Astro-particle Physics

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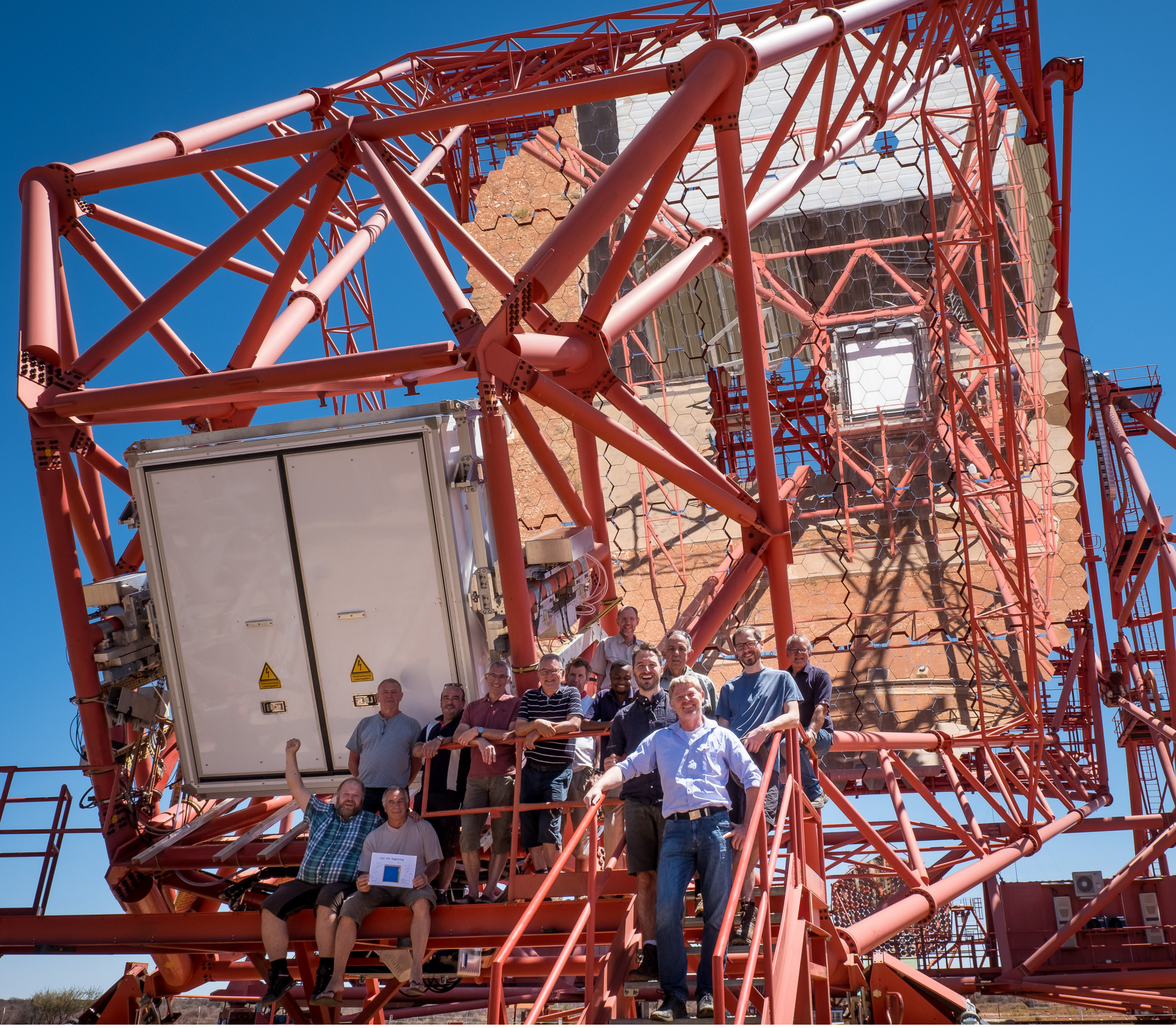
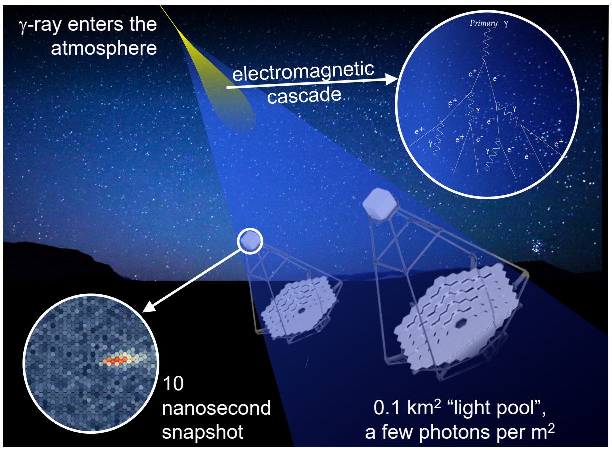


1.1 The Non-Thermal Universe

In autumn 2019, the large H.E.S.S. telescope was equipped with a new high-performance camera, which shortly after installation captured its first image of the Crab nebula.

Cherenkov Telescopes and Water Cherenkov Detectors

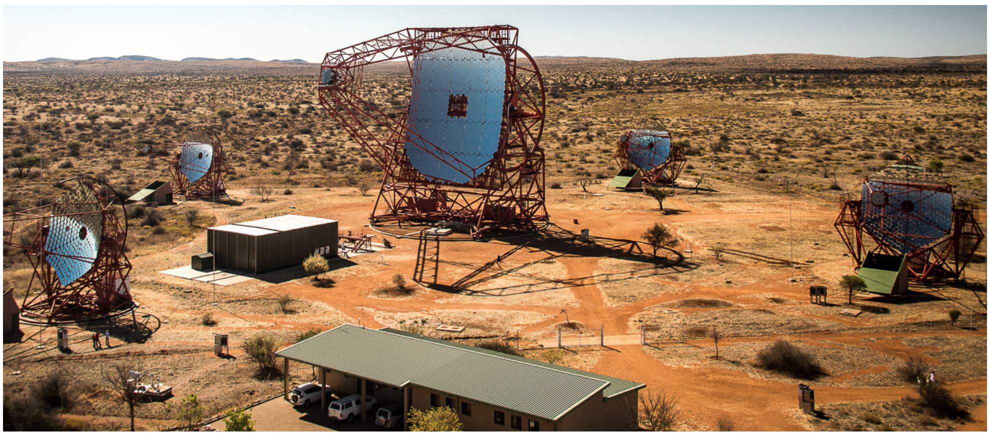


Observing gamma rays with Cherenkov telescopes.

