gravitational Wave Astrophysics Theory (GWAT) group at DESY, uses computational methods from two disciplines of modern theoretical physics: effective field theory (EFT) and high-energy particle scattering. The former is used to handle the different length and mass scales in the problem – from a near-zone description of the gravitational field around a compact body (described itself by an EFT) to gravitational radiation far away from the source. The latter, as surprising as its appearance in the study of a classical bound system may be, has induced a fruitful interaction between the fields of GW physics, general relativity and scattering amplitudes.

The idea is the following: We use highly advanced tools from high-energy physics, such as Feynman diagram techniques, to study the gravitational scattering of two massive bodies (Fig. 1). Through the boundary-to-bound (B2B) dictionary [1, 2, 3], which provides analytical relations between the scattering and bound motion, we can infer observables for the binary coalescence from scattering results. Analytical data describing a bound two-body system is, in turn, an essential input for waveform models – theoretical predictions of the GW signals measured by observatories. Finally, in order to find a GW signal within all the environmental and detector noise and to read out information about the system that produced the signal in the first place, accurate waveform templates are needed. The analytical waveform models obtained in this setup are ideally suited to produce such templates by

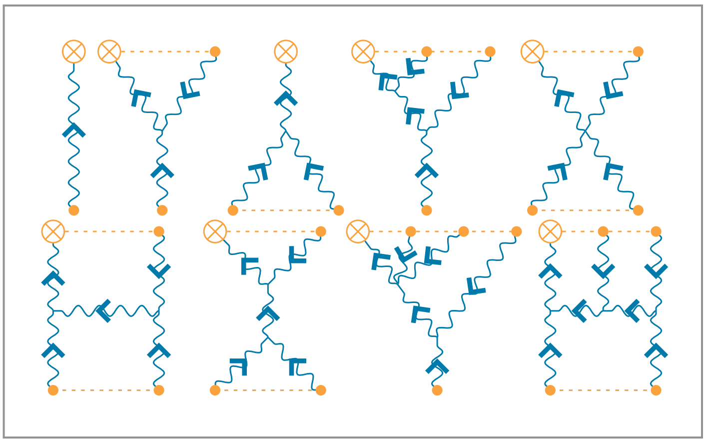

Figure 1
Example Feynman diagrams for the gravitational scattering of two black holes. The orange sources at the top and bottom represent the two black holes, while the blue edges are propagating gravitons, representing Green's functions for the perturbative solution of Einstein's equations.

LISA	$10^6 M_\odot + 10 M_\odot$	$10^5 M_\odot + 10 M_\odot$	$10^4 M_\odot + 10^4 M_\odot$
3.5PN	$224615.\hat{S}_\ell + (47903.6 + 23951.8\kappa_+)\hat{S}_\ell^2 + 67352.3\hat{\Sigma}_\ell + (47902.6 - 23951.8\kappa_- + 23951.3\kappa_+)\hat{S}_\ell\hat{\Sigma}_\ell + (448.6 - 11975.6\kappa_- + 11975.6\kappa_+)\hat{\Sigma}_\ell^2$	$24002.2\hat{S}_\ell + (5119.3 + 2559.6\kappa_+)\hat{S}_\ell^2 + 7195.6\hat{\Sigma}_\ell + (5118.2 - 2559.6\kappa_- + 2559.1\kappa_+)\hat{S}_\ell\hat{\Sigma}_\ell + (47.5 - 1279.6\kappa_- + 1279.6\kappa_+)\hat{\Sigma}_\ell^2$	$4.7\hat{S}_\ell + (1.2 + 0.6\kappa_+)\hat{S}_\ell^2 - 0.6\kappa_-\hat{S}_\ell\hat{\Sigma}_\ell + (-0.3 + 0.2\kappa_+)\hat{\Sigma}_\ell^2$
4PN	$-164123.\hat{S}_\ell + (76034.4 - 8979.\kappa_- - 25119.6\kappa_+)\hat{S}_\ell^2 - 55624.3\hat{\Sigma}_\ell + (60639.1 + 16140.8\kappa_- - 16140.1\kappa_+)\hat{S}_\ell\hat{\Sigma}_\ell + (24160.6 + 8070.1\kappa_- - 8070.1\kappa_+)\hat{\Sigma}_\ell^2$	$-16758.5\hat{S}_\ell + (7764.3 - 916.7\kappa_- - 2565.\kappa_+)\hat{S}_\ell^2 - 5678.7\hat{\Sigma}_\ell + (6191.1 + 1648.5\kappa_- - 1647.8\kappa_+)\hat{S}_\ell\hat{\Sigma}_\ell + (2466.7 + 824.\kappa_- - 824.\kappa_+)\hat{\Sigma}_\ell^2$	$-2.8\hat{S}_\ell + (1.5 - 0.4\kappa_+)\hat{S}_\ell^2 + 0.4\kappa_-\hat{S}_\ell\hat{\Sigma}_\ell + (0.2 - 0.1\kappa_+)\hat{\Sigma}_\ell^2$
ET	$100\ M_\odot + 1.4\ M_\odot$	$10 M_\odot + 10 M_\odot$	$10 M_\odot + 1.4 M_\odot$
3.5PN	$163.2\hat{S}_\ell + (35.2 + 17.6\kappa_+)\hat{S}_\ell^2 + 47.3\hat{\Sigma}_\ell + (34.2 - 17.6\kappa_- + 17.1\kappa_+)\hat{S}_\ell\hat{\Sigma}_\ell + (-0.1 - 8.5\kappa_- + 8.5\kappa_+)\hat{\Sigma}_\ell^2$	$7.7\hat{S}_\ell + (2. + \kappa_+)\hat{S}_\ell^2 - \kappa_-\hat{S}_\ell\hat{\Sigma}_\ell + (-0.5 + 0.2\kappa_+)\hat{\Sigma}_\ell^2$	$20.5\hat{S}_\ell + (4.7 + 2.4\kappa_+)\hat{S}_\ell^2 + 4.4\hat{\Sigma}_\ell + (3.6 - 2.4\kappa_- + 1.8\kappa_+)\hat{S}_\ell\hat{\Sigma}_\ell + (-0.5 - 0.9\kappa_- + 0.9\kappa_+)\hat{\Sigma}_\ell^2$
4PN	$-119.9\hat{S}_\ell + (56 - 6.4\kappa_- - 18.4\kappa_+)\hat{S}_\ell^2 - 39.4\hat{\Sigma}_\ell + (43.5 + 12.2\kappa_- - 11.5\kappa_+)\hat{S}_\ell\hat{\Sigma}_\ell + (17.3 + 5.8\kappa_- - 5.8\kappa_+)\hat{\Sigma}_\ell^2$	$-6.1\hat{S}_\ell + (3.3 - \kappa_+)\hat{S}_\ell^2 + \kappa_-\hat{S}_\ell\hat{\Sigma}_\ell + (0.5 - 0.2\kappa_+)\hat{\Sigma}_\ell^2$	$-15.\hat{S}_\ell + (7.4 - 0.6\kappa_- - 2.4\kappa_+)\hat{S}_\ell^2 - 3.8\hat{\Sigma}_\ell + (4.5 + 1.9\kappa_- - 1.1\kappa_+)\hat{S}_\ell\hat{\Sigma}_\ell + (1.8 + 0.6\kappa_- - 0.7\kappa_+)\hat{\Sigma}_\ell^2$

Figure 2
Estimation of the number of GW cycles in the frequency bands of future detectors operating at their design sensitivity for different mass configurations of the constituents. $\hat{\Sigma}_l$ and $\hat{S}_l$ are spin variables, κ_+ and κ_- are tidal deformability parameters. From [5].

scanning over a wide range of parameter space, including e.g. the masses of the constituents, their initial velocities and separation, their spin and any other degrees of freedom, such as tidal deformability parameters.

New frontiers

The analytical data that results from these calculations is organised as a perturbation series in powers of the gravitational coupling strength, Newton's constant *G*. The more orders are included in the results, the better the model describes the motion close to the merger, where one deals with high relative velocities and large forces. But, of course, the higher the order, the more elaborate the calculations become. Towards the end of 2022, we established a new frontier at the next-to-next-to-next-to leading order [4] by completing the description of the motion for spin-less and point-like constituents with radiation reaction forces, which appear due to gravitational radiation back-reacting with the mechanical two-body system.

