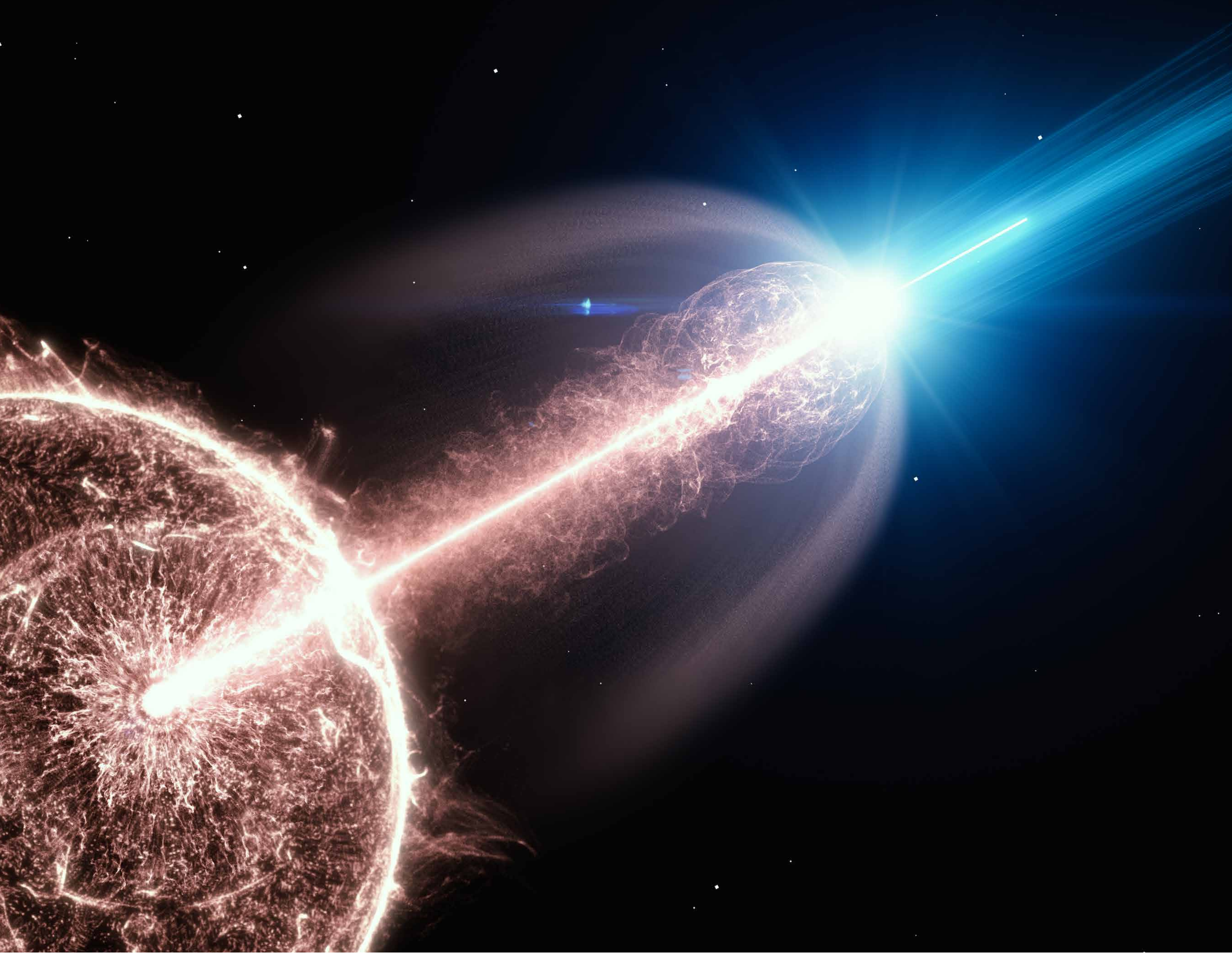


ASTROPARTICLE PHYSICS 2021.

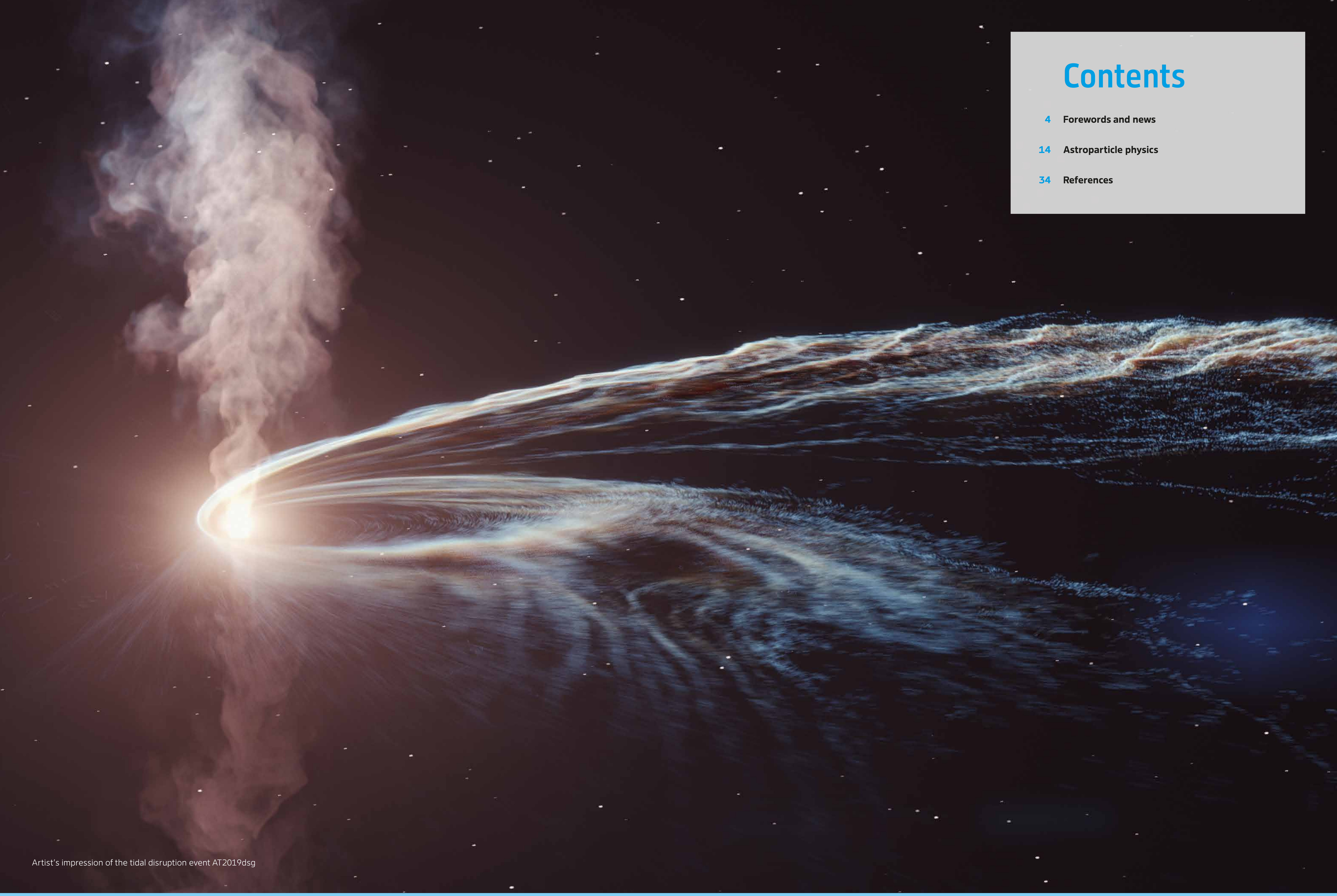
Highlights and Annual Report

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

ASTROPARTICLE PHYSICS 2021.

Highlights and Annual Report

Cover
Artist's impression of a relativistic jet of a gamma-ray burst, breaking out of a collapsing star and emitting very-high-energy photons



Artist's impression of the tidal disruption event AT2019dsg

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The year 2021 at DESY

Chairman's foreword

Dear Colleagues and Friends of DESY,

German Nobel Laureates in physics and chemistry in 2020 and 2021 and the rapid development of a COVID-19 vaccine through the outstanding research and development work in the BioNTech company: These are spectacular scientific breakthroughs that impressively show the strong German role in worldwide fundamental and applied research.

To open up completely new possibilities of knowledge generation, DESY has a highly ambitious future plan at its two sites to shape the research campus of the 21st century. Here, applied research that leverages the potential of cutting-edge research infrastructures and rapid transfer to industry and society will be promoted and shaped in a smart "ecosystem".

To implement this plan in a highly competitive environment, we need to get important construction projects under way quickly in the current funding period so as not to fall behind internationally. This applies to the various construction projects in the areas of research, transfer and knowledge communication on the DESY sites in Hamburg and Zeuthen, but especially to the PETRA IV project, the world-leading lighthouse in research with synchrotron radiation. With the newly developed revolutionary storage ring technology, the hybrid six-bend achromat (H6BA) lattice, we are pushing the performance of German and European light sources ahead of those in the USA and China.

The lessons learned from the coronavirus pandemic and the acute climate crisis are forcing us to leave our comfort zones. For us at DESY, this means that we are questioning the daily life we have become used to. How will we work and conduct research at DESY in the future? How and how much will we travel in the future? How will we organise a sustainable research campus in the future?

Figure 1
DESY tour during the Karl Heinz Beckurts Prize ceremony in October 2021 (from left): Oliver Seeck, Wim Leemans, Roland Busch (Siemens), Helmut Dosch, Ingmar Hoerr (formerly CureVac), Vasilis Ntziachristos (Helmholtz Zentrum München and TU München), Venetia Ntziachristos, Christian Stegmann, Arik Willner

Figure 2
The newly opened Start-up Labs Bahrenfeld building close to the PETRA III experimental hall "Max von Laue"

How do we coordinate climate-friendly operation for users at our large-scale research facilities without any compromises in quality? Will it then still be possible to be appealing to new user groups from academia and industry? If we find the right answers and smart solutions, I am convinced that DESY will remain a future-oriented research centre, perhaps even more diverse and even more climate- and family-friendly, and continue to attract the best talents from all over the world.

In October 2021, we were privileged to host the award ceremony for this year's Karl Heinz Beckurts Prize at DESY. The Karl Heinz Beckurts foundation, which confers the prize, was established by the Helmholtz Association together with Siemens AG. Alongside the prize winner Vasilis Ntziachristos (Helmholtz Zentrum München and TU München), Ingmar Hoerr (formerly CureVac), Uğur Şahin and Özlem Türeci (BioNTech) were also honoured with a special prize. The guests included Roland Busch, CEO of Siemens, who was very impressed by the tour of the DESY site. Personally, I was touched by the first names of the award winners: Vasilis, Ingmar, Uğur, Özlem. There is no shorter or better way to show where our future lies – DESY has lived this diversity since its foundation.

This year, DESY signed the Diversity Charter ("Charta der Vielfalt"), thus becoming part of Germany's largest diversity network. DESY is actively committed to a diverse and prejudice-free working environment and to the appreciation of all employees regardless of their gender and gender identity, nationality, ethnic origin, religion or belief, disability, age, sexual orientation and identity. Here at DESY, we attach great importance to an appreciative working atmosphere, the equality of all employees and a better work–life balance.

Since September 2021, the Start-up Labs Bahrenfeld, a project jointly managed by DESY, Universität Hamburg and the City of Hamburg, has been the new place for science entrepreneurship on DESY's research campus. The variety of fields covered by our young entrepreneurs is huge, ranging from synchronisation systems to individualised tests for diagnosing cancer.

DESY and the Hamburg University of Applied Sciences (HAW Hamburg) agreed on a new strategic Cooperation for Application and Innovation (KAI) with a focus on joint research and development programmes, dual education as well as innovation and technology transfer. KAI will help shape Hamburg's structural transformation into a science and innovation metropolis in northern Germany.

Finally, I would like to mention our public outreach format "Wissen vom Fass" (Science on tap), in which scientists from Universität Hamburg and DESY explain science topics to the public and answer exciting questions from the world of research. This year, the event was purely digital, but it was just as entertaining and enjoyable for everyone as before.

In these challenging times, I would like to thank our staff and all our national and international users and partners for their valuable contribution to DESY. Please remain very careful in this tricky winter period and beyond. I wish you all the best!

Helmut Dosch
Chairman of the DESY Board of Directors

Astroparticle physics at DESY

Director's foreword

Dear friends of DESY,

The wealth of highlights that the DESY Astroparticle Physics division has achieved in this second year of the COVID-19 pandemic shows that we have managed to successfully adapt to the situation. On-site operations at DESY in Zeuthen ran smoothly with strict hygiene and distancing regulations in place, while seminars were routinely held online, attracting a broad audience. A vaccination campaign was organised on campus in the summer and, later in the year, we were even able to welcome the first school classes in person again to our School Lab.

The major event of the year was the successful organisation of the International Cosmic Ray Conference ICRC2021 in July, the main conference in the field, which was originally planned to take place in Berlin but could only be realised online due to the pandemic. The conference was organised in a huge effort by a consortium of 15 German institutes led by DESY and featured many new formats, such as a comprehensive online open-access conference archive, with the overall control centre located on the DESY campus in Zeuthen. Thanks to the novel online format, attendance was twice as high as usual, with 1800 participants across 22 time zones presenting around 1400 contributions – an impressive achievement in these difficult times.