High-energy gamma rays from space – a trillion times more energetic than visible light – do not reach the Earth's surface. Nevertheless, they can be detected at ground-level via the particle cascades (known as air showers) that they generate in the Earth's atmosphere. One detection method makes use of the faint, bluish, and extremely short flashes of light (Cherenkov light) which the air showers produce. On dark nights these flashes can be detected using very large reflecting telescopes equipped with very fast and highly specialised cameras. To determine accurately the direction of the incoming gamma ray, the shower is observed stereoscopically by several of these telescopes.

H.E.S.S. (the High Energy Stereoscopic System) consists of five telescopes, four of them each with 107 m^2 mirror area deployed in a square of side length 120 m. A camera composed of 960 photomultiplier sensors is placed at the focus of each mirror. H.E.S.S. was the first instrument that was able to produce true images of astrophysical gamma-ray sources. In the centre of the array, a fifth, huge telescope with 614 m^2 mirror area and a camera with 2048 pixels has been operational since 2012, enhancing the sensitivity of the system and extending observations to lower energies.

Preparations are underway for a next generation observatory with dramatically improved performance. The Cherenkov Telescope Array (CTA) will consist of two arrays, in Chile and the Canary Island of La Palma, with around 100 telescopes of three different sizes. CTA will bring much better resolution, higher sensitivity, a much wider energy range, and a collection area of many square kilometres at the highest energies. The MPIK instrumentation effort is in developing state-of-the-art cameras for two of the different telescope types. In 2019 the camera technologies developed at MPIK for CTA were used to upgrade the central telescope of H.E.S.S.



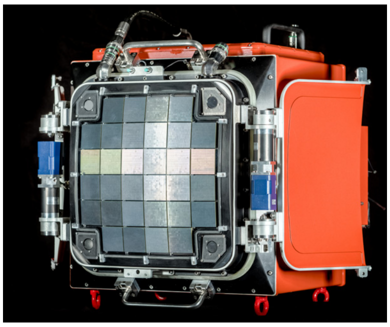
The H.E.S.S. Cherenkov telescope system in Namibia.

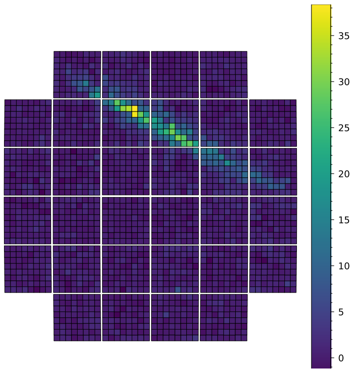
The CTA SST camera

The Cherenkov Telescope Array (CTA) will host up to 70 Small-Sized Telescopes (SSTs) at the CTA Southern Hemisphere site at Paranal in Chile. The SSTs are distributed over several square kilometres and provide sensitivity in an energy range between a few TeV and 300 TeV. Several international groups have developed options for the SST design. One such proposal involves a dual-mirror optical design with a primary mirror of 4 m in diameter, a secondary mirror 2 m in diameter and a compact camera of roughly 0.5 m in diameter.

MPIK has led the development of a camera for use in such an optical system. The Compact High-Energy Camera (CHEC) features a modular design and provides full waveform information for all 2048 pixels with a sampling rate of one giga-sample per second. The CHEC collaboration includes institutes from Australia, Germany, Japan, the Netherlands, and the UK. MPIK is coordinating the project and leading the effort into full-camera assembly, integration, and verification. A prototype camera, CHEC-S has been developed, built, and commissioned. CHEC-S was installed on a prototype SST structure at the INAF observatory site in Serra La Nave on Mt Etna (Sicily) in spring 2019. The camera was commissioned and on-sky gamma-ray observations taken. The third figure shows an event lasting a few tens of nanoseconds captured in the camera. Following commissioning, CHEC-S underwent review within CTA and has recently been selected from three candidates as the basis for the final SST Camera. A final design phase will proceed to optimise the camera design for the production phase of CTA.

References:
[1] J. Zorn et al., NIMA 904, 44-63, (2018), DOI: 10.1016/j.nima.2018.06.078
[2] R. White et al., 35th International Cosmic Ray Conference, ICRC2017, arXiv:1709.05799





One of the ‘outrigger‘ tanks in front of the main detector array of HAWC in Mexico.

At high-altitude sites, the shower particles can be observed directly – and around the clock – using water-filled detectors, where they also produce Cherenkov light. The main detector of HAWC (the High Altitude Water Cherenkov gamma-ray observatory) consists of a dense array of 300 tanks at an altitude of 4100 m. The tanks are filled with high-purity water and equipped with light sensors. They are surrounded by a sparse array of 350 smaller ‘outrigger‘ tanks, which significantly improve the characterisation of particle showers hitting the boundary area of the main array. The MPIK is playing a major role in the development of a next-generation gamma-ray survey observatory in the southern hemisphere, the Southern Wide field-of-view Gamma-ray Observatory (SWGO). SWGO will make use of the same detection principle as HAWC, but cover a larger area and a wider range of gamma-ray energies.