While this result is an important milestone on our path towards the required high-precision waveform templates for future detectors, there are other areas of parameter space to be covered and different expansion schemes targeting different kinematical regimes and observables. Of course, neutron stars and black holes are usually neither spin-less nor point-like. Including the compact structure of such objects, described by an EFT, was the goal of another study [5] within our group in 2022. As long and complicated as these results may look, they are important for future analyses of gravitational radiation from compact cosmological objects. The impact of spin on the GW phase evaluation can for example be seen in the number of GW cycles that take place within the frequency bands of future detectors (Fig. 2). It shows that, for binary systems with an unequal mass configuration, which are also expected to exhibit larger spins, spin effects become more important.

Another paper involving DESY scientists goes one step further from the description of the two-body motion towards results for the gravitational radiation far away from the source. In [6], expressions for the multipole moments, which describe the propagation of GWs outside the source's near zone, are obtained with high precision. These are some of the last missing pieces for a complete knowledge of orbital phasing in a binary inspiral at the state-of-the-art order.

Equipped with this simple and elegant framework and efficient computational tools, we are ready to face the challenges the future of precision gravity will bring.

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Studying Greenland ice to get ready for neutrino detection

Attenuation, scattering, layers and birefringence

The Radio Neutrino Observatory Greenland (RNO-G) – a pioneering project that aims to detect very-high-energy astrophysical neutrinos using radio antennas – is moving forward in construction. In addition to having installed 7 of the planned 35 stations, time in the field is being used to study details of the glaciological ice. Understanding the ice in which the neutrinos interact is a prerequisite for better neutrino simulation and reconstruction studies. DESY graduate students were part of every installation campaign and became ice experts during the data analysis.

The ice and neutrinos

The largest neutrino detectors targeting astrophysical neutrinos all use naturally occurring media to provide the necessary detector volumes of at least a cubic kilometre. Using naturally occurring media is the only way to finance the construction of such detectors, but it also means that the detector medium cannot be controlled as in a human-made detector. In water-based detectors such as KM3NeT in the Mediterranean, for example, whales and other creatures swim through the detector, and bioluminescence lights up the detector. These signatures have to be studied as neutrino background, providing a flurry of data for biological studies at the same time.

Similarly, the ice of detectors such as IceCube or RNO-G, in both of which DESY scientists are strongly involved, has to be studied in detail to understand how the signals propagate from the neutrino interaction vertex to the signal receivers (Fig. 1). Despite their focus on astroparticle physics, these studies provide insights into how glacial ice behaves, how the polar ice sheets form and how ice as a medium works.

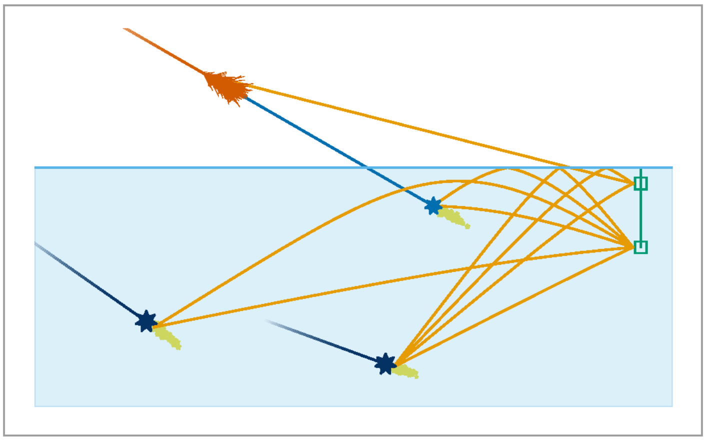

Figure 1
Radio signal paths through ice for radio emission caused by neutrino interactions (blue stars) and air showers (red). The signal paths (yellow) reach the detector (green) via curved trajectories owing to the changing index of refraction in the ice. The signal trajectories depend strongly on the profile of the index of refraction in the ice.

Ice properties

Ice is a dielectric medium with many fascinating properties. In polar regions, the accumulated snow compactifies over several hundreds of years to a homogeneous crystalline medium, which is exceptionally transparent to electromagnetic waves. Radio waves are detected after propagating over kilometres through the ice to the RNO-G receivers. The attenuation length depends on local parameters and signal frequencies and has the largest influence on the signal power received. Accordingly, the first priority for RNO-G was to measure the attenuation length at Summit Station in Greenland, where the detector is being installed, to refine earlier preliminary estimates.

For this purpose, a strong radio transmitter was placed on the surface and a signal was sent vertically downward to bounce off the bedrock and be detected again. From the received power and the time delay (Fig. 2), the attenuation length was extracted as a function of frequency [1, 2]. These types of measurements nicely complement those from boreholes by glaciologists, which focus more on small-scale properties and often use assumptions about global quantities, which the RNO-G measurements help to improve.

The bulk attenuation length is only the first step. Neutrino signals can be reflected off internal layers in the ice, such as those formed by eruptions of Mount Vesuvius (78 AD) or the Mionian eruption of Thera (1636 BC). Layers resulting from both these historic events are clearly visible in the radio survey data taken at Summit Station, at depths of 550 m and 770 m, respectively. Thankfully, their reflectivity is too small to significantly affect the neutrino detections [3].

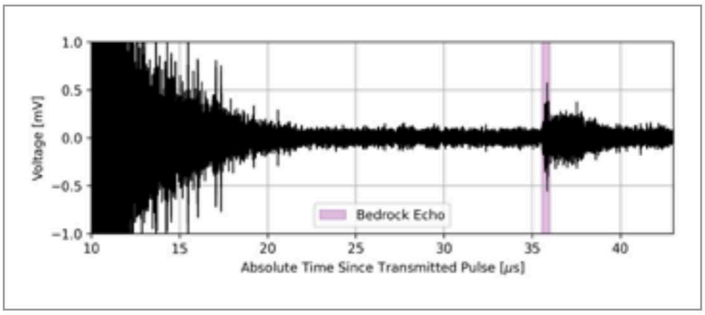

Figure 2
Bedrock echo measured at Summit Station. Within 35 µs, the radio emission travelled up and down through 3000 m of polar ice. The coherent reflection at the bedrock is clearly visible. Additional lines visible at up to 20 µs stem from layers in the ice caused by global events such as volcanic eruptions. Their reflectivities are additional important parameters needed to simulate the neutrino signal propagation. From [1].

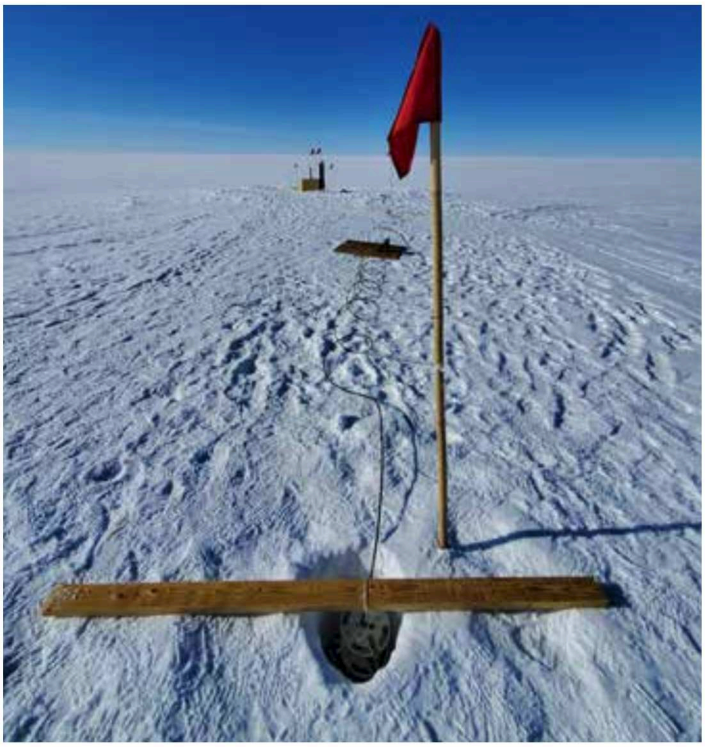

Figure 3
Measurement setup to obtain the ice parameters. Top: Small shallow holes are used to transmit vertically polarised signals. Bottom: Larger slots are needed for horizontally polarised signals.