Overall, the year 2021 was marked by key advances in several major projects pursued by the DESY Astroparticle Physics division. The IceCube-Gen2 project, an extension of the IceCube neutrino observatory at the South Pole, and the Einstein Telescope, a third-generation gravitational-wave detector planned in Europe, were accepted for inclusion in the Research Infrastructure Roadmap of the Helmholtz Association. The proposed German Centre for Astrophysics (DZA) was selected for the final round of a competition initiated jointly by the German Federal Ministry of Education and Research (BMBF) and the federal states of Saxony and Saxony-Anhalt, which aims to create two large-scale research centres, one in the Lusatia area and one in the area around Leipzig. The DZA is to bundle and process the huge data streams of future large telescopes and will also comprise a new technology centre that will develop new techniques for future observatories. In addition, the DZA pursues the option of building the Einstein telescope in the granite formations of Lusatia.

Figure 1
Artist's impression of the tidal disruption event AT2019dsg: View of the accretion disc around the supermassive black hole, with jet-like structures flowing away from the disc. The extreme mass of the black hole bends space–time, allowing the far side of the accretion disc to be seen as an image above and below the black hole.

Among the major scientific highlights of the year was the identification, through multimessenger observations by IceCube, the Zwicky Transient Facility (ZTF) in California and the space-based Swift Observatory, of two tidal disruption events (TDEs) as the likely sources of two cosmic high-energy neutrinos detected by IceCube. TDEs are caused by a star approaching a supermassive black hole too closely, so that it is torn apart by tidal forces exerted by the black hole's gravity. These rare events were now shown for the first time to emit high-energy neutrinos – a key result that demonstrates the might of the multimessenger approach.

A critical milestone was also achieved in the preparations for ULTRASAT, an astronomical satellite mission led by the Weizmann Institute of Science in Israel, whose wide-angle telescope is to image the sky in the near-ultraviolet. The critical design review (CDR) for the camera of ULTRASAT, which DESY has committed to provide, was held on the Zeuthen campus in October, paving the way for the production and integration phase. To conclude the CDR process, DESY will now respond to the comments recorded during the meeting and complete and submit the documents for final evaluation.

On the Zeuthen campus, construction work began in September for the Science Data Management Centre (SDMC) of the Cherenkov Telescope Array (CTA), the major next-generation gamma-ray observatory with telescopes located in Chile and on the Canary Island of La Palma. The SDMC will store and further process tens of petabytes of simulated and measured data gathered at both CTA telescope sites and make them accessible for analysis. It will be the scientific gateway to CTA for scientists from all over the world.

September also saw the visit of Manja Schüle, Science Minister of the federal state of Brandenburg, to DESY in Zeuthen. Taking a tour of the campus to learn about its history, current developments and ongoing and planned research projects, she was deeply impressed by the centre's research achievements in Zeuthen. Its diverse activities offer an excellent basis for the further expansion of cooperation with other research institutions and universities in the region, she added. Strategic topics, such as internal and external cooperation or the expansion of the Zeuthen campus into an international centre of astroparticle physics, were also the subject of the traditional Liebenberg Meeting, the yearly retreat of DESY in Zeuthen, which took place in person again after one and a half years of pandemic.

As Chairman of the Board of the Karl Heinz Beckurts Foundation, which aims to promote the partnership between science and business, I was honoured to present this year's Karl Heinz Beckurts Prize to the awardees at DESY in Hamburg in October. The foundation was established by the Helmholtz Association together with Siemens AG in honour of physicist and manager Karl Heinz Beckurts, who died in a terrorist attack in 1986. This year's prize went to Vasilis Ntziachristos, head of the Institute of Biological and Medical Imaging (IBMI) at Helmholtz Zentrum München and professor at Technische Universität München, while the pioneers of mRNA vaccine, Uğur Şahin and Özlem Türeci (BioNTech) as well as Ingmar Hoerr (founder of CureVac), received Medals of Honour.

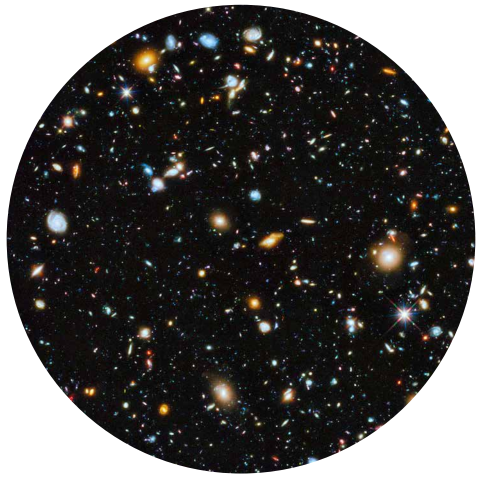
This award is not only a tribute to outstanding scientific achievements, but also emblematic of how science enables us to successfully tackle the great challenges of our time. In this spirit, let us meet these challenges together, with mutual respect and in peaceful cooperation across national borders. Many thanks to all our staff and our partners in Germany and around the globe for holding up this spirit and enabling great science in these trying times.

Christian Stegmann

Christian Stegmann
Director in charge of Astroparticle Physics

News and events

Highlights in 2021



In a small patch just a 40-millionth of the sky, the Hubble space telescope photographed about 10 000 galaxies.

January

Bruno Rossi Prize awarded to IceCube

The international IceCube collaboration, which operates the IceCube neutrino observatory at the South Pole, and its principal investigator Francis Halzen were awarded the 2021 Bruno Rossi Prize. The prize recognises the discovery of a high-energy neutrino flux of astrophysical origin and was announced at the 237th annual meeting of the American Astronomical Society (AAS). DESY is the largest European IceCube partner in the collaboration, which involves over 300 researchers from 53 institutions in 12 countries.

IceCube's first observations of high-energy cosmic neutrinos had already garnered the 2013 *Physics World* Breakthrough of the Year Award. The Bruno Rossi Prize is conferred annually by the High Energy Astrophysics Division of the AAS for significant contributions to high-energy astrophysics, with particular emphasis on recent, original work.

Rafael Porto receives Buchalter Cosmology Prize 2020

For groundbreaking work on the origin of structure in the universe, DESY leading scientist Rafael Porto was awarded the Buchalter Cosmology Prize 2020 together with his colleague Daniel Green from the University of California San Diego, USA. Their study "Signals of a Quantum Universe" was honoured at the annual meeting of the AAS for proposing a novel test to prove the quantum origin of the large-scale structure we observe in the cosmos today.

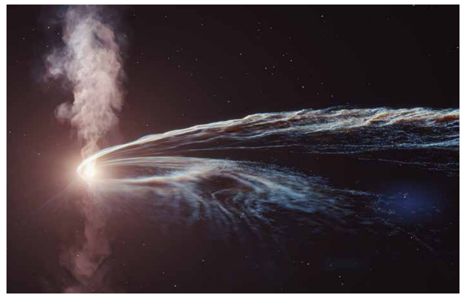
Together with Green, Porto noticed that a correlation test that looks for three-point correlations instead of two-point correlations might deliver evidence that the cosmic structure could originate from minute quantum vacuum fluctuations in the early universe. The proposed method is the first within practical reach, as such three-point correlations between (three) galaxy clusters could be observed with the next generation of astrometry satellites, such as the European Space Agency (ESA)'s Euclid, providing the necessary data for the analysis.

The Buchalter Cosmology Prize is awarded annually for groundbreaking theoretical, observational or experimental work in cosmology that has the potential to produce a breakthrough advance.

February

First neutrino from tidal disruption event identified

An international team team led by DESY scientists successfully traced back a cosmic high-energy neutrino detected by IceCube to a tidal disruption event (TDE), an event in which a star approaches a supermassive black hole too close and the gravitational pull from the black hole tears it apart. The finding provides evidence that these little-understood cosmic catastrophes can be powerful natural particle accelerators. The observations also demonstrate the power of exploring the cosmos using a combination of different "messengers", such as photons and neutrinos, also known as multimessenger astronomy. The team reported its findings in the journal *Nature Astronomy*. For details, see the scientific highlight report on page 32.



Artist's impression of the tidal disruption event AT2019dsg

April

DZA

Science initiative champions German Centre for Astrophysics in Lusatia

An initiative of leading scientists is advocating the establishment of the German Centre for Astrophysics (Deutsches Zentrum für Astrophysik, DZA) in the Lusatia area. The initiative, which is supported by the Max Planck Society, the Leibniz Institute for Astrophysics Potsdam, DESY and the Technical University of Dresden, submitted its proposal for the new research centre to the ideas competition "Wissen schafft Perspektiven für die Region!" organised by the German Federal Ministry of Education and Research (BMBF) and the federal states of Saxony and Saxony-Anhalt. The DZA could have a lasting impact on the structural change in Lusatia, create jobs in various fields and form collaborations with research centres in the Czech Republic and Poland. It would be a milestone for research and technology in this region in the centre of Europe.

The DZA proposal was eventually selected in July 2021 for the first funding phase, together with five other project proposals. The full proposal was then to be submitted at the end of April 2022.

May

#Impfluencer

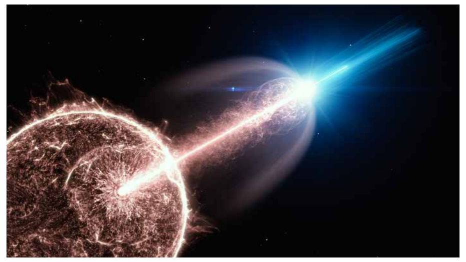
In early 2021, vaccination of the German population against COVID-19 had just begun, and some scepticism still prevailed among parts of the public. To counteract this, DESY in Zeuthen created a short movie under the hashtag "Impfluencer" (from the German verb "impfen", i.e. "to vaccinate"), in which various employees presented their arguments in favour of vaccination. The overall theme was that people should get vaccinated to help others.

#Impfluencer: DESY staff members spoke out in favour of vaccination.

June

Observation challenges theory of gamma-ray bursts

An international team of scientists including researchers from DESY gained the best view yet of the brightest explosions in the universe: The High Energy Stereoscopic System (H.E.S.S.) observatory in Namibia recorded the most energetic radiation and longest gamma-ray afterglow of a gamma-ray burst (GRB) to date. The observation challenges the established idea of how gamma rays are produced in these colossal stellar explosions, which are the birth cries of black holes, as the team reported in the journal *Science*. The comparatively short distance to the gamma-ray burst allowed detailed measurements of the afterglow's spectrum, revealing curious similarities between the X-ray and very-high-energy gamma-ray emission of the burst's afterglow. For details, see the scientific highlight report on page 28.



Artist's impression of a relativistic jet from a gamma-ray burst, breaking out of a collapsing star and emitting very-high-energy photons

July

Installation of first antenna stations at RNO-G

Summit Station is located in the middle of the Greenland ice sheet.

The Radio Neutrino Observatory Greenland (RNO-G) is a pioneering project that relies on a new method of detecting very-high-energy cosmic neutrinos using radio antennas. The scientists involved in the project installed the first antenna stations in and on the ice at Summit Station in summer 2021. Overall, they plan to set up 35 antenna stations, each 1.25 km apart, around the station on the Greenland ice sheet. Because neutrinos are so difficult to detect, however, even when the installation is completed, it could take months before the observatory records a signal. For details, see the scientific highlight report on page 20.

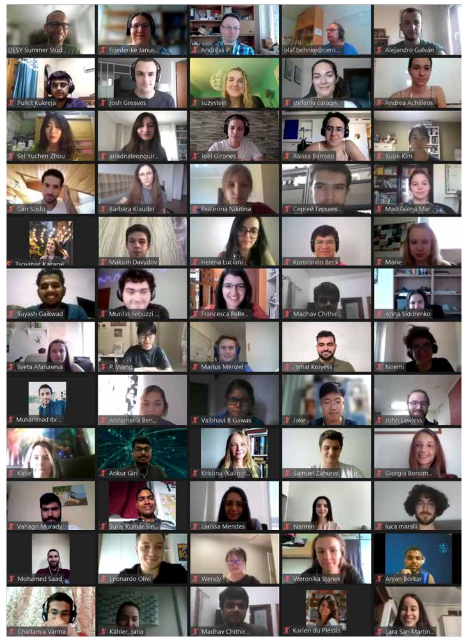
International Cosmic Ray Conference 2021

The 37th International Cosmic Ray Conference ICRC2021, the main conference in the worldwide astroparticle physics community, was held in Germany in July. It was organised by a consortium of 15 German institutes led by DESY. Originally planned to take place in Berlin, it could only be realised as an online conference due to the COVID-19 pandemic. Personal interactions were thus hampered, but, compared to previous years, the event drew a much bigger audience due to far lower costs and time demands for participants and a large (and lasting) open-access archive of sessions, talks and papers. The organisation, technical setup and smooth operation benefitted greatly from the DESY infrastructure and its dedicated staff. For details, see the report on page 18.

First virtual summer student programme

Almost 80 students of physics and related natural sciences took part in the DESY summer student programme 2021. The majority of them participated remotely using online tools due to the COVID-19 pandemic, while seven students were integrated in the research groups on the DESY campus in Hamburg.

The DESY summer student programme has been running for several decades and is one of the largest of its kind in Europe, offering insights into particle physics, photon science, accelerator technology, computing and astroparticle physics. The programme includes a lecture series introducing the main areas of research at DESY. Because of the online nature of the 2021 event, the lecture programme was open to everyone, resulting in one of the largest attendances on record with several hundred participants from around the globe.