Cosmic Accelerators – Astronomy at the Highest Energies

High-energy astrophysics at MPIK is characterized by a close cooperation between experimentalists and more theoretically oriented astrophysicists. They study non-thermal phenomena in the Universe using the High Energy Stereoscopic System H.E.S.S. in Namibia and the High Altitude Water Cherenkov Detector HAWC in Mexico to detect very-high-energy (VHE) gamma rays from the cosmos, and investigate the acceleration of particles to extreme energies in cosmic sources and the role that these particles play in astrophysical systems.

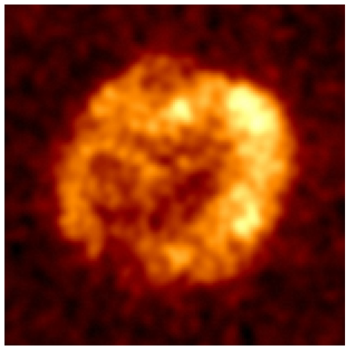
Particles in the VHE range cannot be produced as thermal radiation, as is the electromagnetic radiation in most other wavelength regimes; only in the Big Bang were high enough temperatures reached for a very short time. VHE gamma radiation is produced when strongly accelerated charged particles interact with the interstellar gas or photon fields. In contrast to the charged particles, known as cosmic rays, the gamma rays travel in a straight line from the source to the observer, allowing the imaging of sources and the study of the astrophysical processes at work.

Charged particles can obtain VHE energies in many astrophysical sources, for example in the giant shock waves generated in supernova explosions or in the plasma jets emerging from the immediate vicinity of the massive black holes at the centres of active galaxies. Considerable effort at the Institute is going into the modelling and theoretical description of processes within the different cosmic accelerators, as well as into VHE observations.

Recent highlights from H.E.S.S. include the detection of gamma-ray bursts and the first resolved emission from the jets of active galaxies in the gamma-ray band. In 2018 a whole issue of the journal Astronomy & Astrophysics was dedicated to H.E.S.S. observations within our own Galaxy, where more than 80 VHE gamma-ray sources have been discovered. These objects include many supernova remnants and pulsar wind nebulae, several discovered in follow-up observations at other wavelengths, following the H.E.S.S. detections. The centre of the Milky Way is of particular interest and with H.E.S.S. VHE emission has been established from very close to the supermassive black hole at the heart of our galaxy, and also from gas clouds in the central region, bombarded by cosmic rays with up to petaelectronvolt energies and glowing in gamma-rays.

HAWC observations complement those of H.E.S.S., providing sensitivity to larger-scale emission and up to higher energies. HAWC recently revealed very extended halos of high-energy electrons around two nearby pulsars and emission from the jets of the enigmatic Galactic ‘micro-quasar’ known as SS 433.

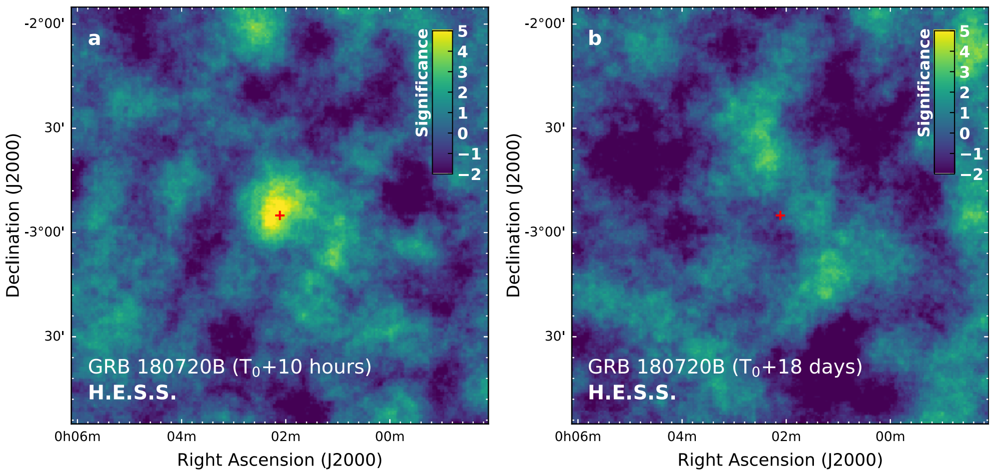
The recent upgrades of H.E.S.S. and HAWC and the future instruments CTA and SWGO will allow us to push forward our understanding of the energetic Universe, and of the role that cosmic rays play in all astrophysical systems – up to the scale of galaxies and beyond.



The supernova remnant RX J1713-3946 as seen by the H.E.S.S. telescopes.

Gamma-ray burst afterglow emission detected in very-high-energy gamma-rays

Gamma-ray bursts (GRBs) are the most dramatic explosive phenomena in the Universe, yet until 2019 no convincing ground-based detection of gamma-ray emission from GRBs had ever been made. Now three GRBs have been detected from the ground – at very high energies – two of them with the H.E.S.S. telescope system. GRBs begin with very luminous and highly variable emission that after some time (typically a few seconds) begins to decrease monotonically. The measurement of emission at VHE with H.E.S.S. from GRB 180720B was not just the earliest measurement from the ground, but remarkable as the emission was detected 10 hours after the beginning of the burst (T_0, see panel a). This discovery was made with the central 28 m telescope of the H.E.S.S. array. The red cross indicates the position of the GRB measured by contemporaneous optical observations. At the same location, significant gamma-ray emission detected by H.E.S.S. can be seen. In panel b the same region of the sky is shown as observed 18 days later. At such late times, the very-high-energy emission has faded to a level that it is no longer detectable. Measurements with H.E.S.S. of another bright GRB, 190829A, starting 4 hours after the burst, confirm the presence of particle acceleration to very high energies very late in GRBs.