Interestingly, by applying the particle physics approach to geology measurements, we were able to extract one of the most precise estimates of the index of refraction of bulk ice to date [3]. In particular, our measurements set high standards for the estimation of confidence levels and uncertainties.

Future studies

It is also known that polar ice can show birefringent properties. This is particularly the case when the ice flows and the ice crystals align in such a way that different polarisations of electromagnetic waves propagate with different indices of refraction, i.e. different speed. Birefringence typically complicates neutrino reconstruction and must thus be understood in all of its components. According to our current knowledge, the ice at Summit Station, which does not flow due to its position on top of the Greenlandic ice sheet, does not seem to exhibit strong birefringent properties. Current measurements (Fig. 3) have not been able to probe the horizontal component of the birefringence tensor with enough sensitivity, however, leaving work for future seasons.

The RNO-G collaboration will continue to install the detector over three more seasons to reach 35 stations. DESY graduate students will play a vital role in the installation, spending five to ten weeks on the ice during the summer. Each installation season will be accompanied by measurements of the glacial properties, which will also be used to set standards for the survey of the polar ice to be made for the radio array planned for the IceCube-Gen2 detector at the South Pole. Several cooperations were set up to share data with glaciologists about snow accumulation and dedicated ice density measurements.

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LSST at the Vera C. Rubin Observatory

Preparing for a new era of time-domain astronomy

The upcoming Legacy Survey of Space and Time (LSST) at the Vera C. Rubin Observatory in Chile will provide the deepest, most precise view of the variable universe to date. The vastly increased rate of detections will make traditional follow-up techniques too slow and expensive, however. DESY is building on its success in operating the AMPEL software platform for the Zwicky Transient Facility (ZTF) in the USA to create a real-time analysis environment for the LSST data. This environment will work as a code-to-data framework through which modern statistical methods can be developed and applied to the LSST detections in real time.

The Vera C. Rubin Observatory

The rapid development of large semiconductor optical detectors has revolutionised optical astronomy in two ways: Subsequent digital images can now be subtracted to find transient objects, and the increased physical wafer size allows the construction of telescopes that can observe a large fraction of the night-time sky in a single exposure. The first facility to make full use of these developments was ZTF, which is able to observe the entire visible sky every night and distribute the detection of any transient or variable celestial object as an alert in real time. While ZTF can observe the full sky, its small mirror size and location in California make the survey relatively shallow.

This will change with the LSST, which is to be carried out at the Vera C. Rubin Observatory (Fig. 1) [1]. The 8.4 m primary mirror telescope is now in the final construction phase at the Cerro Pachón ridge in northern Chile and is expected to produce first data in 2024. The camera consists of three billion pixels (corresponding to around 1500 HD TV screens) and will take a new exposure every 18 s during the 10-year survey. Taken together, LSST will obtain an image of the variable universe that is 10 times deeper than what is available today. Besides exploring the transient optical sky, core LSST science areas include studying dark energy and dark matter, taking an inventory of the solar system and mapping the Milky Way.

Big-data challenges in transient astronomy

This leap forward in terms of sensitivity to extragalactic variable sources comes with a vast increase in the rate of detections (Fig. 2). This has in turn necessitated a change in how astrophysicists work, a change that DESY is leading through the development of the AMPEL software platform [2]. Instead of inspecting individual events, prepared workflows are applied to the incoming alert streams to select the small subset of alerts caused by unique astronomical phenomena.

The breadth of astrophysical research means that the definitions of "unique" or "interesting" vary significantly; each AMPEL user hence develops their own sub-experiment through the workflow design. AMPEL thus constitutes the first example of code-to-data realised in time-domain astronomy: Scientific programs are developed locally in a test environment and then transferred to an agent that applies them to the full data streams on behalf of the user. This mode of operation on the ZTF data stream has led, for example, to the association of extragalactic neutrinos with tidal disruption events (TDEs) [3], searches for kilonova counterparts to gravitational-wave detections [4] and the systematic detection of supernovae only hours after explosion [5].

The LSST detection rate will also force a paradigm change in how astronomical data are analysed. Traditionally, transients detected through astronomical facilities have been followed up by dedicated spectroscopic observations, and the type and distance of the source have been inferred from atomic lines. Sources detected in LSST will be too numerous and faint to observe with spectrographs, however. Classification tasks will instead fall to modern statistical techniques such as deep learning, using the temporal evolution of the six different wavelength bands (colours) that LSST observes. DESY has also pioneered this approach by putting to use the first model developed on the basis of ZTF observational data.

Community brokers for LSST alerts

While the Vera C. Rubin Observatory plans to release catalogues of detections to the public on a yearly basis, real-time detections will only be available through a set of community brokers, which receive the full alert stream and filter and augment it on behalf of users from the astrophysics communities.

The AMPEL platform at DESY was selected as one of seven such community brokers worldwide. This will make DESY a hub for real-time LSST data and provide users with the same pre-planned,

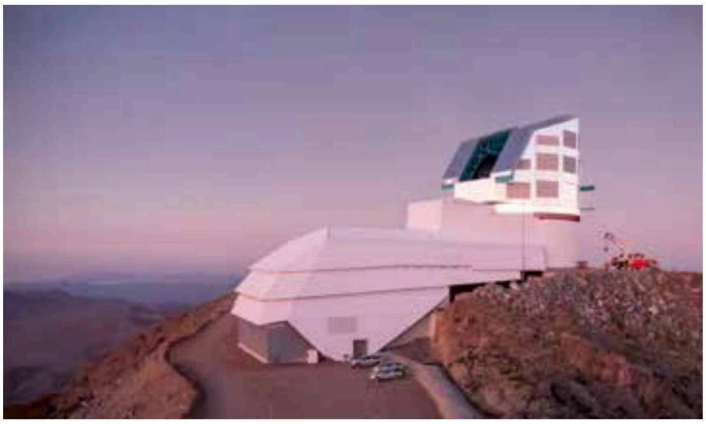

Figure 1
The Vera C. Rubin Observatory under construction in northern Chile

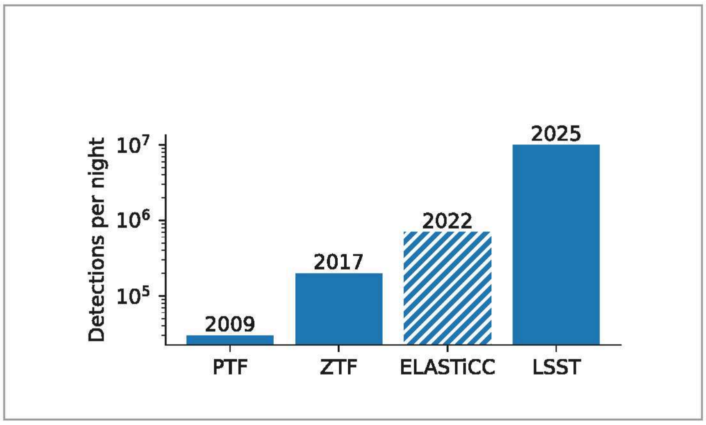

Figure 2
Detection rates in past and future optical surveys. PTF and ZTF ran at Palomar Observatory in California, USA, while LSST will run at the Vera C. Rubin Observatory in Chile. ELASTiCC is a simulation of LSST.

code-to-data analysis capabilities for LSST data as for ZTF.

Trial run for LSST

From October 2022 to January 2023, DESY participated in the Extended LSST Astronomical Time Series Classification Challenge (ELASTiCC), a data challenge prepared by the Dark Energy Science Collaboration (DESC). The challenge comprised 10 years' worth of simulated detections of nearly 40 different kinds of transient objects that were streamed to community brokers over the course of three months, resulting in a data rate roughly 10 times higher than expected in the real LSST. (Real alerts will also include artifacts and faint detections, which will increase the raw-data rate, but be filtered out at an early stage.)