In 2021, the "summies" were given a virtual welcome.

August

DESY again first in city cycling event

In August, the DESY Zeuthen team covered more than 13 200 km in 21 days during the "Stadtradeln" city cycling campaign in the Dahme-Spreewald region. Whether it was the daily ride to the campus, the bike tour around the home office or ambitious weekend excursions, every kilometre counted. The team thus successfully defended its titles from 2019 and 2020 as the largest team (69 participants) with the most kilometres in the region. The effort saved almost 200 t of CO_2.

DESY signs Diversity Charter

By signing the Diversity Charter ("Charta der Vielfalt"), DESY became part of Germany's largest diversity network. The Diversity Charter is an initiative that aims to promote diversity in companies and institutions. Since its inception in 2006, it has been signed by over 4500 organisations with a total of more than 14.6 million employees.

DESY stands for open-mindedness and tolerance. It is committed to a diverse, prejudice-free working environment and appreciates all employees regardless of their gender and gender identity, nationality, ethnic origin, religion or belief, disability, age, sexual orientation and identity.

charta der **vielfalt** UNTERZEICHNET

September

DESY participates in apprenticeship fair

DESY is not only an excellent place for research, but also one of the most important vocational training centres in the Dahme-Spreewald region. It offers training as an IT specialist, electronics technician and industrial technician. DESY regularly takes part in apprenticeship fairs to promote and inform the public about its training and employment opportunities. In 2021, DESY in Zeuthen welcomed six new apprentices, bringing the total number of trainees on the Zeuthen campus to 18.

School Lab back to life

New explanatory video on the subject of "vacuum"

After one and a half years in hiatus, the DESY School Lab in Zeuthen slowly picked up speed again. Starting with one event per week, school classes could come to DESY again, conduct experiments and learn everything about the topic of "vacuum". The School Lab team had used the pandemic-related break to produce a number of videos, which are available on the DESY website.

QR code to the School Lab videos:

Diversity Round Table celebrates first anniversary

The DESY Diversity Round Table takes a bottom-up approach to tackling diversity, equity and inclusion issues at DESY. Originally launched in 2020 in response to the worldwide #BlackLivesMatter movement, the initiative addresses diversity dimensions such as ethnicity, gender, sexual orientation, ability and more.

Highlights of the Round Table's first year of work comprised, among other things, the initiation of regular trainings on unconscious bias by DESY's continuing education department and the increased social-media presence of DESY on international STEM minority recognition days. Plans for 2022 include organising a cinema club to reduce unconscious bias. All DESY employees in Zeuthen and Hamburg are welcome to get involved (for information, contact diversity-roundtable@desy.de).

September

Start of construction work for CTA Science Data Management Centre

After a long period of preparation, construction work started on the DESY campus in Zeuthen for the Science Data Management Centre (SDMC) of the Cherenkov Telescope Array (CTA), the next-generation gamma-ray telescope. The SDMC will be in charge of many science operations and make the CTA data available to the worldwide community. As the gateway to the scientific harvest of CTA, the centre will attract researchers from all over the world. The new building will decisively shape the campus, as parts of it will be accessible to the public and foster interaction with the local community. In addition to the actual SDMC facilities, it will also house a new canteen for the campus and several meeting rooms.

Start of the CTA SDMC construction work

Brandenburg's Science Minister visits DESY in Zeuthen

Manja Schüle, Science Minister of Brandenburg, and Christian Stegmann, DESY Director in charge of Astroparticle Physics, on the Zeuthen campus

The Minister for Science, Research and Culture of the German federal state of Brandenburg, Manja Schüle, visited the DESY site in Zeuthen and learned about current and upcoming plans for the campus. After the official welcome by DESY Directors Helmut Dosch and Christian Stegmann, she was guided around the campus and introduced to the various science topics. These ranged from the PITZ accelerator beamline to the construction site of the new Science Data Management Centre for the forthcoming CTA gamma-ray telescope. The minister stated that she was „deeply impressed by the excellent scientific output at the DESY Zeuthen site" and that the diverse activities on the campus are a good basis for future cooperation with other research facilities and universities in the region.

October

Election of women's representatives at DESY in Zeuthen

Ulrike Schulz and Silvia Alessandria (deputy) were elected as the new women's representatives at DESY in Zeuthen. They represent the equal opportunities officer in Hamburg and thus participate in all job interviews to ensure that women are not disadvantaged. In addition, they deal with issues such as equal opportunities, work–life balance and sexual harassment and are available for personal consultations.

Ulrike Schulz (l.) and Silvia Alessandria (r.), the new women's representatives at DESY in Zeuthen

Third-year celebration of Postdoc Network Zeuthen

In collaboration with the COAST career centre for postdocs at DESY, the Postdoc Network Zeuthen invited all postdoctoral researchers on campus to a barbecue by the lake. The COAST career counsellor at DESY in Zeuthen presented the workshop programme, followed by a feedback discussion on how to further tailor the programme to the needs of postdocs. With this event, DESY in Zeuthen celebrated the third year of the self-organised postdoc network, the only such network on the entire DESY campus.

November

Funding for centre for quantum computing

The German federal state of Brandenburg is supporting research and development of applications of novel quantum computers at DESY in Zeuthen. A new Centre for Quantum Technology Applications (CQTA) is to be created on campus, with the help of 12.8 million euros in funding to be paid over a period of five years from the Future Investment Fund of the state of Brandenburg. The centre will give researchers from DESY, along with external partners in research and industry, access to quantum computers in order to perform calculations on existing problems and to design and optimise new applications for quantum computers.

Quantum technologies and particularly quantum computers are currently undergoing a rapid development worldwide and promise entirely new possibilities for research. With its scientific excellence and expertise, DESY and CQTA will not only be actively participating in this development, but also helping to shape it.

10$^{\text{th}}$ anniversary of International Cosmic Day

Organising the 10$^{\text{th}}$ International Cosmic Day at DESY in Zeuthen

In 2021, the International Cosmic Day (ICD) took place for the 10$^{\text{th}}$ time. Many of the people from research and school involved in the ICD over the years sent congratulations on the anniversary. The number of young people participating increased once again compared to previous years, with 6800 students from 17 countries taking part this time.

From the very beginning, the ICD has been organised by DESY in Zeuthen, in cooperation with the "Netzwerk Teilchenwelt" network in Germany as well as on an international level with the International Particle Physics Outreach Group (IPPOG), the Fermilab research centre in the USA and its teacher network QuarkNet. Over the years, many supporters have been added and intensive partnerships have been formed with networks and research institutes worldwide, so that the ICD has been able to establish itself excellently over the years.

December

Astroparticle physics prize winners from DESY

In 2021, four young researchers from DESY in Zeuthen were honoured for their scientific output. Richard Naab received the Physics Study Award 2021 of the Physikalische Gesellschaft zu Berlin, a regional association of the German Physical Society (DPG), for his master thesis. Gregor Kälin won the Best Paper Award from the Cluster of Excellence Quantum Universe for his seminal contributions to the derivation of "Conservative Dynamics of Binary Systems to Third Post-Minkowskian Order from the Effective Field Theory Approach" to the two-body problem in gravity. Konstancja Satalecka was honoured with the Best Talk Award at the 37$^{\text{th}}$ ICRC in July for her work on "Searching for VHE gamma-ray emission associated with IceCube neutrino alerts using FACT, H.E.S.S., MAGIC, and VERITAS", and Alexander Trettin received the IceCube Impact Award for key contributions to the treatment of systematic uncertainties in oscillation analyses and for his leading role in promoting diversity, equity and inclusion within the IceCube collaboration.

Prize winners from DESY (clockwise from top left): Richard Naab, Gregor Kälin, Alexander Trettin and Konstancja Satalecka

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.

Experiments, theory, projects and infrastructures

Artist's impression of the tidal disruption event AT2019dsg

Progress towards the IceCube Upgrade

First look at new multi-PMT digital optical modules

The IceCube neutrino observatory at the South Pole has been detecting GeV to PeV neutrino interactions for over a decade, providing unique knowledge about the characteristics of astrophysical neutrinos and precise measurements of fundamental neutrino properties. To improve these studies, the IceCube Upgrade will be deployed in 2025/2026. For this upgrade, over 800 new devices will be installed in the ice, including special calibration devices to reduce systematic errors and newly designed optical modules with improved photon detection capabilities compared to the original IceCube sensors. One sensor – the multi-PMT digital optical module (mDOM) – has been developed with significant investment from DESY, the Karlsruhe Institute of Technology (KIT) and German universities. The first modules have been produced at DESY, and studies to validate the design are under way.

IceCube is a Cherenkov neutrino detector buried deep in the glacial ice at the South Pole. Over 5000 digital optical modules (DOMs) span a volume of 1 km^3, each ready to capture a flash of blueish light that signals a rare neutrino interaction. At the GeV energy scale, where the flux is dominated by atmospheric neutrinos, studying their flavour as a function of energy and how far they have propagated (determined by their direction) has led to the most precise measurements of atmospheric neutrino oscillations ($\nu_\mu \rightarrow \nu_\tau$) [1]. At the TeV–PeV scale, IceCube has firmly established the existence of an astrophysical neutrino flux and identified blazars and tidal disruption events as promising sources of a few events [2, 3] (see page 32). Researchers at DESY play a leading role in measurements performed in both of these energy regimes.

Despite significant progress in understanding both atmospheric and astrophysical neutrino properties, there is still much to learn. To enhance neutrino detection across the full energy range of interest and improve our understanding of neutrinos and their sources, IceCube will receive an upgrade.

The IceCube Upgrade

Seven new, densely instrumented cables will be deployed in the centre of the existing IceCube DeepCore array (Fig. 1) [4]. The layout has been optimised for improved resolutions around 10–60 GeV, where the atmospheric oscillation signal is strongest. At these energies, neutrino interactions produce very little light, making their detection and reconstruction challenging. As a fill-in to the existing 6-megatonne DeepCore volume, the Upgrade will collect more light from each interaction and improve detector performance. The Upgrade will feature multipixel optical module designs and significantly increased optical module density. The inter-module spacing will be about a factor of 2 closer than the modules in DeepCore, and most will be deployed between 2150 m and 2430 m depths, where the ice is clearest.

The Upgrade will push the threshold for neutrino detection down to 1 GeV and increase the rate of detected neutrinos by a factor of 2–4, depending on the type of interaction. Studies estimate that the energy resolution will improve by a factor of 2 and the zenith resolution by a factor of 3–4. This will enable measurements of the neutrino mass splitting Δm^2_{32} with higher precision than that of current long-baseline accelerator neutrino experiments. The Upgrade will also record an unprecedented number of ν_τ interactions with an uncertainty of 10% on the number of detected events within the first year of operation, providing a model-independent probe of unitary mixing among the known neutrino flavours [1, 4].

Several calibration devices will also be deployed that can be used to characterise the entire IceCube volume. New calibrations will improve our ability to reconstruct neutrino interactions in the future and can also be applied to the existing 10+ years of IceCube data to elicit even more information from events already recorded.

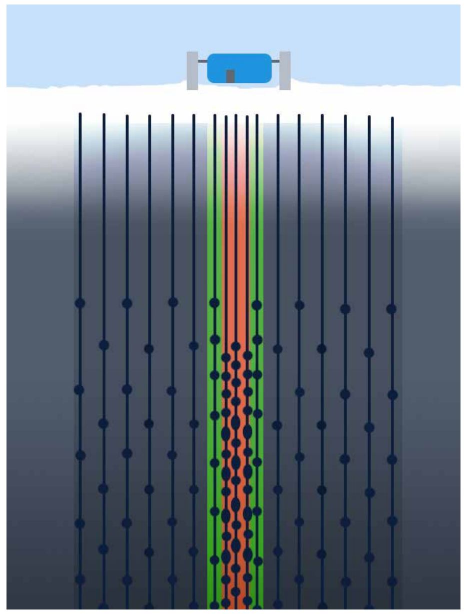


Figure 1
Artist's impression of the IceCube Upgrade (red) compared to the existing IceCube (dark blue) and DeepCore (green) arrays

Figure 2
First prototype mDOM being joined in the DESY mDOM integration lab

Figure 3
Two mDOMs being prepared for testing inside the new walk-in freezer on the DESY campus in Zeuthen

Multi-PMT digital optical modules

The optical sensors for the Upgrade have been designed to maximise their photosensitive area while retaining excellent time resolution. The large photosensitive area collects as many photons as possible from the dim GeV neutrino interactions, while the timing resolution drives the direction reconstruction and particle identification. Two main sensor types have been developed for the Upgrade, and both will be installed in about the same numbers. The Japanese D-Egg sensor [5] comprises two 8" photomultiplier tubes (PMTs) that point up- and downwards. The mDOM has been developed and will be produced by DESY and the German university groups in the IceCube collaboration. It features 24 3" PMTs in a glass pressure housing, providing 4π solid-angle coverage and improved timing resolution compared to large-area PMTs.

The mDOM (Fig. 2) was inspired by the optical sensor of the KM3NeT detector [6]. The design was adapted to meet the unique needs for deployment in the Antarctic glacier, and the sensor diameter was reduced for installation in bore holes. To achieve this, shorter PMTs were developed in cooperation with the PMT manufacturers. The mDOM readout and communication electronics were developed at DESY to capture full waveforms from all PMTs and stamp the photon arrival time with nanosecond precision. The output signal from each PMT is digitised at 120 MHz to measure the total charge and late photons delayed by scattering in the ice or decaying secondary particles. The arrival time of the first photon is determined from a discriminator whose output is sampled with 960 MHz in a field-programmable gate array (FPGA). All data are preprocessed in the mDOM in an on-board ARM CPU. Each mDOM also contains ten fast LED flashers for calibration and three cameras to evaluate the optical properties of the ice after deployment. An mDOM consumes about 10 W of electric power during normal operation.