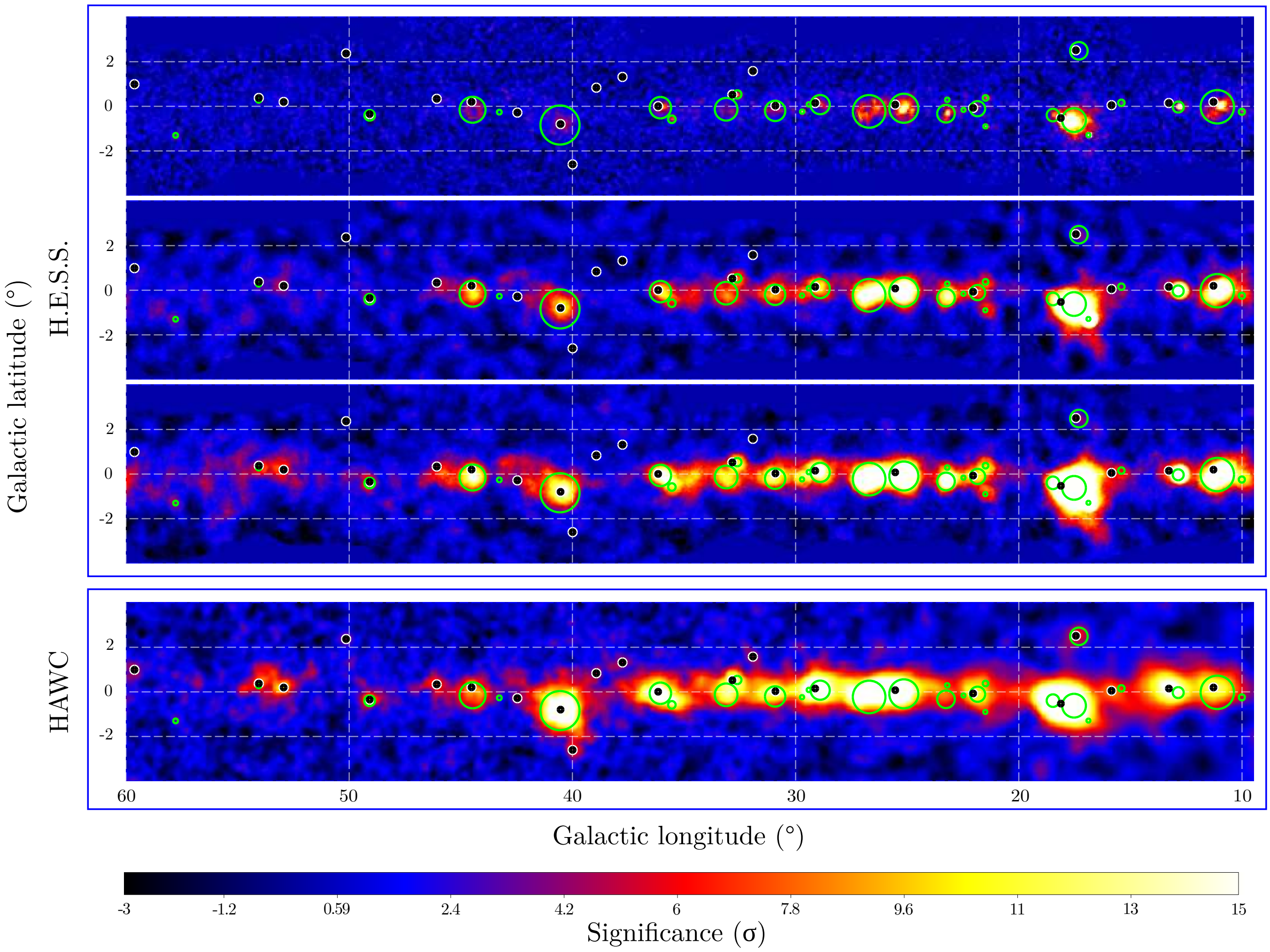
Reference:

H.E.S.S. Collaboration (H. Abdalla et al.), Nature 575, 464–467 (2019), DOI: 10.1038/s41586-019-1743-9

Galactic plane surveys with H.E.S.S. and HAWC

The H.E.S.S. Galactic Plane Survey (HGPS) was a 10 year long observation program where the H.E.S.S. telescopes in Namibia systematically scanned the band of the Milky Way for very high energetic (VHE) gamma-ray emission. The analysis of the data, led by MPIK, resulted in the first homogeneous catalogue of Galactic VHE gamma-ray sources and a set of sky images, both published in 2018 [1]. In total 78 sources were discovered of which 31 could be firmly identified and associated with already known supernova remnants, pulsar wind nebulae, binary objects, and stellar clusters. Most of the remaining unidentified sources had possible associations with already known objects, but a firm identification can only be established, when the results from the HGPS are combined and compared with data from other instruments.