AMPEL and other participating brokers consumed and classified these alerts and continuously reported the results back to the DESC. This challenge proved that AMPEL is able to handle LSST-like alert rates and confirmed that its photometric classification techniques can be used to classify transient objects even at high redshifts (Fig. 3). Kilonovae, the optical signatures of merging neutron stars, were found to be recognisable up to distances of several hundred megaparsecs, even without accompanying gravitational-wave signatures. Brighter events, such as the TDEs caused when stars are tidally disrupted by getting too close to black holes, will be detectable up to even greater distances, corresponding to lookback times of up to 10 billion years (more than half the age of the universe).

Fundamental data set for time-domain astronomy

LSST is now around the corner. It will influence and change the way astrophysics is done through a deep, precise view of the sky and a catalogue of variability of most of the universe. The result will be a fundamental data set in itself in terms of understanding dark matter and dark energy, but also a reference data set to which all other transient variability will be compared.

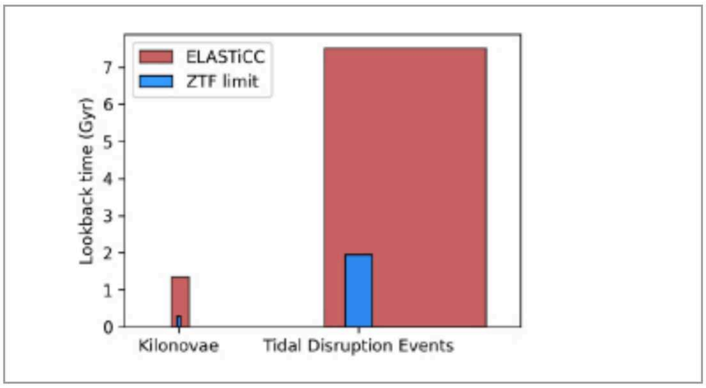

Figure 3
Volumetric sensitivity to transients. Searches for kilonovae and tidal disruption events using current observatories such as ZTF are only sensitive in the nearby universe (area of the blue bars). The AMPEL classification pipeline applied to the first realistic LSST simulation, ELASTiCC, confirmed the drastically increased volume in which transients will be identifiable (area of the red bars).

Multimessenger astronomical programmes in the next decade will be able to use LSST as an optical cornerstone in the southern hemisphere, to be combined with other next-generation observational facilities, such as CTA (gamma rays), IceCube-Gen2 (neutrinos), ULTRASAT (ultraviolet) and upcoming gravitational-wave detectors.

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H.E.S.S. telescope operations

Current status and operations in the first extension phase

The High Energy Stereoscopic System (H.E.S.S.) in Namibia is the world's only hybrid array of imaging atmospheric Cherenkov telescopes (IACTs), consisting of telescopes with different collection areas and footprints. The array has been in operation since 2002 and has been upgraded with new telescopes and cameras several times. Recent hardware upgrades and changes in operation procedures, made with strong contributions from DESY, partially in leading roles, have increased the amount of observing time, which is of key importance for time-domain astronomy. H.E.S.S. operations saw record data taking in 2020 and 2021. This article reports on current operations with specific emphasis on system performance, operational processes and workflows as well as quality control.

Introduction

H.E.S.S. is an array of five IACTs operating in the Khomas Highland in Namibia. In October 2019, the H.E.S.S. collaboration launched a first extension phase, which lasted until the end of September 2022, with the goal to increase telescope and instrument reliability and total observing time. The following sections describe the main technical activities and changes in operation procedures implemented in the first extension phase. Overall, they led to an increase of around 50% in yearly total observation time and to a significant improvement in telescope uptime – which now reaches 98% per telescope – and overall data quality.

Hardware upgrades and availability

Since the installation of the first telescope in 2002, H.E.S.S. has undergone frequent hardware upgrades and maintenance efforts to improve or maintain telescope performance. Figure 1 shows a timeline with major hardware upgrades conducted throughout the 20-year history of H.E.S.S. In 2015/2016, DESY and its H.E.S.S. partners upgraded the four Cherenkov cameras of the smaller H.E.S.S. telescopes (HESS-IU) [1]. At the beginning of the first extension phase, the camera of the CT5 telescope was replaced by a Cherenkov Telescope Array Observatory (CTAO) prototype FlashCam camera [2]. The installation and integration of the camera went very smoothly, with detection of the Crab Nebula on the first night of observations [3].

In preparation for the CT5 camera upgrade and the expected longer-term operations of H.E.S.S., the DESY H.E.S.S. group proactively upgraded the data acquisition (DAQ) system and the on-site computing cluster in early 2019 with strong support from DESY computing centre. The overall downtime due to DAQ problems was halved to around 0.5% in the first extension phase and is now plateauing around an excellent 0.3%. The increased hardware availability of the cameras in particular led to a more stable overall

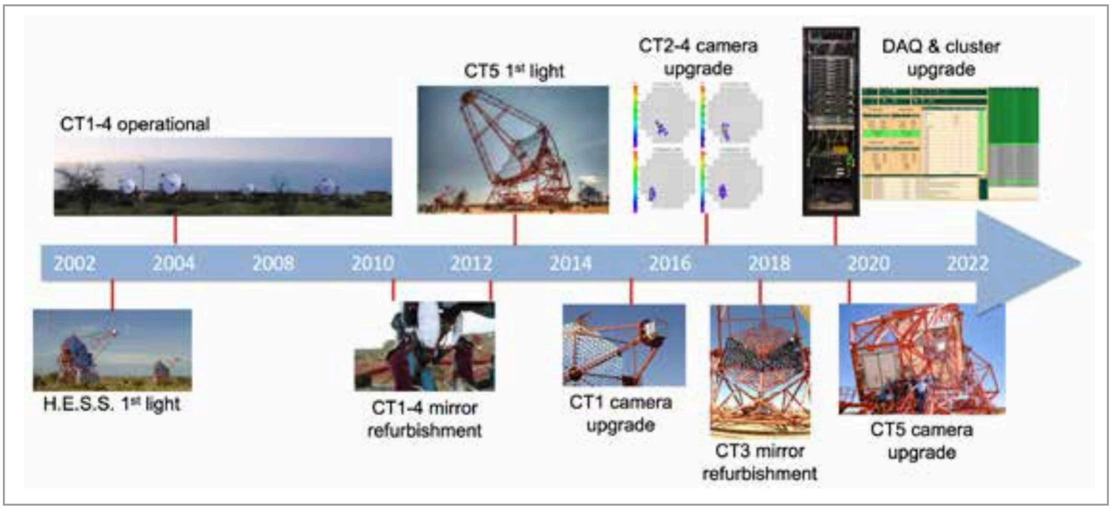

Figure 1

Timeline illustrating major H.E.S.S. hardware upgrades and maintenance campaigns over the last 20 years. Additionally, regular Winston cone exchanges and cleanings, Cherenkov camera gain adjustment and other works have been conducted, which are not listed here.

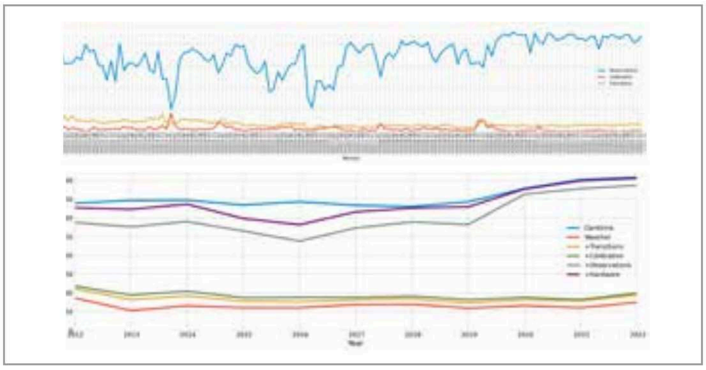

Figure 2
Top: H.E.S.S. data-taking efficiency. Some dips in efficiency are related to upgrades and maintenance campaigns, as indicated in Fig. 1. Bottom: Time available for science observations per year. Also shown are other contributions for various telescope operation modes and downtimes.