We have verified that the mDOMs meet all the design requirements set by the Upgrade project, and the development phase will be completed with a final design review in April 2022. The series production will start in the summer; 225 mDOMs will be integrated at DESY and 205 at Michigan State University in the USA. Since the mDOMs will be frozen into the ice and cannot be accessed after deployment, quality control is essential. During final acceptance testing, before being shipped to Antarctica, each mDOM will be operated in a freezer for three weeks under realistic conditions (Fig. 3).

From the Upgrade to IceCube-Gen2

The Upgrade is also a step towards realising the future IceCube-Gen2 project [7], which foresees to expand the detector volume for astrophysical neutrinos. Four boreholes will be drilled down to 2600 m to characterise the ice at this unexplored depth and ensure that it is suitable for hosting new optical modules. In addition, production and testing facilities for the Upgrade modules can be repurposed for IceCube-Gen2. Thus, the Upgrade promises to both improve IceCube science and build useful expertise and infrastructure for future activities at DESY.

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37th International Cosmic Ray Conference

Updating scientific results in astroparticle physics

The 37th International Cosmic Ray Conference (ICRC, the main astroparticle physics conference) was held in Germany in July 2021 [1]. It was organised by a consortium of 15 German institutes under the leadership of DESY. Originally planned to take place in Berlin, it could only be realised as an online conference due to the COVID-19 pandemic. Personal interactions were thus hampered, but participation was twice as high as at previous meetings, thanks to the far lower costs and time demands and a large (and lasting) open-access archive of sessions, talks and papers. The organisation, technical setup and smooth operation benefitted greatly from the DESY infrastructure and dedicated staff. Despite COVID-19-related limitations, a wealth of interesting scientific results was reported.

Figure 1
Impressions from ICRC mission control at DESY in Zeuthen

The conference

The ICRC is the main, biannual conference of the IUPAP Commission C4: Astroparticle Physics and covers the topics cosmic-ray physics, gamma-ray astronomy, neutrino astronomy and neutrino astrophysics, dark-matter physics as well as solar and heliospheric physics. For the first time, the conference also featured the topics multimessenger astrophysics as well as outreach and education in astroparticle physics. Owing to the online conference format, only a short timespan was suitable for scheduled sessions for all participants across 22 time zones. These were used for plenary talks (reviews, highlights and summaries). It was decided to pre-record all contributions and upload them to the conference archive where they could be viewed from the start of the conference.

There were also 60 parallel discussion sessions at less central times on topical physics subjects, with rather short mentions of relevant contributions, but nevertheless extensive, moderated discussions. These sessions turned out to be very popular. In two virtual poster sessions, small-group discussions between presenters and interested participants were offered. In total, 1800 participants presented about 1400 contributions. Conference materials and proceedings articles can be found in [2, 3].

Selected results

Multimessenger (MM) astrophysics has long been hailed as a major advance in our understanding of high-energy cosmic particle accelerators. In recent years, exciting experimental results have made this increasingly evident. MM astrophysics relies on coincident observations of variable or flaring objects by means of messengers that travel mainly undeflected from source to observer (photons from radio waves to ultrahigh-energy (UHE) gamma rays, neutrinos, UHE cosmic rays and gravitational waves). Coincident observations require fast and efficient real-time alerting systems and quick changes in observing schedules through close cooperation between different instruments and teams. Exciting results have been achieved on transient objects, such as flaring blazars, active galactic nuclei and tidal disruption events. First coincidences have even been observed of neutrinos with gamma rays and gravitational waves with gamma rays. With the advent of more sensitive instruments, the latter two in particular promise increasing event rates with many more coincident observations and discoveries.

Gamma-ray astronomy has continued its boom with enormous progress in theory and observation. Highlights were the discovery of numerous galactic PeVatrons (accelerators of cosmic rays to PeV energies) and transients, such as gamma-ray bursts at very high energies. The Large High Altitude Air Shower Observatory (LHAASO), although not yet fully built, has already been taking data and brought the count of PeVatrons to 14 (!). The MAGIC and H.E.S.S. telescopes unambiguously detected first gamma-ray bursts using the Cherenkov technique (see page 28). Ground-based instruments thus make astronomy at the highest energies currently very exciting. With the High Altitude Water Cherenkov (HAWC) Observatory operating, the LHAASO construction being completed and construction of the Cherenkov Telescope Array (CTA) starting soon at the northern and southern sites, as well as further plans for the Southern Wide-field Gamma-ray Observatory (SWGO), exciting times lie ahead for galactic astrophysics at very high energies.

Many space-based gamma-ray missions reported results too. The landscape has matured, with numerous gamma-ray telescopes now in space and in the pipeline and new ones being proposed. The diversity of telescopes brings many opportunities, but also challenges in unifying tools and combining data.

Neutrino astronomy provides exciting results, but is still limited by very low statistics. The neutrino field is booming with new ideas for detectors with better sensitivity. The community is becoming ready for many more neutrinos. The IceCube observatory is still the most sensitive instrument (Fig. 2), and DESY is playing a major role in its planned extensions.

In the direct measurement of cosmic rays (CRs), the main progress has been in investigating and modelling CR spectra better and studying their impact on their environments. New measurements are pushing the boundaries in energy and extending the reach in species (i.e. their charge). The picture emerging is significantly more complicated than thought even a decade ago, with many spectral features between 1 GeV and the CR "knee" at a few PeV. These new data will be extremely valuable for exploring the origin of CRs. On the theory side, one main effort is to bridge the gap between first-principles simulations (particle-in-cell, PIC) and other approaches (mostly magnetohydrodynamics, MHD) for studying the dynamics of sources on larger, sometimes dynamical time scales. The backreaction of CRs is important well beyond the field amplification in non-relativistic shocks. High-precision future observations will provide an ever-richer picture of galactic CRs.

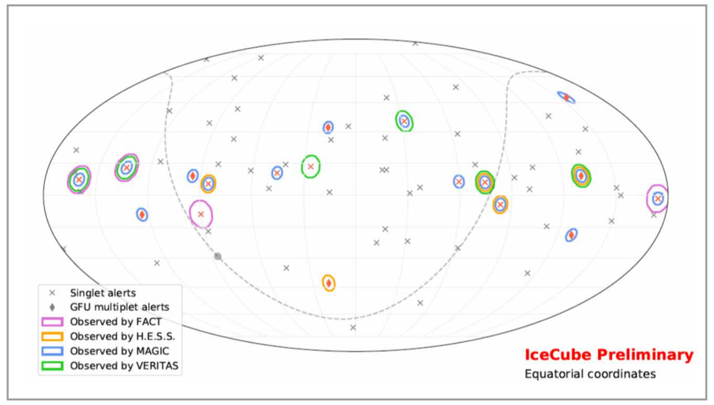

Figure 2
IceCube alerts followed up by gamma-ray observatories (October 2017 to March 2021) [5]

With its involvement in gamma-ray and neutrino telescopes (Fig. 2 and [5]), its theoretical work on source emission mechanisms in cosmic accelerators and its expertise in alerting and time domain physics, DESY is a prime player in MM astrophysics.

For a quick overview of the key results from all topics, including those not mentioned here, see the rapporteur talks either on the proceedings webpage or in the ICRC2021 conference archive [4].

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[4] Rapporteurs talks (topic summaries): https://pos.sissa.it/395/, articles 044–051 or recordings of the talks in the conference archive: https://indico.desy.de/event/27991/contributions/ (search for "rapporteur")
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First stations of RNO-G installed

Searching for neutrinos in the Greenland ice

In summer 2021, installation of the Radio Neutrino Observatory (RNO-G) started at Summit Station in Greenland. RNO-G targets the discovery of astrophysical neutrinos above 10 PeV energy, exploiting the radio emission that follows a neutrino interaction in the ice. DESY hosts one of the largest groups in the RNO-G collaboration, providing the main data centre, simulation, calibration, engineering and analysis support. Two DESY PhD students joined the successful deployment campaign for the first three stations. The stations are fully autonomous, operate on renewable energies and search for small signals just above the thermal noise level. After completion in 2024, RNO-G is designed to operate for at least five years.

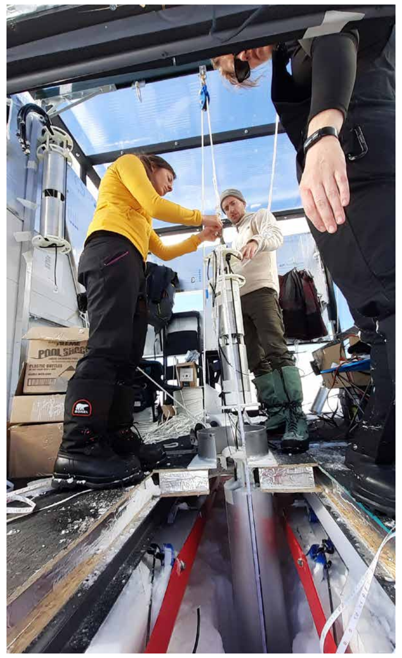

Figure 2
Deployment of RNO-G antennas in a borehole. The team is connecting the signal cables of an antenna that is being lowered into the ice. Two types of antennas are visible within the deployment shed that protects the team from the environment during installation.

Neutrinos of EeV energies
Since the discovery of astrophysical neutrinos by the IceCube experiment at the South Pole and first multimessenger coincidences, it has become clear that detectors with even larger effective volumes are required to find the sources of ultrahigh-energy cosmic rays. These are the elementary particles of highest known energy, and since their discovery, their origin has been a mystery. As neutral particles, neutrinos generated either in the sources of the cosmic rays or during their propagation towards Earth can be used to tag these sources.

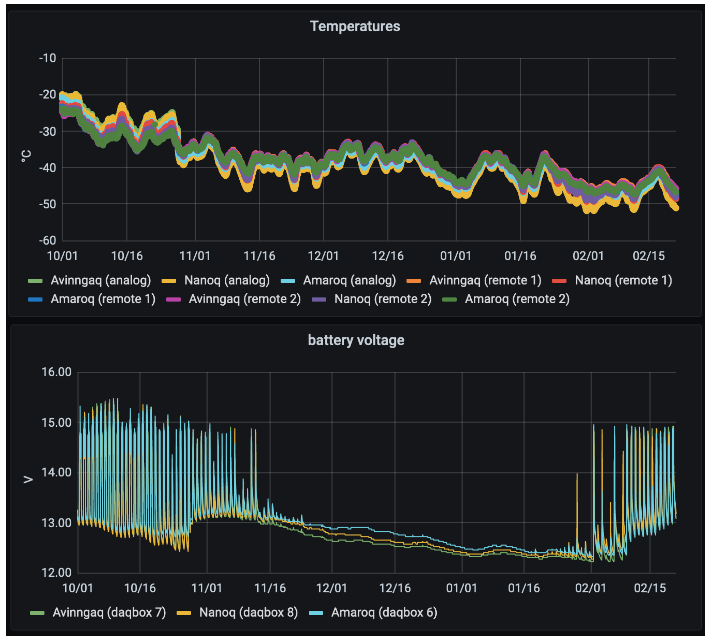

Figure 1
Monitoring of the RNO-G stations. The stations are performing as expected at temperatures down to -50°C through the polar night. From mid-January, the first charging peaks from the solar panels indicate that the winter has come to an end. Full science operation is resumed once the batteries are fully charged.

Exploiting the radio emission following a neutrino interaction in combination with the kilometre-scale attenuation length of polar ice allows for the construction of large and sparse neutrino detectors at moderate costs. The energy threshold in the PeV regime provides an interesting complement to the optical detection as used in IceCube.

RNO-G
RNO-G is the first large-scale implementation of a neutrino radio detector [1]. It surpasses previous installations in size by a factor of more than 5 and combines the technology experience of four smaller installations that provided the proof of principle.

The temperatures in Greenland (Fig. 1) and the need to operate autonomous stations pose the technological challenge of constructing robust, easy-to-install, low-power (25 W), broadband (100 MHz – 1 GHz) and fast-sampling (3 GHz) electronics. At the heart of RNO-G is a phased array trigger that optimises the experiment for an effective volume for neutrino detection. It is combined with three different antenna types that capture the different electric field polarisations and are needed to reconstruct the neutrino trajectory. As the first of its kind, RNO-G operates its own LTE wireless communication network and has access to real-time data transfer. DESY acts as the main data centre and receives a fraction of the recorded data in real time, laying the foundation for future real-time alerts. Such alerts have already been instrumental in identifying tantalising sources, with leading contributions from DESY [2].

The first three stations were installed in July 2021 (Fig. 2). The 100-metre-deep holes for RNO-G are drilled with a custom-made drill from the British Antarctic Survey (BAS) that was constructed for the project. The drill is both fast (one hole per shift) and provides comparatively wide (23 cm) holes, which are required for the installation of the sensitive antennas. The first field test of the drill took place in 2021, as other opportunities had to be cancelled owing to the COVID-19 pandemic. The drill will be further optimised in the coming seasons to allow for (almost) automatic drilling, which will reduce the number of operators needed – an important milestone, given that the deployment team was the largest science team at Summit Station in the 2021 season.