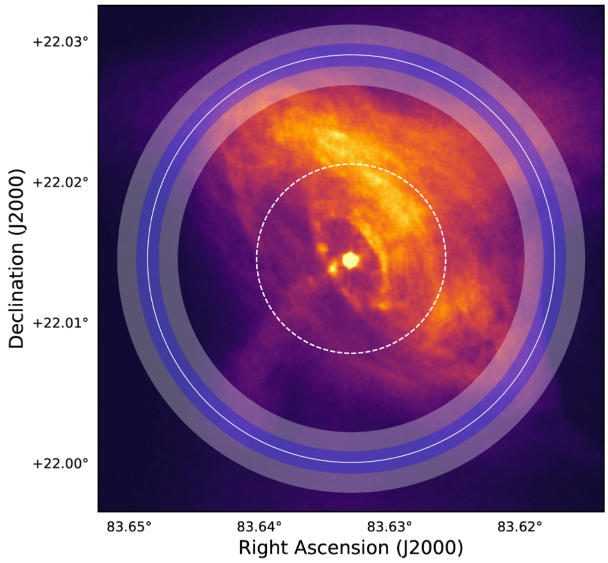
On the other side of the Atlantic ocean, the HAWC gamma-ray observatory located in Mexico has been continuously monitoring the northern sky for more than 4 years and produced a sky map of the VHE gamma-ray emission. Part of it overlaps with the galactic plane scanned by H.E.S.S.. A recent comparison of updated HGPS data and data from the HAWC observatory is shown in the figure [2]. It illustrates the part of the Galactic plane at longitudes between 60° and 10°, where both instruments have reasonable sensitivity. The green circles are the 68% containment of the H.E.S.S. sources and the black dots are the location of the sources detected by HAWC. To be able to compare the data obtained by the two completely different instruments, the HGPS data had to be processed as similarly as possible to the HAWC data. The procedure is illustrated in the panels of the figure top to bottom: first an energy threshold of ~1 TeV was selected in both datasets as a compromise between sufficient statistics, good quality reconstruction, and reasonable angular resolution. Secondly, the resolution of the H.E.S.S. data was downgraded to the angular resolution of HAWC of ~0.4°. Finally, a special background subtraction method, named "field-of-view background method" was applied to the H.E.S.S. data. The lowermost panel shows the image measured by HAWC. After the special processing of the HGPS data, the agreement between both instruments becomes obvious: most of the structures can be found in both maps. The remaining small differences can be explained by a lack of sensitivity of one instrument compared to the other to detect a specific source for example. Despite their intrinsic differences, both instruments have shown to be very complementary and give a very consistent image of the Galactic plane in VHE gamma rays.



References:
[1] H.E.S.S. Collaboration, A&A 612, A1 (2018), DOI: 10.1051/0004-6361/201732098
[2] A. Jardin-Blicq, V. Marandon, F. Brun, 36th International Cosmic Ray Conference, ICRC2019, arXiv:1908.06658v1

Crab size measurement

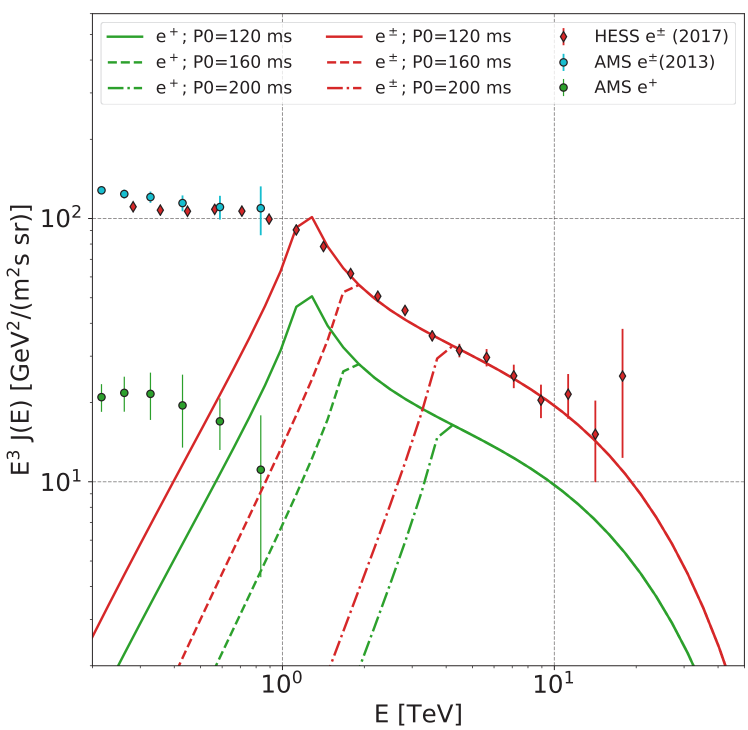
The Crab Nebula is a bright and well known object to astronomers at all wavebands, but as the first detected and brightest steady source it holds a special place for very-high-energy (VHE) gamma-ray astronomers. The nebula belongs to the source class known as pulsar wind nebulae (PWN), which are formed by a wind of electron-positron pairs streaming from the central pulsar. Upon colliding with the surrounding medium, a wind termination shock is created where electrons and positrons are accelerated to ultra-relativistic energies. These energetic particles go on to radiate their energy away by the synchrotron process and via inverse Compton scattering, which results in gamma rays in the VHE range (> 100 GeV). Since its first detection in 1986 this source has been deeply studied by VHE observatories and many of its properties are well understood, however measurement of the size of the emission region has until now proved impossible. This difficulty is due to the size of the Crab Nebula being smaller than the point spread function (PSF; the precision with which the direction of gamma-ray photons is measured) of VHE gamma-ray observatories. However, recently the H.E.S.S. collaboration have been able to control and understand the instrument PSF to the degree where this challenging measurement could be made, determining a size of 52 arcseconds (blue ring), significantly larger than the extension seen in X-rays (dashed circle and background image). As the first measurement of the size of the nebula in inverse Compton emission, this represents a significant step forward in understanding the distribution of ultra-relativistic particles and magnetic fields in the nebula, and hence in our understanding of this whole class of astrophysical particle accelerators.



Reference:
H.E.S.S. Collaboration (H. Abdalla et al.), Nature Astronomy (2019), DOI: 10.1038/s41550-019-0910-0