Figure 3
H.E.S.S. remote control room established at DESY in Zeuthen. The setup closely resembles the control room on the H.E.S.S. site and enables joint and stand-alone operation of the telescopes.

system and reduced downtime of other components as well. With further improvements made to other subsystems, such as the HESS-IU cameras – again under DESY leadership – we estimate the improvement in additional observation time to amount to 100–150 hours per year. Figure 2 shows the data-taking efficiency since the installation of the CT5 camera in 2012. A significant increase in efficiency from around 60–80% before October 2019 to about 90% afterwards is clearly visible.

Moonlight and twilight observations
Another goal for the first H.E.S.S. extension phase was to increase total observation time by extending observations into periods with moderate amounts of moonlight. Initial tests of observations under moonlight were conducted at DESY in 2019. To increase the lifetime of the HESS-IU cameras, the DESY H.E.S.S. group conducted and implemented observations with a single gain setting both in astronomical darkness and under moderate moonlight [4].

Observations with H.E.S.S. can now be conducted for around 250 hours extra each year, without significant loss in sensitivity or performance, during periods of moderate moonlight. A further increase in available observation time resulted from a widening of the observing window, with an earlier start and a later end of observations each night. This extra gain in observation time was again implemented with significant support and coordination by the DESY H.E.S.S. group.

Observation procedures and data quality monitoring
As travel was severely impaired during the COVID-19 pandemic, observations were performed by shift experts on site, who are nowadays supported by shifters from the H.E.S.S. partner institutes. To this end, a remote H.E.S.S. control room was established at DESY (Fig. 3). The remote control room increases flexibility, reduces the CO_2 footprint and enables the training of technical experts.

A major overhaul of the documentation of telescope operations, a compilation of how-to's and troubleshooting guidelines for (sub-)system failures improved procedures further. An off-site data quality team now checks and flags errors for timely fixing. Problems and technical activities are documented in shift workbooks. Discussions between on-site and remote shift crew, day shifters and subsystem experts are mainly conducted via Slack. Weekly virtual meetings summarise data taking and provide a forum for more detailed discussions. Monthly operation calls discuss longer-term operational activities, such as the implementation of new observing modes or preparations for maintenance campaigns. These platforms have proved to be critical for information exchange and troubleshooting. Monthly mails about technical activities, telescope operations and data-taking efficiency are prepared and sent to the collaboration.

Summary
The efforts described here resulted in a significant increase in operational efficiency and record-breaking data taking in 2020 and 2021. That this enhanced performance is no exception can be seen in Fig. 2. While downtime due to weather and transitions of the telescopes from one object to the other can hardly be reduced, the downtime due to hardware problems was cut considerably to the level of a few percent.

Another advantage of the much more stable operation is the homogeneity of the collected data. Since 2020, the vast majority of data has been taken with the full five-telescope array. Throughout the first extension phase, H.E.S.S. operations have been optimised to maximise telescope availability for target of opportunity (ToO) observations. The DESY H.E.S.S. group was crucial in this undertaking, leading the key DAQ and HESS-IU system upgrades and coordinating the entire operation of the H.E.S.S. telescopes during the extension phase.

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Hydrogen absorption shapes characteristics of galactic-centre gamma-ray excess

Dark-matter identification still elusive

Some ten years ago, the Large Area Telescope on board the Fermi Gamma-ray Space Telescope (Fermi-LAT) discovered an excess of gamma rays coming from the region of the galactic centre [1, 2]. This so-called galactic-centre excess (GCE) has remained one of the most intriguing open questions in astroparticle physics ever since. Although published interpretations concentrate on explanations involving dark matter or a millisecond pulsar, there is as yet no consensus on the origin of the GCE. Recently, researchers from the Astroparticle Physics Theory group at DESY presented a new model that reconstructs the distribution of atomic hydrogen in the inner galaxy. Using the new model to estimate the cosmic-ray-induced diffuse gamma-ray emission yielded a significantly better fit to the Fermi-LAT data. The fit provided no evidence for a dark-matter signal, rendering any interpretation of the GCE as a signature of dark-matter annihilation premature.

Introduction

Gamma rays can be produced by cosmic-ray electrons and ions in what is referred to as leptonic and hadronic radiation processes. The main leptonic emission processes are inverse Compton scattering of very-high-energy electrons off ambient photons and non-thermal bremsstrahlung. Hadronic emission processes involve the production of secondary particles in collisions of cosmic rays with gas nuclei and their eventual decay to gamma rays. Both non-thermal bremsstrahlung and hadronic emission scale with the gas density. They therefore provide the dominant contribution to the diffuse galactic gamma-ray intensity for lines of sight through the galactic plane and in particular towards the galactic centre region, where the density of the gas column is very high.

Modelling the diffuse interstellar gamma-ray emission thus requires knowledge of the distribution of gas in the galaxy, which must be convolved with the spatial distribution of cosmic rays to estimate the gamma-ray emissivity along each line of sight. Care must be exercised, for mismodelling of the diffuse galactic gamma-ray emission may introduce artificial excess features or deform the morphology of a true excess signal.

Modelling the gas flow in the galaxy

Line spectra of atomic hydrogen (HI) or CO as tracer of molecular hydrogen provide information on the line-of-sight velocity of the gas, whereas what is needed is the distribution along the line of sight. Modelling the gas flow in a realistic gravitational potential provides estimates of the Doppler shift that allow the gas to be placed on the line of sight [3]. This approach solves the problem for molecular gas and leads to improved estimates of the gamma-ray foreground in the galaxy [4]. But much of the gas is atomic, and atomic hydrogen can carry strong absorption features in the line spectra that hide gas.

Researchers from the Astroparticle Physics Theory group at DESY recently modelled the full radiation transport of atomic hydrogen including continuum emission and found more gas toward the inner galaxy than previously thought. The new HI model is based on explicit modelling of the radiation transport of line and continuum emission and on a gas flow model in the barred galaxy that provides distance resolution for lines of sight toward the galactic centre. The main benefits of the new gas model are, firstly, the ability to reproduce the negative line signals seen with the line spectra and, secondly, the accounting for gas that primarily manifests itself through absorption. Figure 1 displays, for one line of sight, a comparison between the observed and the modelled line spectrum, indicating how well the negative signal can be reproduced.

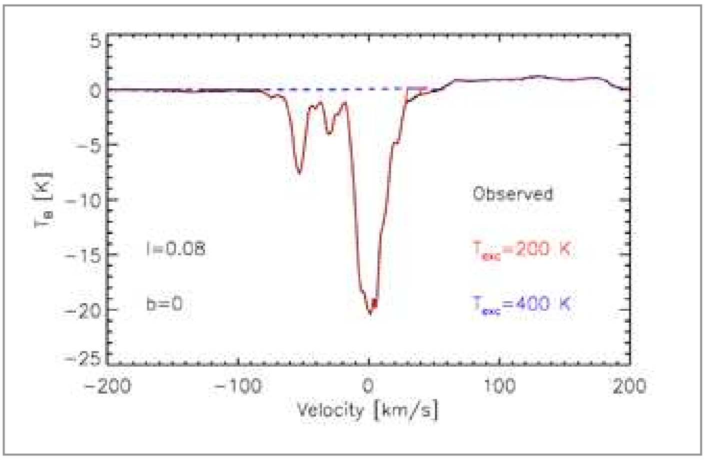

Figure 1
Observed (black) and modelled (red) line spectrum of atomic hydrogen toward the inner galaxy. The modelled spectrum depends on the excitation temperature, high values of which provide a poor fit and can hence be excluded.