After the holes are drilled, the stations are installed by a team of four within three days and immediately put into operation. The 2021 season was also used to perform important measurements of the ice properties, which feed into the neutrino simulations [3].

With nominally five years of operation, RNO-G will target optimistic scenarios of astrophysical sources, such as close neutron star mergers, and the regime in which the cosmic-ray composition is relatively light, as suggested by data from the largest northern air shower array, the Telescope Array in Utah, USA. In addition to searching for neutrinos [4], RNO-G is designed to provide insights into various topics, such as the muon content of air showers, ice properties, tribo-electric effects and the operation of long-lived wind turbines in polar regions.

With its minimal operation costs thanks to the fully renewable power sources (solar panels and wind turbines), it is envisionable to continue operating RNO-G beyond the initial five years. There are currently no concrete plans for an array with rivalling sensitivity in the northern hemisphere.

Towards IceCube-Gen2
Even with RNO-G in operation, the neutrino flux may be too small to be detected – or it may stem from (transient) sources that are outside of the field of view of this northern detector. This is reason enough to consider future steps already today.

The largest current neutrino detector, IceCube, is gearing up for a next generation, IceCube-Gen2, which would provide excellent complementarity in the field of view. In addition to an extension of the very successful optical component and in order to better cover the highest energies, IceCube-Gen2 is also baselined to include a radio array. This array will be heavily based on the experience with and the technology of RNO-G, but improved in sensitivity by an order of magnitude. The IceCube-Gen2 collaboration is currently in the process of preparing a technical design report, in which DESY scientists play leading roles in various functions, such as project scientist as well as project managers at the L2 and L3 levels.

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Discovery of gamma rays from a recurrent nova

H.E.S.S. reveals efficient cosmic-ray acceleration in RS Ophiuchi’s 2021 outburst

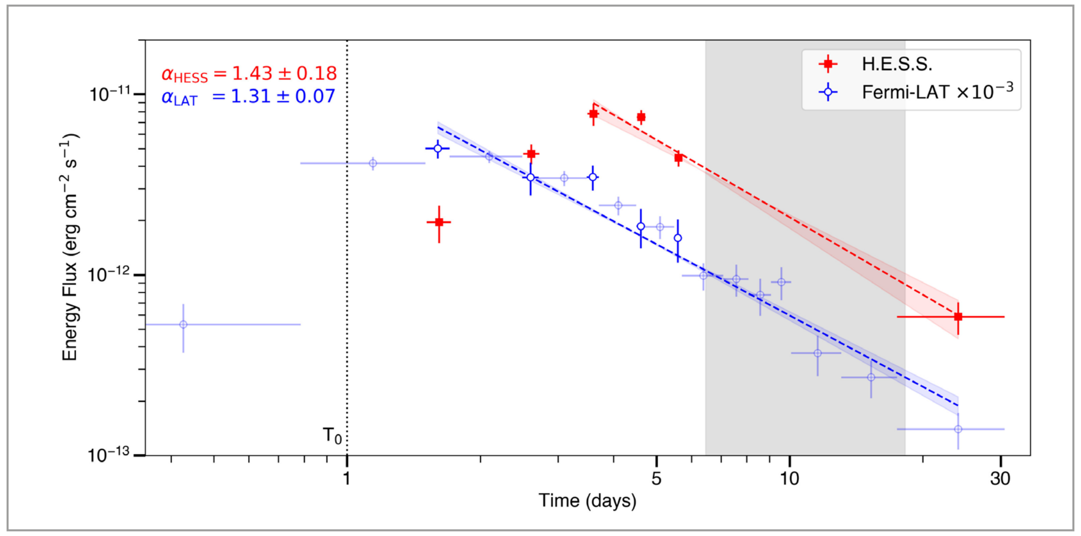

Figure 2
H.E.S.S. and Fermi-LAT light curves of the RS Oph 2021 outburst. The decay rates in H.E.S.S. (red squares) and Fermi-LAT (blue circles) are in agreement with each other, suggesting a common origin. T_0 marks the time of the peak magnitude in the optical waveband.

In summer 2021, a new apparent star dotted the night sky as the well-known recurrent nova RS Ophiuchi erupted into a bright spectacle. This transient astrophysical phenomenon was closely observed by astronomers and astrophysicists all over the world. The international collaboration operating the H.E.S.S. gammaray observatory in Namibia, in which DESY is strongly involved, counted among the observers. In its observations of the nova, H.E.S.S. not only confirmed gamma-ray emission up to TeV energies from a galactic transient source for the first time, but also managed to resolve the evolution of the particle acceleration over a time frame of four weeks. This discovery breaks the record on nova energetics and offers new insights into cosmic-ray acceleration at the theoretical limit.

The recurrent nova RS Ophiuchi
Novae are astrophysical transient phenomena arising from binary systems consisting of a white dwarf (WD) and a low-mass companion star. Such binary systems typically have short orbital periods, on the order of a few hours, meaning that the stars will come close to each other very often. The more massive WD, when close enough, will consistently accrete matter from its companion star. The accretion process forms a dense layer of hydrogen on the WD’s surface. As the hydrogen layer grows, the pressure and temperature at the bottom of the layer keep rising until a critical limit is reached. A thermonuclear reaction is then triggered, which blows away matter from the WD in the form of a rapidly expanding shell, similarly to a supernova. The nova is then seen as a bright outburst of light in the sky, which disappears after a few weeks.

The brightest novae are visible with the naked eye and appear as if a new star came and went. Recurrent novae (RNe) are known to experience multiple such eruptions every few years. The well-known RN RS Ophiuchi (RS Oph) was first recorded to erupt in 1898 and has erupted every 9 to 26 years since [1]. RS Oph underwent its latest eruption in August 2021. At its peak, the nova reached a visual magnitude of about 4.5, far higher than the binary’s usual magnitude of about 12.5. The eruption was well noticed by hobby astronomers and reported to the wide network of astronomers and astrophysicists [2], triggering numerous follow-up observations worldwide.

H.E.S.S. observations of the 2021 outburst
The High Energy Stereoscopic System (H.E.S.S.) is an array of imaging atmospheric Cherenkov telescopes (IACTs) situated in Khomas Highland, Namibia, which observes the night sky in the very-high-energy (VHE) gamma-ray regime of few tens of GeV to few tens of TeV. During the rise of the RS Oph 2021 outburst, telescopes across multiple wavebands reported heightened flux levels coincident with the nova. Once the nova was reported as detected by the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope [3], the H.E.S.S. telescopes rapidly responded by conducting a follow-up observation. The first night of observations by H.E.S.S. on 9 August led to a clear detection of the nova, establishing, for the first time in history, RNe as galactic transients reaching TeV energies.

The detection by H.E.S.S. was quickly communicated to the world, informing everyone of the historical event and prompting further follow-up observations [4]. H.E.S.S. then continued to take data of the RS Oph outburst for four more consecutive nights, resulting in five nights with clear detection of the nova (Fig. 1, left). Observations were halted after 13 August as the moon became too bright, preventing further observations with the telescopes. Data taking continued afterwards from 25 August to 10 September, resulting in about two more weeks of data about 17 days after the initial burst. The data taken over the two weeks showed that the outburst was much fainter in gamma rays, but still detectable (Fig. 1, right). The light curves derived over the observed time frame (Fig. 2) show a consistency in the temporal decay between the Fermi-LAT waveband (O(1 GeV)) and the H.E.S.S. VHE waveband, hinting at a common origin.

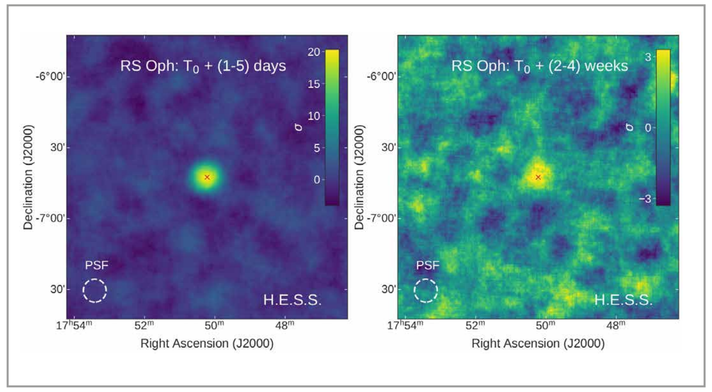

Figure 1
Significance maps of RS Ophiuchi as seen by H.E.S.S. The two panels show the detection significance above 100 GeV for early (left) and late-time (right) H.E.S.S. observations. T_0 marks the time of the peak magnitude in the optical waveband. The dashed white circles indicate the point spread function (PSF).

Interpretation
The H.E.S.S. detection of VHE gamma rays in the RS Oph 2021 outburst has strong implications for the physics in the environment of RNe. As the hydrogen layer accreted by the WD detonates and expands, it crashes into the stellar wind of the companion star. The interaction between the expanding shell and the companion wind creates an astrophysical shock. In shocks such as these, the kinetic energy of ejected matter is converted into acceleration of cosmic rays, such as protons, electrons and heavier nuclei, through a process known as diffusive shock acceleration. Accelerated particles subsequently cool down through interactions with matter and magnetic fields, which in the end leads to the emission of photons over several wavebands. The detection of gamma rays in particular gives insight into the efficiency of the particle acceleration.

The efficiency of acceleration is key to understanding the origin of the cosmic rays that constantly surround us. By comparing the energetics derived from important parameters, such as wind speeds and mass loss rates, with the measured maximum gamma-ray energies, H.E.S.S. was able to confirm that the efficiency of particle acceleration in the RS Oph 2021 outburst reached the theoretical limit. Additionally, the changes of the nova environment throughout its evolution are reflected in the observed gamma-ray emission (Fig. 3). This discovery bodes well for theoretical studies aiming to determine the origin of galactic PeV cosmic rays, as these are assumed to originate from supernova remnants. An extrapolation of the nova conditions to the related phenomenon of supernovae would be able to support the theory of supernova remnants being the origin of galactic PeV cosmic rays.

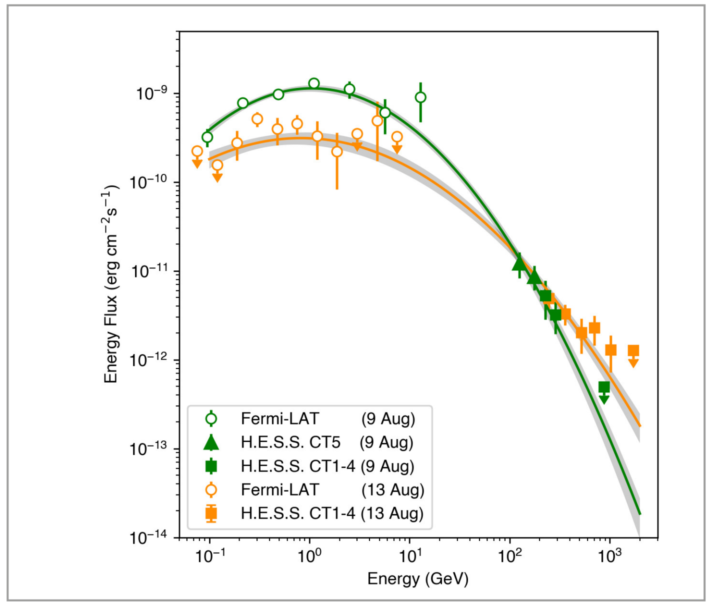

Figure 3
Gamma-ray spectrum of the RS Oph 2021 outburst. Shown is the spectrum for day 1 (9 August) and day 5 (13 August) of H.E.S.S. observations. The spectra show that the lower-energy gamma-ray flux (Fermi-LAT, circles) decreases, while the maximal energy (H.E.S.S., squares and triangles) increases.

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Magnetic field amplification at high Mach number shocks

Explaining spacecraft measurements with plasma simulations

An international group of theorists led by DESY studies processes of magnetic field amplification in supernova remnant (SNR) and planetary bow shocks. The strong and turbulent magnetic field in these shocks is a key ingredient for efficient particle acceleration and for the intense non-thermal radiation detected using space- and ground-based observatories. The newly proposed model describes how the magnetic field is amplified due to ion-driven waves, and the results of large-scale kinetic particle-in-cell (PIC) plasma simulations are fully consistent with measurements made *in situ* at Saturn's bow shock using the Cassini spacecraft.

Astrophysical and planetary shocks

It is widely accepted that SNR shocks are responsible for the production of the galactic cosmic-ray component. In our letter [1], we propose a new mechanism of magnetic field amplification in SNR shocks, which might modify the classical diffusive shock acceleration (DSA) mechanism of cosmic-ray acceleration. Radio and X-ray observations of synchrotron radiation emitted by relativistic electrons can reveal magnetic field properties, but only on scales that are orders of magnitude larger than the shock thickness of nearby SNRs.