Cosmic ray electrons

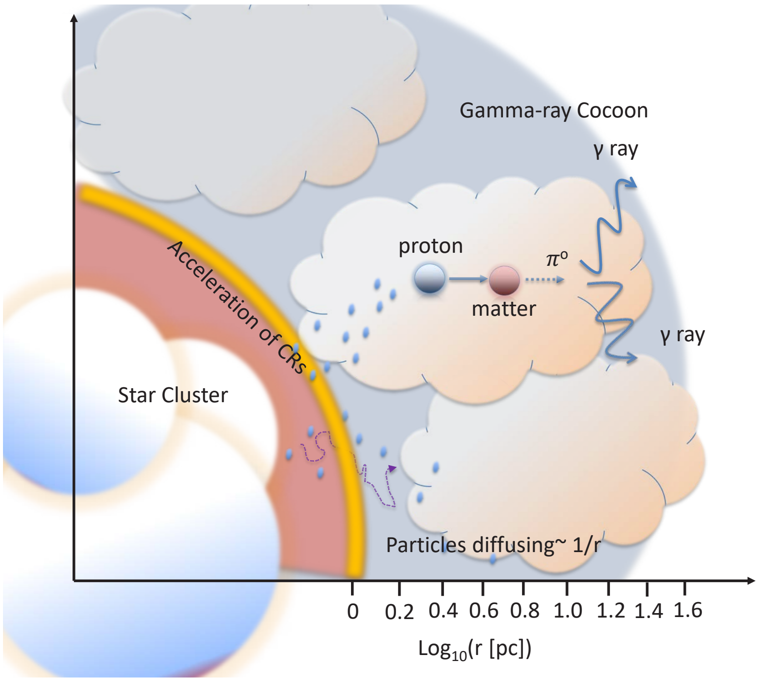
A small fraction of the cosmic rays bombarding the Earth are electrons and positrons. Unlike the much more numerous protons, these particles lose their energy rather quickly. Recently, the electron spectrum has been measured with H.E.S.S. to extend up to around 10 TeV. At these energies electrons cool so fast that they must originate in very nearby sources. Using the new constraints from HAWC on the diffusion speed of cosmic particles, the properties were calculated that would be needed for a local source to match the H.E.S.S. measurements. A very plausible culprit is a pulsar inside the so-called 'Local Bubble', very close to the solar system, that has so far evaded detection. This object may reveal itself in the near future in a number of different ways: a sharp rise in the positron fraction at high energies, as a new very extended gamma-ray nebula, or a new radio pulsar detectable for the first time with SKA. The figure shows the electron flux at the Earth (multiplied by energy cubed for clarity) versus electron energy. Model curves are shown for electrons and positrons together (red) and just positrons (green), for different assumptions on the initial spin period of the pulsar.



Reference:
R. López-Coto, R.D. Parsons, J.A. Hinton, G. Giacinti, Phys. Rev. Lett. 121, 251106 (2018), DOI: 10.1103/PhysRevLett.121.251106

A new paradigm for Galactic Cosmic Rays?

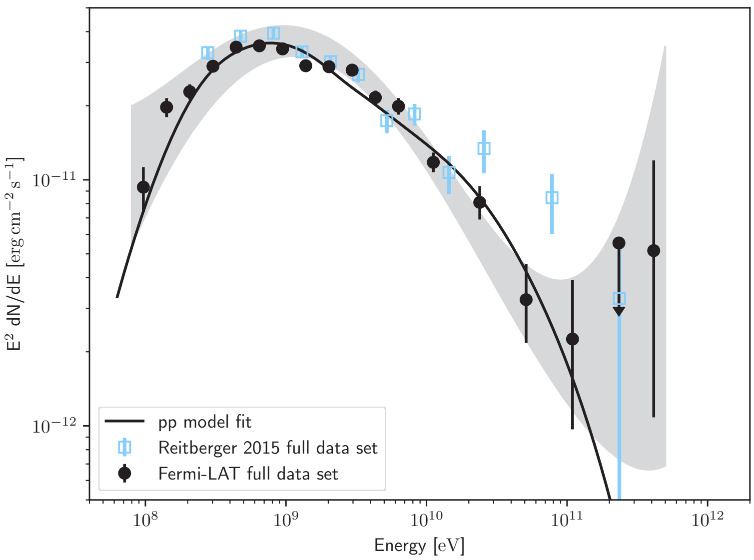
There are many recent hints that the long-held standard paradigm of Galactic cosmic ray acceleration and propagation is in trouble. The paradigm holds that supernova remnants (SNRs) accelerate all of the locally measured protons and nuclei from GeV up to PeV energies. Newly measured features in the spectra of cosmic rays, and secondary particles produced in the interstellar medium, suggest that this picture is too simplistic and, furthermore, the measured gamma-ray emission of sources suggests two distinct classes of particle accelerators. The known gamma-ray SNRs exhibit rather soft spectra indicating acceleration up to at most 100 TeV. An emerging class of harder spectrum / higher energy sources appear to be associated with clusters of massive stars. The prominent massive stellar clusters Cygnus OB2, Westerlund 1, and the ultracompact stellar clusters located in the heart of the Galactic Centre, are all coincident with such-hard spectrum emission. Work is ongoing at MPIK to better understand these gamma-ray sources, and to improve our understanding of cosmic-ray transport in the galaxy. A new paradigm for the Galactic cosmic rays may be emerging.



References:
[1] F. Aharonian, R. Yang, E. de Oña Wilhelmi, Nature Astronomy 3, 561-567 (2019), DOI: 10.1038/s41550-019-0724-0
[2] R. Yang, F. Aharonian, Phys. Rev. D 100, 063020 (2019), DOI: 10.1103/PhysRevD.100.063020

Particle acceleration in the binary system Eta Carinae

The naked eye object Eta Carinae houses the most massive and luminous star in the local Milky Way Galaxy. Since the 1990s it is also known to contain a lower mass binary companion in a regular 5.5 year period with high eccentricity. At a distance of ~7 500 light-years, and with an orbit comparable to that of Uranus around the Sun, the binary system is not resolvable. We therefore must rely exclusively on indirect evidence to infer the properties of this fascinating system. With recent detections in both hard x-rays and gamma rays, a new window into Eta Carinae's inner workings has been opened. Using multi-wavelength data, we can test predictions regarding the nature of the stars, their surface properties and wind parameters. A new analysis of the Fermi-LAT satellite measured Gamma-ray data provides the most convincing evidence to date that the gamma-ray emission has its origins in pion decay from interactions between nuclei accelerated at the shocks in the wind collision region and the shocked material of the winds. Accounting correctly for the hard x-rays, which must be produced via Inverse Compton scattering of light from the stars, requires detailed modelling of the stellar luminosities and associated phase dependence of the emission zone, and tightly constrains/rules out many other existing models. The physical processes regulating the non-thermal particle acceleration at the shocks are remarkably similar to those frequently invoked to account for cosmic-ray acceleration in young supernovae, in particular with regards nonlinear magnetic field amplification by cosmic-ray currents. In combination with the predictable orbital periodic variability of shock conditions, the non-thermal emission from Eta Carinae provides a powerful laboratory for high-energy astrophysics.