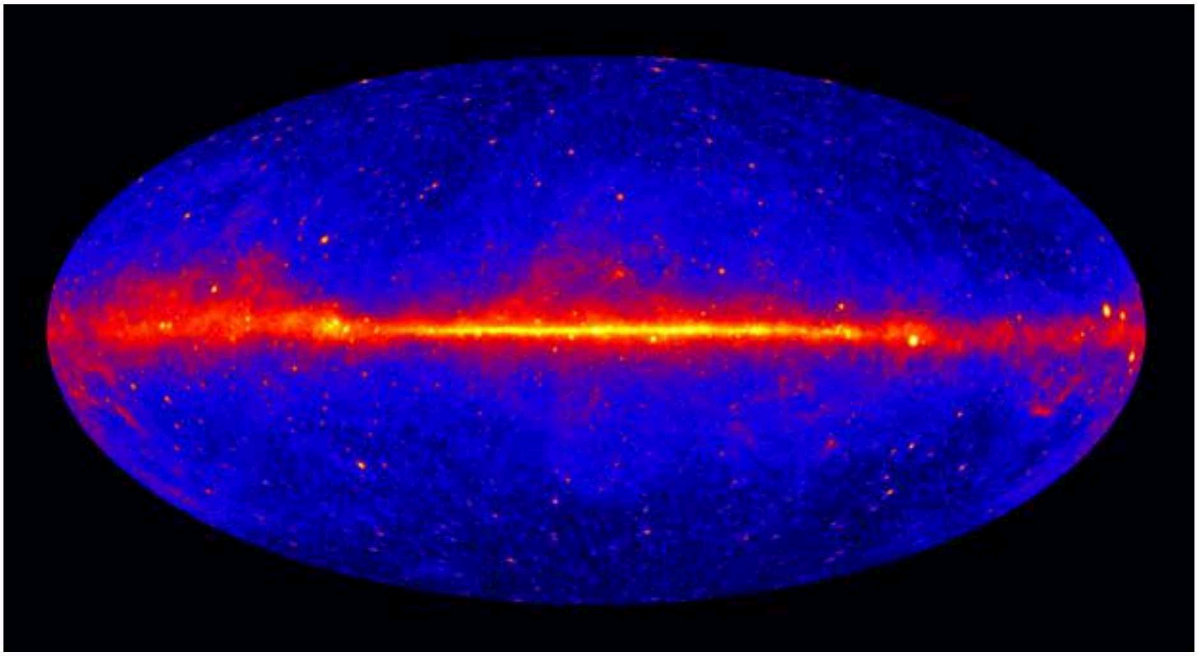

Figure 2
Fermi LAT 60-month image, constructed from front-converting gamma rays with energies greater than 1 GeV. The most prominent feature is the bright band of diffuse glow along the map's centre, which marks the central plane of our Milky Way galaxy.

The new model of galactic atomic hydrogen was then used to analyse the diffuse gamma-ray emission from the inner galaxy, where Fermi-LAT had discovered the GCE at a few GeV. The approach resulted in a significantly better fit to the Fermi-LAT data [5]. The fit still required a nuclear bulge at high significance. Once this was included, there was no evidence for a dark-matter signal, be it cuspy or cored. But an additional so-called boxy bulge was still favoured by the data. The finding was robust under the variation of several parameters, such as the excitation temperature of atomic hydrogen.

Figure 2 shows the all-sky map of gamma-ray emission as measured over 60 months by Fermi-LAT. The diffuse glow from the galactic centre comprises the GCE modelled in this work.

Summary

The new model of the gas distribution in the galaxy revises our expectation of the diffuse galactic gamma-ray emission. It provides a considerably better fit to the data taken with Fermi-LAT, but there is still an extended excess component toward the inner galaxy. The morphology of this excess component is incompatible with that expected for a dark-matter signal, but is well aligned with the distribution of massive stars, suggesting that stellar interactions are at the origin of the excess emission.

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The mystery of the ultrahigh-energy cosmic-ray spectrum

Experimental systematics or astrophysical explanation?

The Astroparticle Physics Theory group at DESY studies ultrahigh-energy cosmic rays (UHECRs), the most energetic particles known in the universe. The Pierre Auger Observatory in Argentina and the Telescope Array in the USA have been collecting data for many years, but there are differences in the energy spectrum of the UHECRs measured by the two experiments. We aimed to explore these differences from a theoretical perspective by considering two possible scenarios [1]. One suggests that the differences are due to complex experimental systematics, the other assumes that there is a local source of cosmic rays that is visible to one experiment and not the other. To compare the two scenarios, we simulated the UHECR propagation using the open-source software PriNCe, developed at DESY [2]. The results show that both scenarios can explain the observed difference in the data equally well.

Ultrahigh-energy cosmic rays

UHECRs are the most energetic particles known in the universe, with energies up to 10^{20} eV. They provide a unique window into the most extreme environments in the universe. However, the sources and acceleration mechanisms of these particles remain unknown. Possible candidates include active galactic nuclei, gamma-ray bursts and tidal disruption events.

In recent years, two observatories, the Pierre Auger Observatory (PAO, Fig. 1, left) and the Telescope Array (TA, Fig. 1, right) have been measuring UHECRs to better understand their properties and origin. PAO is a large-scale experiment located in Argentina that covers an area of 3000 km^2 and has been observing UHECRs since 2004. The observatory uses a network of water Cherenkov detectors and fluorescence telescopes to detect the air showers produced when UHECRs interact with particles in the atmosphere. TA is a similar experiment located in Utah, USA. It covers an area of 700 km^2 and has been operating since 2008.

Although the two experiments observe the same chemical composition of UHECRs within systematic uncertainties, their spectral data show differences that have led to much debate in the scientific community. Understanding the differences in the UHECR data from these two observatories is crucial for studying UHECRs.

Mystery of the UHECR spectrum

Figure 2 shows the differences reported by PAO and TA in the energy spectrum of the UHECRs measured by the two experiments. In the left plot, using the energy scales native to both experiments, there is a difference in the overall flux normalisation and in the spectral shape at energies above 30 EeV. Previous studies [3] showed that shifting the energy scales by a constant value can help reduce differences in spectra below 30 EeV (Fig. 2, right). However, that shift cannot explain the differences above that energy, where TA predicts a higher flux than PAO. Although Fig. 2 shows data from the whole sky, there are also differences in the part of the sky that both observatories can see, but they are less significant due to higher statistical uncertainties.

Figure 1
Left: Pierre Auger Observatory. Right: Telescope Array.

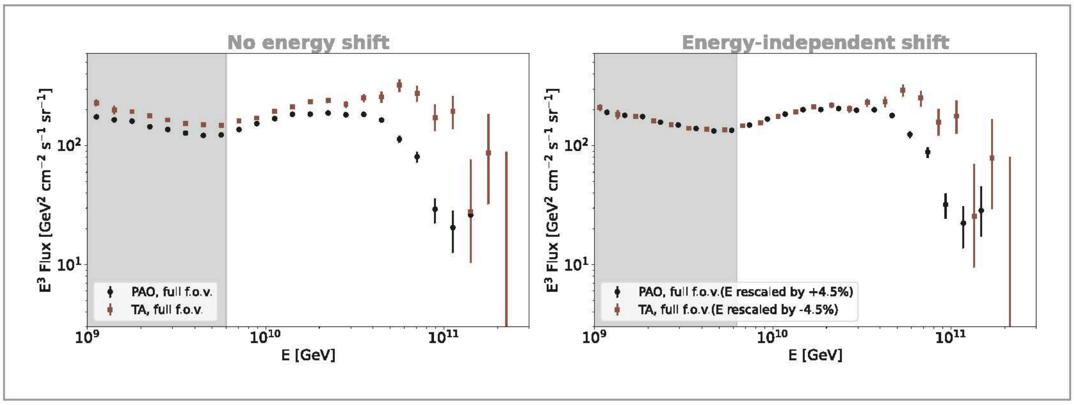

Figure 2
Energy spectrum of the UHECRs as measured by PAO and TA in the full fields of view of each observatory. Left: Data in the native energy scale. Right: Energy scales shifted by the amounts specified in the legend. Figure adapted from [3].