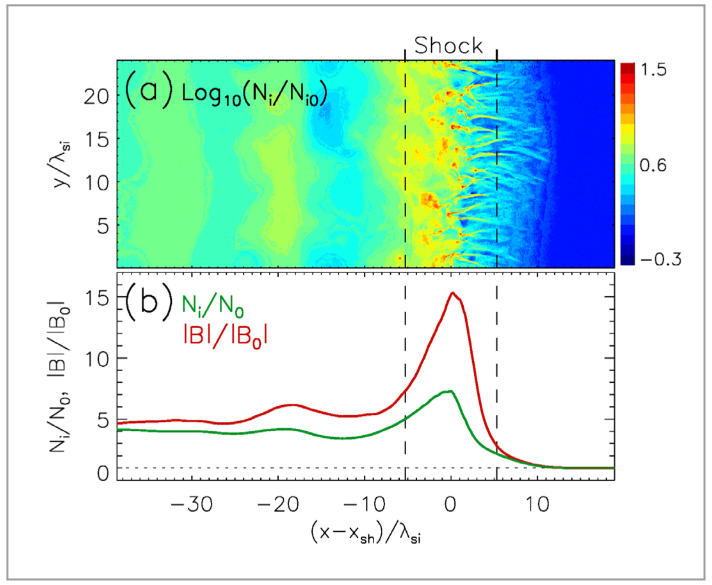

Figure 1
Density and magnetic field at the shock transition.
(a) Ion density in logarithmic units. (b) Red line: profile of normalised ion density; green line: profile of normalised magnetic field. The shock region is marked by dashed lines. x_{sh} is the shock position.

Fortunately, some planetary bow shocks in the solar system, which can be studied *in situ*, exhibit characteristics similar to SNR shocks. The interaction of the solar wind with planetary magnetospheres results in so-called bow shocks. One of them, Saturn's bow shock, has been explored *in situ* by the Cassini mission for over 12 years, allowing for much more detailed investigation of the shock physics compared to telescope observations of SNRs. Both SNR and Saturn's bow shocks are characterised by almost the same parameters, e.g. sonic and Alfvénic Mach numbers. These show how much faster the shocks are compared to propagation velocities of the basic waves in plasma, such as acoustic and Alfvén waves. Therefore, the results for one of these shocks can be directly applied to the other.

PIC simulations vs. Cassini *in-situ* measurements

As both the interstellar medium and the solar wind are plasmas consisting mainly of protons and electrons, there is no better tool for this study than fully kinetic plasma simulations, e.g. PIC simulations, which consider individual particles moving in a self-generated electromagnetic field. Also, PIC simulations can cover the same spatial and temporal scales that were measured *in situ*.

PIC simulations of high Mach number non-relativistic shocks demonstrate that the magnetic field at the shock transition is amplified not only due to compression, but also via ion-driven waves (Fig. 1). The interaction of counterstreaming ion beams excites the so-called Weibel instability, where tangled magnetic field lines decelerate incoming plasma and convert the bulk kinetic energy into plasma heating. Properties of the Weibel instability growth rate indicate that the magnetic field amplification is defined exclusively by the Alfvénic Mach number of the shock.

Amplification processes do not depend on the absolute shock velocity, the artificial ion-to-electron mass ratio used in PIC simulations and the upstream plasma beta. This makes our result applicable to shocks with various parameters and allows for a direct comparison of PIC simulation results with the *in-situ* measurements made using the Cassini spacecraft [2] (Fig. 2), which indicates an almost perfect match between them.

The obtained result is fundamentally important for both the shock microphysics and macrophysics. A strong and turbulent magnetic field works as a mediator between protons and electrons in the shock transition, allowing efficient energy dissipation and redistribution. In addition, the DSA mechanism, which is believed to be the most efficient way to produce cosmic rays, accelerates particles only if they have enough energy to cross the shock unaffected. It is easy to see that the strong magnetic field in the shock transition can spoil this process, and some modification of the DSA mechanism may be required to account for the obtained result.

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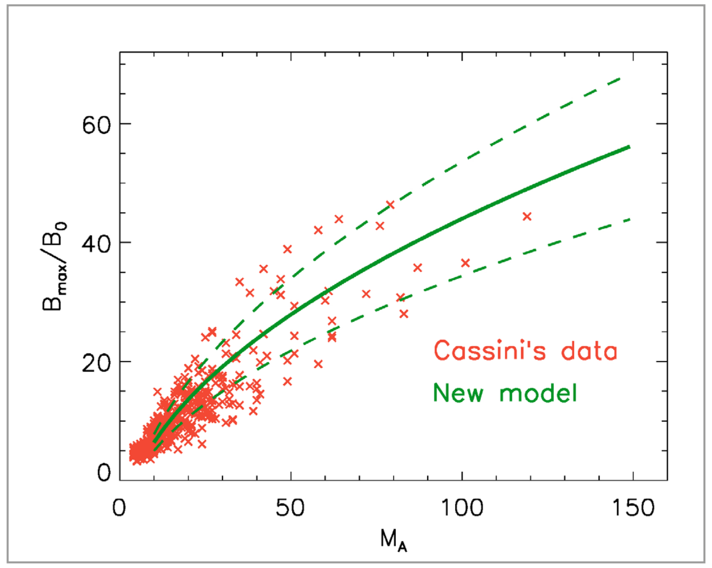

Figure 2
Cassini measurements [2] (red crosses) and PIC simulation data (green curves)

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Modelling active galaxies

… and prospects for their detection with next-generation neutrino experiments

Active galaxies are some of the most powerful sources in the universe. In recent years, the IceCube experiment, a neutrino telescope located at the South Pole, has shown that a small number of these objects also emit high-energy neutrinos, a type of particle produced in cosmic-ray interactions. However, neutrinos are not detected from the vast majority of known active galaxies, which presents a conundrum to observers and theorists alike. A recent numerical study at DESY in Zeuthen [1] brings good news: Active galaxies may simply be "hiding" a vast amount of neutrinos in an energy range even higher than that covered by IceCube. The planned new generation of neutrino experiments, such as IceCube-Gen2, will then be able to detect the neutrino emission from this elusive source population.

The question

Experiments such as the Pierre Auger Observatory in Argentina have shown that the top of our atmosphere is bombarded by cosmic rays of ultrahigh energies. Cosmic rays are protons and other atomic nuclei that have been accelerated to quasi-luminal speeds, and "ultrahigh energies" means up to a million times higher than those of the protons accelerated in the Large Hadron Collider (LHC) at the CERN particle physics centre near Geneva, Switzerland.

As complementary evidence to this, the IceCube experiment, a cubic-kilometre detector located deep in the Antarctic ice, has been observing a flux of high-energy neutrinos from the cosmos since 2013. Because we know that high-energy neutrinos are by-products of cosmic-ray interactions, these detections must therefore point us to the cosmic-ray accelerators. What the accelerators of these cosmic rays are is an old question that still prefaces many papers today, in the field we have come to call multimessenger astrophysics.

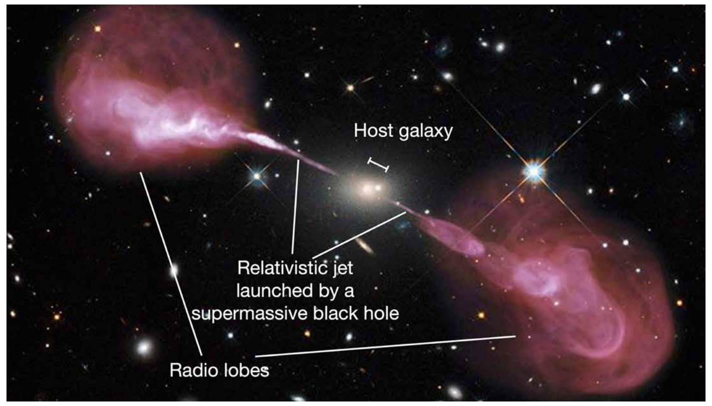

Figure 1
The active galaxy Hercules A can be seen in the centre of the picture in the optical band. Its supermassive black hole launches a relativistic di-jet that extends far into the intergalactic medium. This picture of the jet was captured in the radio band, thanks to synchrotron radiation emitted by accelerated electrons.

The hypothesis

When wondering about potential cosmic-ray accelerators, active galaxies are one of the most obvious contenders. A galaxy is said to be "active" when a supermassive black hole in its centre has attracted an enormous amount of matter to its surroundings, forming a hot disk and, in some cases, launching a powerful relativistic jet that extends far beyond the host galaxy itself (Fig. 1). In even rarer instances, this jet points directly towards Earth, in which case the object is more specifically called a "blazar".

The fact that jets like the one in Fig. 1 are observable in the radio band (and in some cases, across the entire electromagnetic spectrum up to the gamma-ray regime) is in itself evidence that they accelerate particles. Therefore, these sources have the potential to be major emitters of both cosmic rays and neutrinos. While cosmic rays get deflected by magnetic fields on their journey to Earth, neutrinos are neutral and must therefore point directly back at their sources. The sky observed by IceCube should then be a clean picture of the cosmic accelerators in the universe.

The larger picture

In reality, the role of active galaxies in the neutrino sector is not yet so clear. On the one hand, IceCube has observed dozens of individual neutrinos from the direction of known active galaxies in recent years, which seems to indicate that they are in fact cosmic-ray accelerators. Numerical cosmic-ray modelling performed recently at DESY also supports this multimessenger picture of active galaxies [2].

On the other hand, after ten years of IceCube observations, these dozens of neutrinos are only a fraction of all the events observed, and the vast majority of them do not seem to significantly overlap with catalogues of gamma-ray-emitting active galaxies [3]. This suggests that this source class is probably not the main source of the IceCube neutrinos.

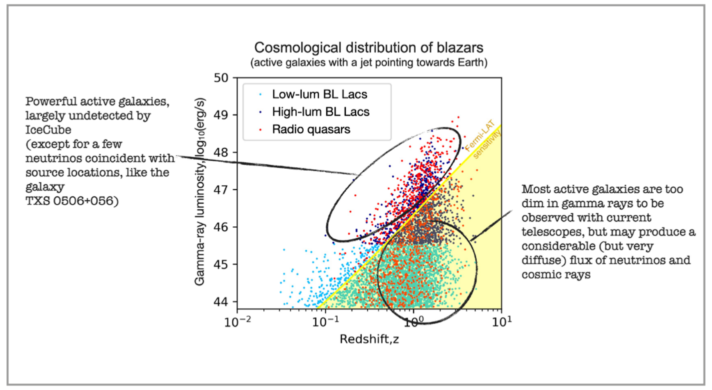

Figure 2
Cosmological distribution of blazars, a subclass of active galaxies. Each point represents one object. The majority of these sources (those in the yellow-shaded region) are too dim to be resolved by current gamma-ray telescopes [1].

To illustrate the situation, Fig. 2 shows our current picture of the entire blazar family, based on gamma-ray observations. Towards the right of the plot are blazars lying further away from Earth, while the brighter gamma-ray emitters are located towards the top. Each point represents one blazar, and the colours indicate different subclasses. The blazars we can actually observe all lie above the yellow line, which represents the sensitivity of the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope. Below this line, the objects are too dim to be resolved as gamma-ray point sources, and we can only theorise about their existence through extrapolation based on cosmological evolution models [4].

This leaves us with two possibilities to interpret the IceCube data:
(1) The brightest active galaxies do not accelerate cosmic rays, but the dimmer ones do – we just cannot see them. These dim sources may even dominate the IceCube flux [5]; but due to the vast number of these sources, the neutrino sky has thus far remained diffuse.
(2) Active galaxies of all luminosities are efficient emitters of cosmic rays (and neutrinos) of ultrahigh energies. In this case, the energy range where IceCube is most sensitive may simply be too low to detect the bulk of these neutrinos.

What we have learned

Scenario 2 is an enticing one, and has recently been tested by simulating the propagation of ultrahigh-energy cosmic rays from the entire population of active galaxies [1]. These cosmic rays interact, producing neutrinos and other secondary particles.

We found that active galaxies may single-handedly explain the cosmic-ray flux observed at Earth, almost up to the highest energies (Fig. 3, top panel). The accompanying neutrino flux would peak at equally high energies (red curve in the bottom panel). The peak sensitivity of the current IceCube detector lies at much lower energies, which explains the lack of spatial correlations. However, the upcoming IceCube-Gen2 facility, as well as future radio neutrino telescopes such as RNO-G and GRAND, may be sensitive enough to detect this signal. These neutrinos should originate mainly from bright active galaxies, which means we may then finally be able to detect these objects as neutrino point sources.

At the same time, this implies that the bulk of the flux currently observed by IceCube (black data points) must be produced by a different class of cosmic accelerators.

What this means

These results suggest that active galaxies may actually be emitting a large flux of cosmic rays and neutrinos in the ultrahigh-energy band. In this scenario, IceCube has thus been observing the low-energy tail of this potentially massive cosmic neutrino flux, together with another larger contribution from an unknown population of cosmic accelerators. In the coming years, a new generation of neutrino telescopes will give us a deep view into the ultrahigh-energy universe, potentially offering us vital information about the inner workings of active galaxies. An exciting new era of multimessenger astrophysics approaches, where DESY is once again bound to play a key role.