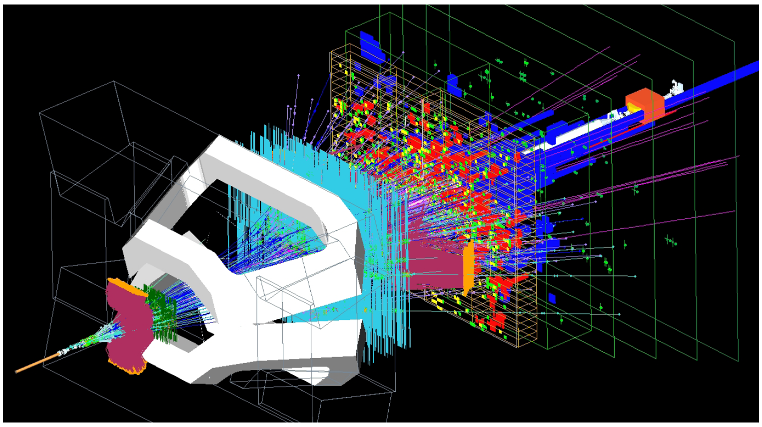


Reference:
R. White, M. Breuhaus, R. Konno, S. Ohm, B. Reville, J.A. Hinton, to appear in A&A, arXiv:1911.01079 (2019)

The Early Universe – Elementary Particles at the Highest Energies

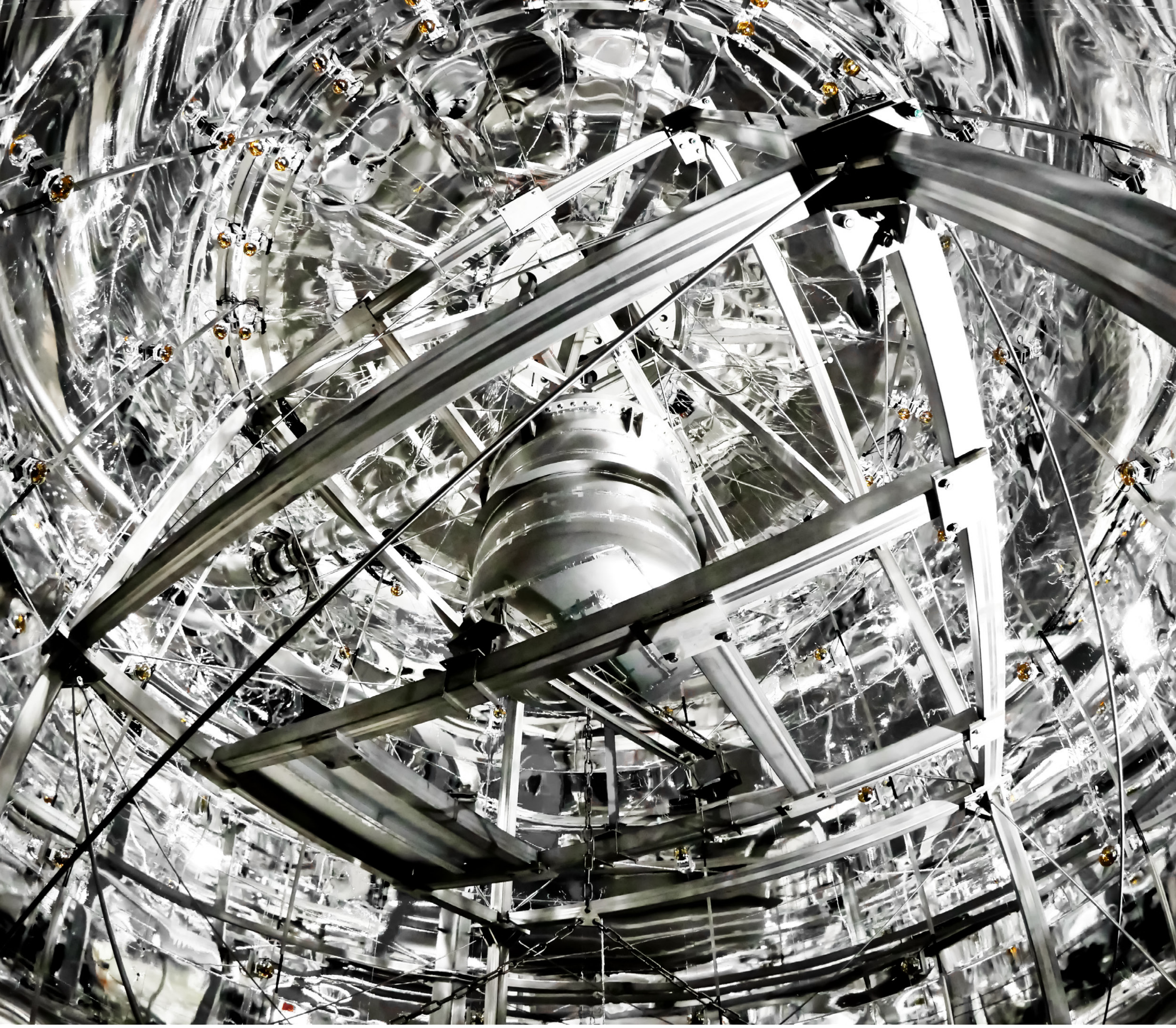
In high-energy collisions between elementary particles, a fraction of the kinetic energy is transformed into short-lived particles normally not found in nature, but that existed in the extremely hot and dense state of the Universe immediately after the Big Bang. Particle collisions at the high-energy frontier thus allow one to study the fundamental interactions between the elementary constituents of our world and to learn about the physics at the beginning of the Universe.