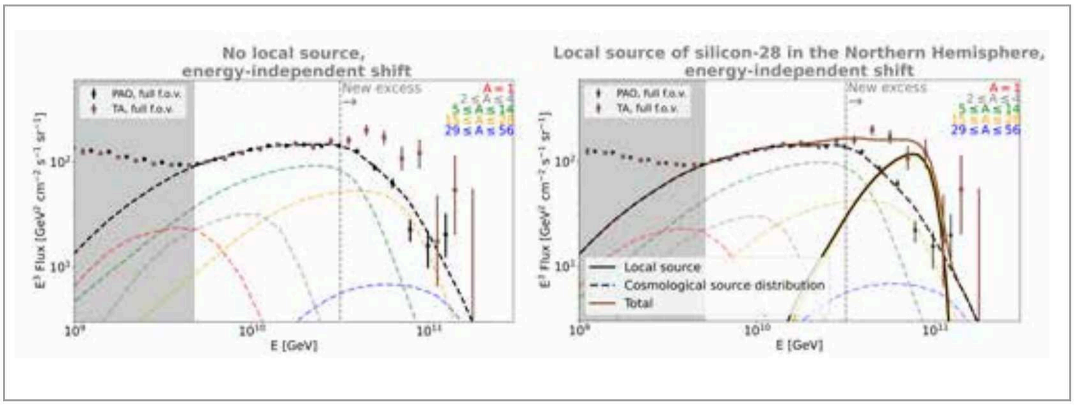

Figure 3
Spectra resulting from the joint fit. Left: Best fit of the systematic scenario. Right: Best fit of the astrophysical scenario.

Goal

We aimed to explore these differences from a theoretical perspective by considering two possible scenarios. The first scenario suggests that the differences may be due to more complex systematics leading to an energy-dependent shift of energy for both observatories. The second scenario proposes that there may be a local source of UHECRs in the northern hemisphere, which could be responsible for the observed differences in the data.

Theoretical model

To investigate these scenarios, we first simulated the UHECR emission from a background UHECR population of sources. The model assumes that each source emits cosmic rays of five elements, each representative of a distinct mass group up to iron-56. Then we simulated a single local source in the northern hemisphere, which can be observed by TA but not by PAO. For simplicity, we explored scenarios in which the local source emits only one of the five mass groups.

Once we characterised the emitted UHECR spectra from the cosmological source distribution and the local source, we injected those cosmic rays into a numerical simulation to calculate their propagation toward Earth using the open-source software PriNCe, which was developed at DESY [2].

Fitting

We performed a joint fit of TA and PAO data above the energy of 6 EeV including their systematics. Both observatories provided data on the spectrum measurements and the average value and standard deviation of the depth of the air showers. We used the chi-square test statistics to estimate the goodness of the joint fit.

What we obtained

Figure 3 shows the best-fit results of both scenarios, obtained using Sibyll as air shower model. In the first scenario (Fig. 3, left), complex energy-dependent systematics can explain the differences at energies above 30 EeV, but the discrepancy appears at lower energy, leading to a poorer fit. In the second scenario (Fig. 3, right), the existence of a local source emitting silicon-28, located 14 Mpc away in the northern hemisphere, provides a convincing explanation for the differences in spectra between PAO and TA.

What we learned

Our study has shown that the differences in the UHECR data from the PAO and TA observatories can be explained equally well (within 0.3 σ) by either complex energy-dependent systematics or a local source of UHECRs in the northern hemisphere. We found that the best-fit parameters of the cosmological source distribution are the same for both scenarios, which is due to the fact that the fit is strongly driven by the low-energy part of the spectrum.

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Pulsars as PeVatrons

On the potential of bright, young pulsars to power ultrahigh-energy gamma-ray sources

The discovery of a dozen ultrahigh-energy (UHE) cosmic accelerators within the Milky Way by the Large High Altitude Air Shower Observatory (LHAASO) in China prompted scientists to rethink the mechanism by which high-energy particles are produced in our galaxy. These cosmic-ray factories accelerate particles up to PeV energies, that is, to energies beyond 1000 TeV. Of these ultrahigh-energy sources, only the Crab Nebula has been clearly identified, while the others remain unknown. Their location close to TeV gamma-ray sources, which were identified as pulsar wind nebulae by Cherenkov telescopes, suggests pulsars could be the machines powering them. We investigated this possibility based on fundamental arguments and confronted it with observational results [1]. Our findings reveal the extreme nature of young, energetic pulsars.

Pulsars as effective PeV accelerators

Pulsars are rapidly spinning and strongly magnetised neutron stars that emit beams of electromagnetic radiation powered by their rotational energy. They inject ultrarelativistic particles into their surroundings. These particles, mostly leptons, form an ultrarelativistic wind, which expands with one of the most extreme bulk Lorentz factors ever observed (10^4–10^7) until it reaches the termination shock [2, 3]. At the shock, particles are believed to be accelerated to multi-TeV energies, inflating a non-thermal nebula that constitutes the plerion. These pulsar wind nebulae (PWNe) are among the most efficient electron factories in our galaxy.
A large fraction of the rotational energy stored in these particles ($\dot{E}$) is radiated in gamma rays up to at least a few tens of TeV via inverse Compton scattering. At these energies ($E_\gamma \gtrapprox 100$ TeV), the electrons lose most of their energy in a single scattering event, and the maximum energy observed in photons roughly coincides with the maximum energy to which the electrons are accelerated.

Based on first principles, we derived the absolute maximum energy in pulsars, which depends ultimately on the maximum potential drop created in the magnetohydrodynamic flow. This is equivalent to the Hillas criterium, meaning that the maximum possible energy of the particle depends on the size of the accelerator, which in the case of PWNe is the size of the termination shock (R_{TS}), and on the magnetic field in the shock (B_{TS}). Defining η_e as the ratio between the electric field and the magnetic field (which is $\eta_e \leq 1$ in ideal conditions) and η_B as the fraction of the pulsar wind energy flux that goes into magnetic energy density (constrained, by energy conservation, to be $\eta_B \leq 1$), we demonstrated that the maximum possible energy of the particles depends only on the rotational energy of the pulsar:

(1) $E_{max} = 2\, \eta_e\, \eta_B^{1/2}\, \dot{E}_{36}^{1/2}$ PeV.

This expression, which is independent of the leptonic or hadronic nature of the particle, can be used in a straightforward way to investigate whether a pulsar can power an UHE source. In the case of electrons, the energy of the observed photons, in the multi-TeV regime, is related to that of the electrons by $E_e \approx 2.15\, E_{\gamma,15}^{0.77}$ PeV, when produced by inverse Compton scattering on the 2.7 K cosmic microwave background (CMB) photons. In this way, a direct link between two observables – the maximum of the observed gamma-ray emission and the pulsar rotational energy – can be proven:

(2) $E_{\gamma,max} \approx 0.9\, \eta_e^{1.3}\, \eta_B^{0.65}\, \dot{E}_{36}^{0.65}$ PeV.

It can immediately be derived that only very energetic pulsars with at least $\dot{E} \gtrsim 10^{36}$ erg/s could power the observed PeV gamma rays.

A second condition is required for cosmic objects to shine in gamma rays up to PeVs: The acceleration rate τ_{acc} should also overcome the radiative losses of the electrons. In the UHE regime, electrons are quickly burned via synchrotron emission for magnetic fields as low as $B \sim 10$ μG. The condition $\tau_{acc} = \tau_{syn}$ results in the following expression for the maximum energy of the electron population required to overcome synchrotron losses:

(3) $E_{e,max} \approx 20\, \eta_e^{1/2}\, B_{-5}^{-1/2}$ PeV $\Rightarrow$ $E_{\gamma,max} \approx 5\, \eta_e^{0.65}\, B_{-5}^{-0.65}$ PeV.

The interplay between the two expressions (2) and (3) limits the maximum energy that can be reached in a pulsar environment.