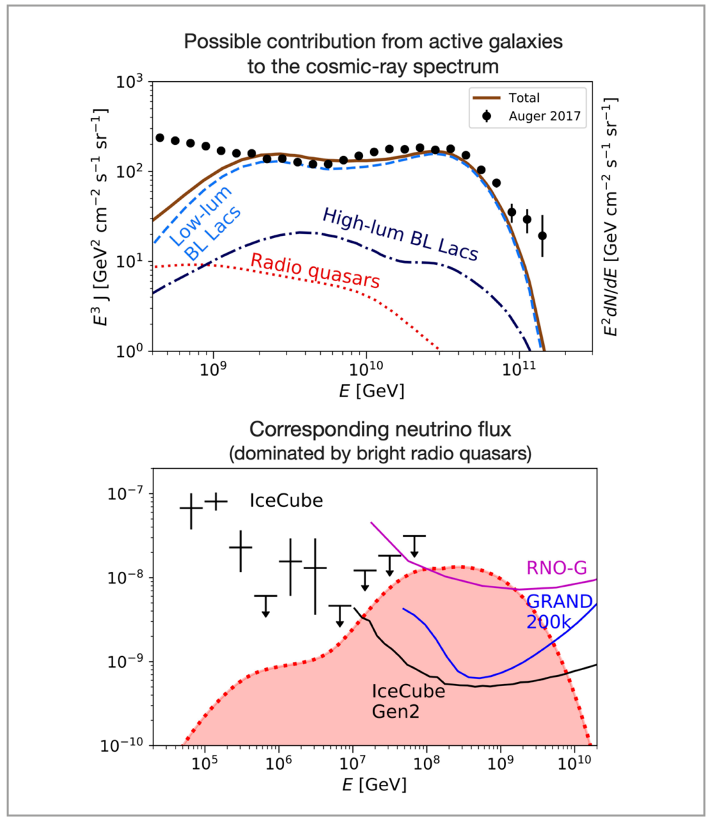

Figure 3
Active galaxies may be the dominant sources of the ultrahigh-energy cosmic rays observed by the Pierre Auger Observatory in Argentina (top). In that case, the brightest of these galaxies can produce a neutrino flux detectable by future experiments such as IceCube-Gen2 (bottom) [1].

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New insights into big explosions

Lessons learned from a record-breaking gamma-ray burst

Maps of the ancient world often depicted unknown areas using broad strokes, simple shapes and declarations of *"Hic sunt dracones/leones"*. The same is true for gamma-ray bursts. We know roughly what happens when a gamma-ray burst occurs: A massive star collapses or two compact objects merge, resulting in a jet that accelerates charged particles, which then produce photons. However, we are only beginning to understand the physical mechanisms that produce photons at the highest energies. Recently, an international team of researchers detected photons of record-breaking energies from a nearby gamma-ray burst, and the study of this burst – led by DESY scientists – is starting to reveal these uncharted territories.

A record-breaking gamma-ray burst

Gamma-ray bursts (GRBs) are some of the most powerful explosions in the universe since the big bang (Fig. 1). They are observed as bright flashes of gamma rays, followed by slowly fading multiwavelength emission; this later emission is known as the afterglow. The hunt for very-high-energy (VHE, >100 GeV) emission from GRBs has been very successful in the last few years. We have learned that the VHE emission can be incredibly bright at early times [1] and that it can last for hours [2]. However, previous GRBs suffered from a common problem: They were at redshifts of $z > 0.4$ (distances of over 4 x 10^9 light years), and at these distances, the highest-energy photons tend to get absorbed by the extragalactic background light on their way to Earth.

Then, in September 2019, the High Energy Stereoscopic System (H.E.S.S.) telescopes in Namibia detected VHE photons from one of the closest GRBs yet, with the results reported in a study recently published in *Science* [3]. GRB 190829A was at a redshift of only 0.0785 (a distance of only 10^9 light years), allowing for photons with energies as high as 4 TeV to be detected by H.E.S.S., far surpassing the previous record of 1 TeV. The GRB's closeness also meant that H.E.S.S. was able to detect it for up to three nights after the initial stellar collapse, giving us the first peek into how the VHE emission changes over days.

The highest-energy photons

When a GRB occurs, the initial catastrophic event produces an ultrarelativistic jet. The jet propagates away from the progenitor event and slams into the surrounding material, which causes a shock to form at its front. Charged particles are swept up by the shock and gain energy; they then twist around magnetic field lines, causing them to lose their energy by emitting photons. This is known as synchrotron emission and has been found to well describe the GRB afterglow emission from radio to X-ray energies. The charged particles struggle to keep up with the fast-moving shock front and eventually fall out of the acceleration zone, and so there is a maximum possible synchrotron photon energy.

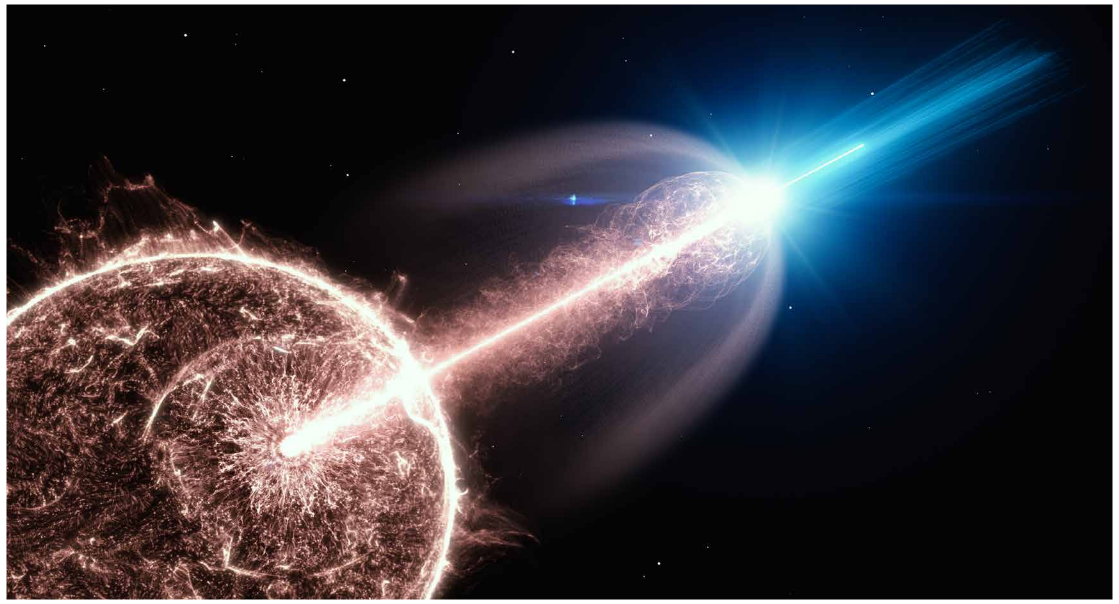

Figure 1
When a massive, rapidly rotating star reaches the end of its life, its core collapses and produces an extremely energetic jet. Particle interactions within and around the jet produce non-thermal emission, which we observe as a gamma-ray burst.

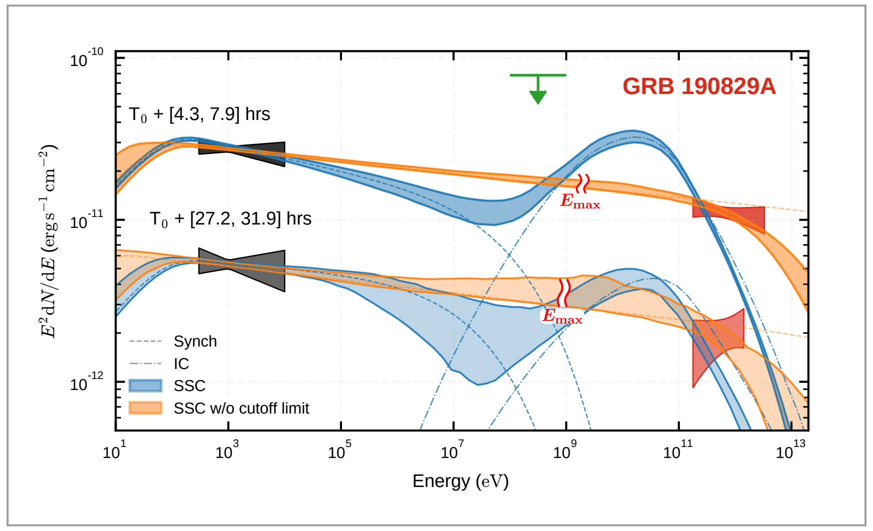

Figure 2
The gamma rays (orange bowties) are better explained as a continuation of the X-rays (grey bowties) than as an additional component; the orange contours provide a statistically better fit to the data than the blue contours do [3].

In order to produce photons of even higher energies – such as those from GRB 190829A detected by H.E.S.S. – it would be natural to invoke an additional process, in which the synchrotron photons are boosted to higher energies by the same population of charged particles that produced them. This would generate an additional spectral component at gamma-ray energies, known as the synchrotron self-Compton component. The overall spectrum would then be a double-peaked structure, as has frequently been observed in analogous phenomena, such as the shock produced by accreting black hole events known as active galactic nuclei.

However, something curious came up when examining the H.E.S.S. data of GRB 190829A. For the conditions in this GRB, the synchrotron self-Compton spectrum in the energy band measured by H.E.S.S. (200 GeV to 4 TeV) should have been soft; i.e. most of the total energy should have been emitted at lower photon energies. Instead, the spectrum was found to be flat (Fig. 2), so that roughly the same amount of energy was emitted at lower and higher photon energies. In addition, the X-rays and the gamma rays seemed to decay at the same rate, suggesting that the same physical mechanism was producing both. The X-ray photons were firmly established as synchrotron photons; as the gamma rays behaved very similarly, this suggested that they too were synchrotron photons – but with energies a thousand times higher than previously thought possible.

Beyond simplified models

At first glance, this seems like an impossible situation: The H.E.S.S. measurements are better explained as synchrotron emission, but they exceed the theoretical maximum synchrotron photon energy by three orders of magnitude, which strains credulity.

How do we resolve this tension? The answer is that the theoretical maximum is in fact based on simplified modelling assumptions that have limited applicability to the true conditions. In particular, it assumes that a single magnetic field strength is involved in both the acceleration and the cooling of the charged particles; *hic sunt dracones*. As in all physics, such a simplification is both necessary and sufficient when there is no data available to compare with the model; or, at least, when the data quality is not good enough to say something interesting. When the data *is* available and of good quality, however, this gives us the opportunity to push beyond our simplified models and explore more complex and realistic magnetic fields.

With GRB 190829A, we have a very nearby event that was detected in VHE gamma rays for over three nights. This grants us an unprecedented window into how relativistic shocks accelerate charged particles. Such a nearby event only occurs once every few years, but the next-generation Cherenkov Telescope Array (CTA) – with a predicted sensitivity ten times greater than the current generation's – will be able to detect much dimmer events and ones out to greater distances. We have only begun to map how GRBs behave at the highest energies, and future observations by CTA will truly make great advancements to the field.

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ULTRASAT

Critical design review

ULTRASAT is a scientific ultraviolet (UV) space telescope that will operate in geostationary orbit. The mission, targeted to launch in 2025, is led by the Weizmann Institute of Science (WIS) and the Israel Space Agency (ISA). DESY is tasked with the development of the UV camera at the heart of the telescope. The camera consists of four backside-illuminated CMOS sensors with 22.4 megapixels each. The Schmidt design of the telescope locates the detector inside the optical path, and the short focal length requires an accurate positioning of the sensors and a flatness of ±10 µm over all four sensors. During operation, the sensors must be cooled to 200 K for dark-current reduction. The critical design review (CDR) of the camera was conducted at DESY in October 2021.

The ULTRASAT mission

ULTRASAT is an astronomical satellite mission whose wide-angle telescope will image the sky in the near-ultraviolet (NUV) at wavelengths between 220 and 280 nm. The mission is designed to survey large fractions of the sky at high cadence (minutes to months) and sensitivity (limiting AB magnitude: 22.3 AB at 5σ in 3 x 300 s integration). The volume of the universe that ULTRASAT will survey per unit time is more than 300 times larger than the one accessible to the most sensitive UV satellite flown to date, the Galaxy Evolution Explorer (GALEX). For hot sources with temperatures exceeding 20 000 K, the volumetric survey speed will be comparable to upcoming surveys, e.g. by the Vera C. Rubin Observatory. The main science objectives of ULTRASAT are the detection of counterparts to gravitational-wave sources and of supernovae. Other science topics are variable and flaring stars, active galactic nuclei, tidal disruption events, compact objects and galaxies [1].

The ULTRASAT satellite is expected to be launched in 2025 and will take data from geosynchronous equatorial orbit for at least three years. The mission is jointly funded and managed by ISA and WIS, under the scientific leadership of WIS. The satellite and the telescope for the mission are being developed by Israeli industry. DESY joined the mission in 2019 and will provide the UV camera [1].

Camera design

The ULTRASAT camera is divided into two parts, the detector assembly (DA), which is located inside the telescope, and the remote electronics (RE) unit, which is placed outside the telescope on the satellite's structure. The DA comprises the sensors as well as the thermal control systems and the power conditioning for the sensors (Fig. 1), while the RE provides the main power converters and the field-programmable gate arrays (FPGAs) for readout of the sensors. In order to increase the overall robustness of the design, the camera is divided into four completely independent camera segments that communicate with the spacecraft through four individual sets of interfaces.