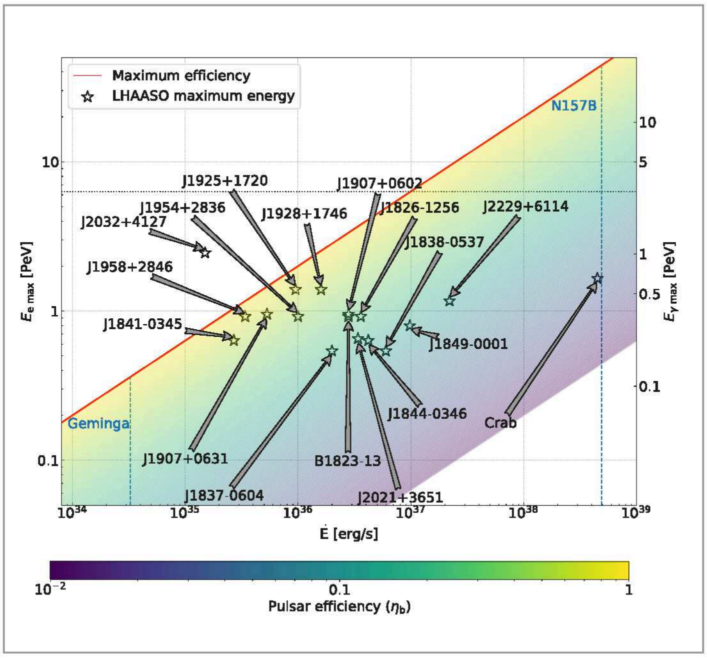

Figure 1

Maximum electron energy derived from the LHAASO spectra versus spin-down power of the co-located pulsars. The right *y*-axis shows the corresponding gamma-ray energy. The coloured area shows the values for $\eta_B\,\eta_e^{1/2}$ ranging from 0.01 to 1, with the red line indicating the limiting value corresponding to maximally efficient acceleration $\eta_B = \eta_e = 1$. The dotted black line marks the upper limit to the maximum energy for young pulsars with a large magnetic field of 100 µG. The blue dashed horizontal lines show the predicted values for PWNe associated to the pulsars Geminga and N157B.

Comparison with the UHE measurements

Twelve UHE gamma-ray sources were reported in [4] in 2021, with a spectral energy distribution extending up to more than 100 TeV. To explore the possibility of an association with pulsars, we searched the catalogue of the Australia Telescope National Facility (ATNF) [5] for relatively young ($\tau < 10^6$ years), energetic ($\dot{E}/d_{kpc}^2 < 10^{34}$ erg/s/kpc², or $\dot{E} > 10^{36}$ erg/s when the distance is unknown) pulsars, located within 1° around the position of the LHAASO sources. For each of the LHAASO sources, we found at least one pulsar (two in some cases) that could potentially be linked to it, except for the source J2108+5157, for which no bright pulsar was found in the vicinity.

To evaluate the possibility of this association, we estimated the maximum energy to which particles can be accelerated by each pulsar. The results are summarised in Fig. 1, in which we show the potential associations in the $\dot{E}$ - $E_{e,max}$ plane and compare them with theoretical predictions based on the equations above. Out of all pulsars considered, the maximum energy is limited by the radiation losses only in the Crab pulsar, while for all other pulsars, the most relevant constraint comes from the saturation of the full available potential drop. The upper limit to the maximum electron (and photon) energy, using $\eta_e = 1$ and a magnetic field of 100 µG, is marked with a dotted horizontal line in Fig. 1. Above the red line, the particle flow would require values of $\eta_B = 1$ and $\eta_e > 1$ and would demand non-ideal mechanisms (see [6] for a review).
Only one of the pairs of UHE source/energetic pulsar (LHAASO J2032+4102/J2032+4127) lies above the absolute maximum, resulting in an impossible connection between the two (if the spin-down power of the pulsar is correct within a factor of ~4).
We also marked in Fig. 1 two remarkable pulsars with vertical blue lines: Geminga and the Crab twin, N157B, located in the Magellanic Cloud, for which we predicted the maximum observable energy.

We investigated this possibility based on fundamental arguments and confronted it with the observation results. Of the 11 sources considered, only two sources stand out in which different accelerators other than pulsars should be investigated. The first, LHAASO J2108+5157, does not have any counterpart at lower energies, and further deep multi-wavelength observations should be performed. The second, LHAASO J2032+4102, is co-located with a bright pulsar in a binary system. The considerations above only apply to the isolated pulsar, however, and the mixing of the two winds could in principle lead to different conclusions. More interestingly, the system is located at the heart of the Cygnus cocoon, a bright GeV and TeV extended diffuse emission, which has also been connected with several individual sources, including the massive stellar cluster Cygnus OB. The potential connection between the Cygnus cocoon and the LHAASO source opens interesting prospects for stellar clusters as contributors of ultrahigh-energy particles.

Overall, our results reveal the extreme nature of young, energetic pulsars, which could potentially be the machines powering the newly discovered UHE sources.

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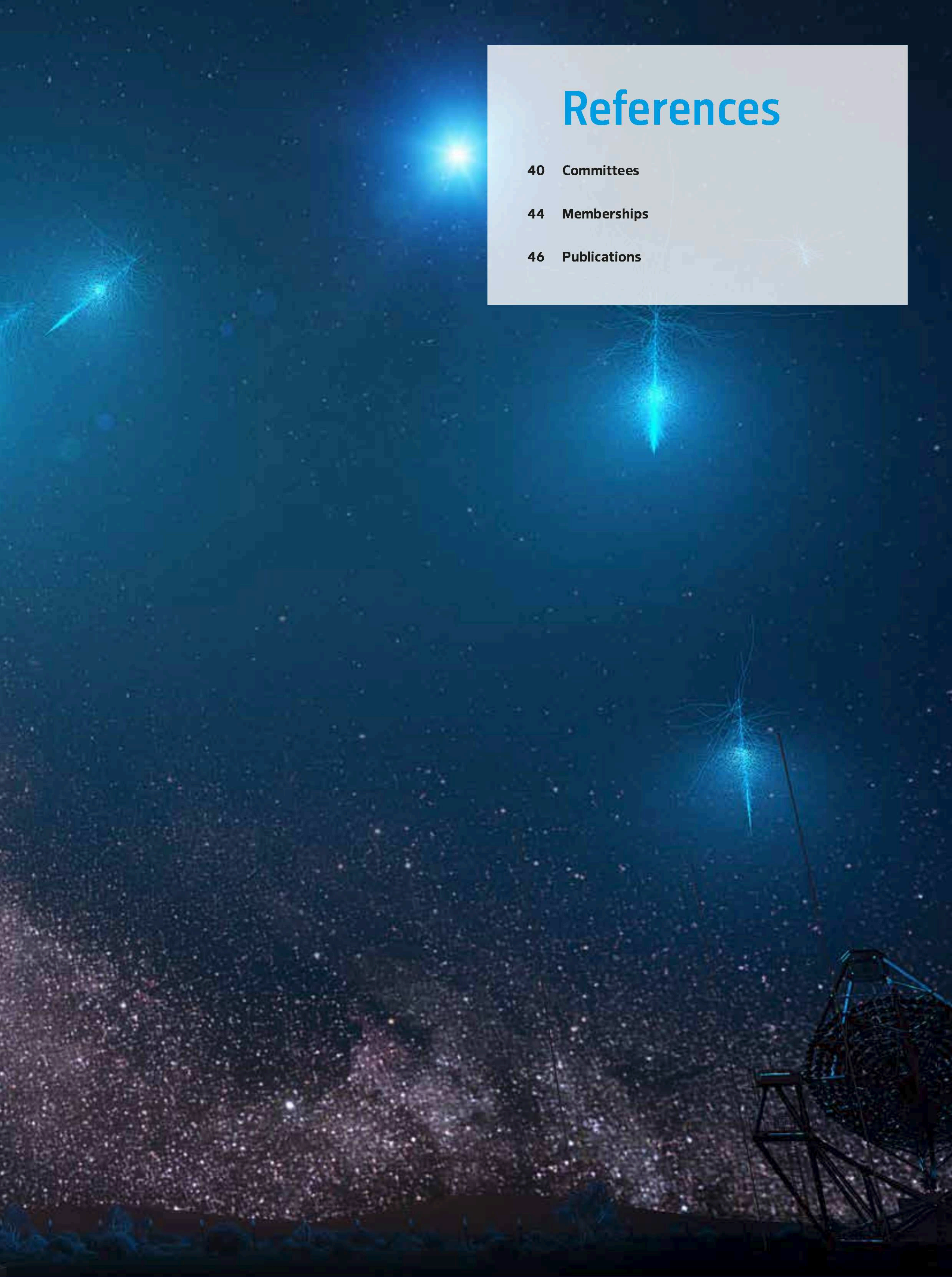
Artist's impression of very-high-energy photons from a gamma-ray burst entering Earth's atmosphere and initiating air showers that are being recorded by the H.E.S.S. telescopes



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