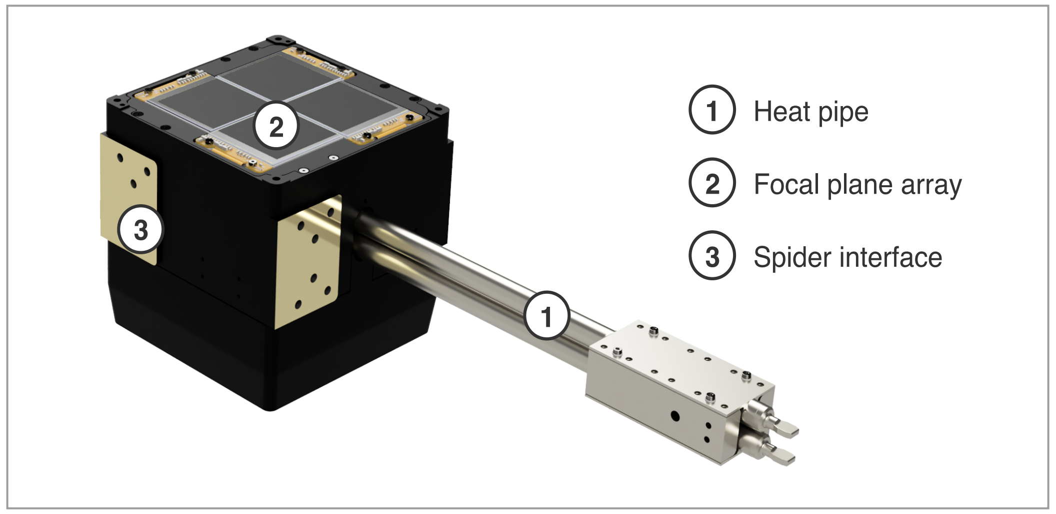

Figure 1

Detector assembly of the ULTRASAT camera developed by DESY. The golden interfaces on the sides of the unit will allow the mounting of the assembly inside the telescope. The sensor is cooled to 200 K by removing excessive heat through two heat pipes connected to a cold sink provided by the spacecraft.

Figure 2

Scientists and engineers from WIS, ELOP and DESY during the critical design review of the ULTRASAT camera

Generally, the design of the camera addresses several technical challenges at the same time. First, a high photon sensitivity needs to be achieved in the NUV over a wide sensitive area. To this end, a backside-illuminated CMOS sensor with 22.4 megapixels and a sensitive area of 4.5 x 4.5 cm^2 was designed specifically for the ULTRASAT mission [2].

Second, the sensor needs to be operated at a temperature of 200 K to achieve the low noise level required for deep observations. At the same time, heating the sensor to 343 K needs to be possible for decontamination. This is achieved by a system of two heat pipes that are connected to the individual sensors by means of four thermal copper straps and that transport the excessive heat from the sensors to a cold sink provided by the spacecraft. To thermally isolate the cold sensors from the DA's structure, which is maintained approximately at room temperature, the sensor package is mounted on four flexures made of a high-performance plastic.

Third, a flatness of ±10 µm over the entire focal plane is required for the fast optics of the telescope. To this end, the four sensors are packaged on four individual tiles made of an aluminium–silicon alloy to minimise the mismatch of the coefficient of thermal expansion between sensor and package. The four tiles are mounted on a plate made of the same alloy that allows for adjustment of the four individual sensor surfaces relative to each other during the integration process.

Finally, the camera needs to be as compact as possible to limit obscuration, as it is located in the light path inside the telescope. In addition, there are very stringent requirements on the cleanliness of the camera, as the UV photons are quickly absorbed by any contamination. This restricts the choice of materials that can be used for the design of the DA and also imposes stringent requirements on the assembly process.

Critical design review

The CDR is conducted to confirm the detailed design within a space project and thus paves the way for the production and integration phase. The CDR of the ULTRASAT camera was held in October 2021 at DESY in Zeuthen. Due to the coronavirus pandemic, on-site participation was limited, allowing only ten researchers and engineers from the project office and from Elbit Systems Electro-Optics (ELOP), the industry partner responsible for the development of the telescope, to join the meeting on site (Fig. 2). Representatives from Israel Aerospace Industries (IAI), which is responsible for the development and production of the spacecraft, and from NASA, which is responsible for the launch of the satellite, as well as several subcontractors of DESY joined the review remotely via video call.

In the review, DESY presented the design as well as the integration and test plan of the camera, and design and process details were discussed in depth. To conclude the CDR process, DESY now has the task of responding to the comments recorded during the CDR meeting and completing and submitting the documents for final evaluation.

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Neutrinos from tidal disruption events

Two neutrino–source associations (and counting)

Neutrinos are cosmic messengers, promising to solve the mystery of the origin of cosmic rays. We have identified the tidal disruption event (TDE) AT2019dsg, named after the Game of Thrones character Bran Stark, as the likely source of a cosmic high-energy neutrino detected by the IceCube observatory in 2019. Massive stars normally die by running out of nuclear fuel. A TDE is a special death, caused by the star approaching a supermassive black hole so closely that it is destroyed by tidal forces exerted by the black hole's gravitation. We have also shown in theoretical models that AT2019dsg was capable of producing a high-energy neutrino. In 2020, we have identified another likely TDE, AT2019fdr, named after Tywin Lannister, as the source of a second high-energy neutrino detected by IceCube.

Neutrinos could solve the cosmic-ray puzzle

Since the discovery of cosmic rays, their origin has been a mystery. Cosmic rays are protons or fully stripped nuclei, i.e. charged particles, which are deflected by magnetic fields on their way through the universe. Therefore, we do not know where they originate. High-energy neutrinos could come to the rescue, as they are most likely produced in the very same sources as cosmic rays. Neutrinos are electrically neutral and therefore travel on straight paths pointing directly back to their sources.

However, the directional uncertainties of the neutrino detections pose a challenge for identifying their sources. So far, only the blazar TXS 0506+056 (an active black hole in the middle of a galaxy whose jet points towards us) and the nearby galaxy NGC 1068, which also has an active galactic nucleus (AGN), have been established as likely sources – among several other candidates.

Tidal disruption events

TDEs have long been proposed as sources of high-energy cosmic neutrinos. In these events, a star approaches a supermassive black hole too close for its own good: The star's front experiences a gravitational pull from the black hole that is much greater than the one at its back. These tidal forces are strong enough to disruptively tear the star apart (hence the name). About half of the shredded remains then fall toward the black hole and form an accretion disk around it, strongly emitting in the optical/UV and/or the X-ray wavelength bands for months. The TDE might also produce outflows (Fig. 1).

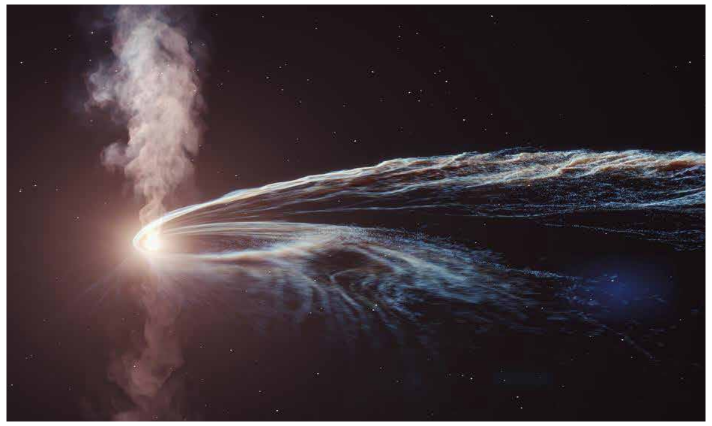

Figure 1
Artistic impression of the TDE AT2019dsg. After the star has been torn apart, roughly half of the debris has formed an accretion disc around the black hole. The system shines brightly across many wavelengths and might have produced energetic, jet-like outflows perpendicular to the accretion disc.

TDEs were predicted in the 1980s, but only modern optical survey telescopes like the Zwicky Transient Facility (ZTF) in California, USA, of which DESY is a collaboration member, have allowed us to detect them in significant numbers. These telescopes scan the whole observable sky every few days, detecting everything that has changed in the meantime (e.g. because something has violently exploded). Still, detected TDEs are rare, with around 50 confirmed events in total.

Our follow-up programme

DESY has long been active in IceCube, a cubic-kilometre-scale neutrino detector located at the South Pole. Whenever IceCube detects a high-energy neutrino, we point ZTF to the sky location where the neutrino came from. We then use AMPEL, a software framework developed at Humboldt-Universität zu Berlin and DESY, to filter the many new things in the sky that have been observed around the time of the neutrino emission, leaving us with a handful of interesting events. These are scrutinised further; we continue to observe and obtain e.g. optical spectra or radio observations.

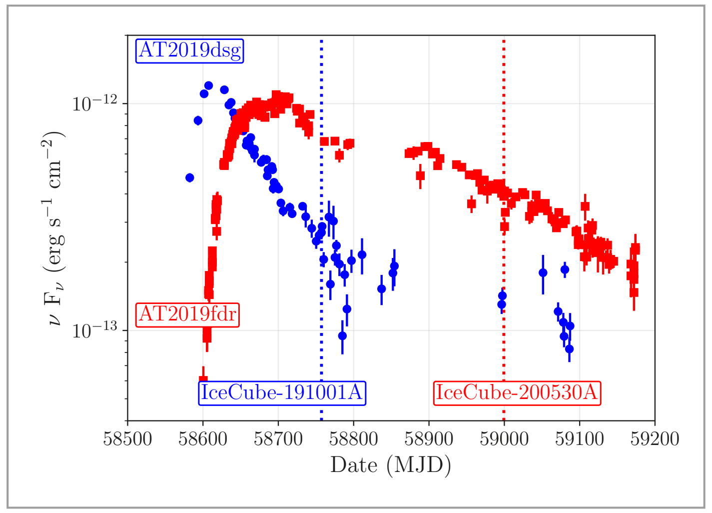

Figure 2
Comparison of the optical flux from the TDEs AT2019dsg (blue circles) and AT2019fdr (red squares). The arrival time of the two neutrinos are denoted by dotted vertical lines. The *x*-axis encompasses a time period of 700 days. Though AT2019fdr is much brighter at the source, it is also further away.

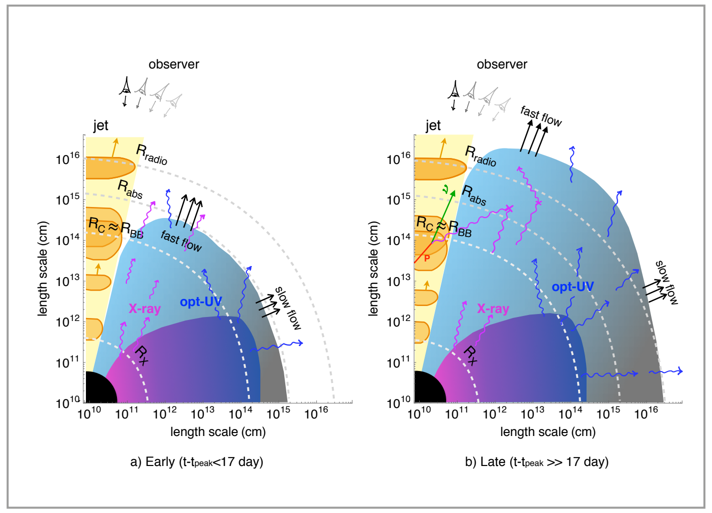

Figure 3
Neutrino production in a model with a relativistic jet. At early times (left panel), protons do not find target photons for head-on collisions. At later times (right panel), X-rays are isotropised by the expanding outflow, and protons can interact efficiently to produce neutrinos. From [2].

AT2019dsg – Bran Stark

In 2019, following up on the high-energy neutrino IC191001A, we found the TDE AT2019dsg to be located within the 90% uncertainty region of the neutrino. It had a redshift of z = 0.051, rendering it quite close compared to the full ZTF TDE sample. We were able to model it as a blackbody with a fairly high temperature of almost 40 000 K. Its peak luminosity (energy output per time) was in the top 10% of all TDEs known back then. The optical light curve (brightness over time) of AT2019dsg can be seen as blue circles in Fig. 2.

AT2019dsg was also observed in the UV and X-ray range. UV measurements are very helpful in constraining the blackbody temperature. The X-ray emission is noteworthy, because it is untypical for TDEs that are detected in the optical and UV. Additionally, emission at radio wavelengths was detected in the months following the discovery. Intriguingly, the radio signal showed clear signs of evolution.

One can use the typical duration of TDEs and the total sky area observed during our programme to calculate the probability of finding such a bright TDE completely by chance. This turned out to be 0.2%, making it very likely that the neutrino indeed came from AT2019dsg. It should be noted that the high-energy neutrino was detected 170 days after the TDE discovery. This needs to be addressed when modelling neutrino emission scenarios.

Neutrino production

Several possible neutrino production scenarios are being discussed in the literature: Neutrinos may come from the disk, a corona, hidden winds, or relativistic jets. A model based on the presence of a jet, developed by researchers at DESY and Arizona State University, USA, is shown in Fig. 3. Protons accelerated within a relativistic jet collide with external target photons at later times, when these are backscattered by an outflow into the jet direction. The model has the advantage that a high enough neutrino flux is predicted and that the neutrino time delay with respect to the optical and UV range is well described, whereas missing direct signatures of the jet challenge the model.

Spoiler alert!

In 2020, we have linked another source with a high-energy neutrino: AT2019fdr, or Tywin Lannister, was a luminous flare located in an AGN. Its classification was initially debated, but we have established further evidence that it is a TDE, albeit an unusual one. Its optical light curve is shown as red squares in Fig. 2. It was of comparable apparent brightness, but lasted much longer than AT2019dsg. This second discovery reinforces the case for TDEs as neutrino emitters. A puzzling question arises from the fact that AGN are far more numerous, injecting significantly more energy into the universe than TDEs. If TDEs contribute significantly to the high-energy neutrino flux, they have to be much more efficient in producing them than AGN.

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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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