A group at MPIK is a member of the LHCb collaboration, which operates one of the four large experiments at the CERN Large Hadron Collider (LHC). With nucleon-nucleon centre-of-mass energies up to 13 thousand times the mass of a proton, it currently is the world's most powerful particle accelerator. In proton-proton collisions the experiment does precision measurements of the properties of the strong, electromagnetic and weak interactions, in proton-nucleus collisions the effects of the nuclear environment are probed. Nucleus-nucleus collisions, finally, give access to collective phenomena in extended systems consisting of free quarks and gluons, so-called quark-gluon plasmas.



Visualisation of a particle shower in the LHCb detector emerging from a proton-lead collision in the LHC.

These measurements shed light on the properties of the Universe when it was less than a nanosecond old. At the same time they contribute to the understanding of the interactions of high-energy cosmic rays with the atmosphere, which is needed for the interpretation of the data collected by the Cherenkov detectors. The experimental particle physics group at MPIK is involved in studies of all types of collisions produced by the LHC. The focus is on the overlap between particle and astroparticle physics, where it uses its expertise from both fields to fully exploit the physics potential of the LHCb detector.



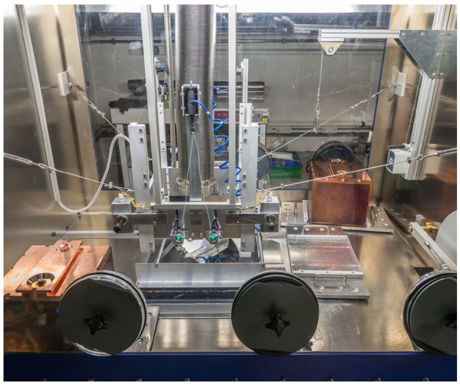
1.2 Dark Matter and Neutrinos

The XENON1T cryostat inside the water tank, which serves as an active veto discriminating against remaining cosmic radiation and radioactivity from the environment.

Low Level Techniques

Very precise low-level techniques are essential for experiments looking for very rare events, where identification and reduction of the background plays a key role. At the MPIK, there is a long tradition and a lot of expertise in that field. The Institute's low-level underground laboratory provides shielding against cosmic rays and thus offers very good conditions for detector development for low-background experiments. Highly sensitive gamma-ray spectrometers and very pure miniature proportional counters serve to check the radiopurity of materials and are the heart of assay techniques for very low concentrations of radioisotopes.

Among the most notorious contaminants are the radioisotopes ^{222}Rn and ^{85}Kr, for which various world-leading screening, measuring and reduction techniques are employed. The "Auto-Ema" system extracts fully automatically the radon outgassing from solid materials allowing for its sensitive measurement and the selection of suitable detector materials. Rare-gas mass spectroscopy was pushed to ppq sensitivity which allows, for example, to control ^{85}Kr in Xe to the level of 10^{-23}. Novel surface coating technologies are developed in order to push the backgrounds to unprecedented levels and to be most sensitive to dark matter.



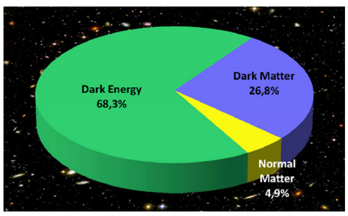
View into the GIOVE germanium spectrometer in MPIK's low-level laboratory.

Dark Matter – Structure Forming Agent in the Universe

Based on cosmological observations such as galactic rotation curves, gravitational lensing at galaxy clusters or the cosmic microwave background, it was shown that the Universe consists to about 27% of dark matter (DM), while the fraction of ordinary visible matter is only about 5%. The remainder is the mysterious dark energy which is responsible for the acceleration observed in the expansion of the Universe. From a theoretical point of view, weakly interacting massive particles, WIMPs, are promising candidates for dark matter, since they should have formed in the early Universe in the required amount and since they are motivated in required extensions of the Standard Model of particle physics. But the researchers also study other solutions motivated by other theoretical aspects. Examples are 'axions', 'sterile neutrinos' or particles only interacting gravitationally. Furthermore, combined analyses and interpretation of different experiments and embedding candidates into consistent theoretical models aim at a global picture and at resolving controversial results.

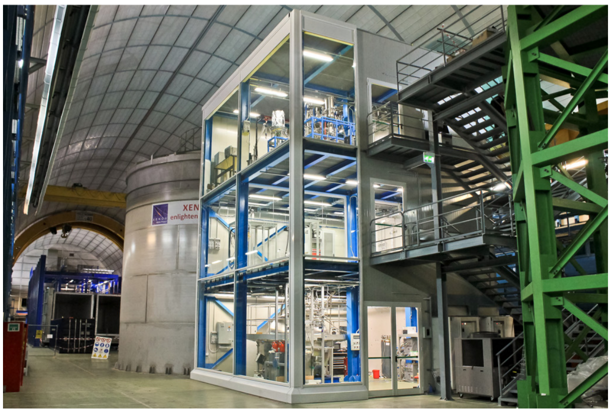
MPIK is involved in the direct search for WIMPs with the XENON experiments in the Gran Sasso underground laboratory in Italy which use ultrapure liquid xenon as the detector medium. The detector observes the combination of scintillation light and ionization emerging from the rare interactions of WIMPs with Xe atoms. XENON1T reached the highest sensitivity of such experiments deeply probing the expected parameter regions where WIMPs and other dark matter candidates are expected. The upgrade to XENONnT is nearing completion and will lead to a ten-fold sensitivity increase.

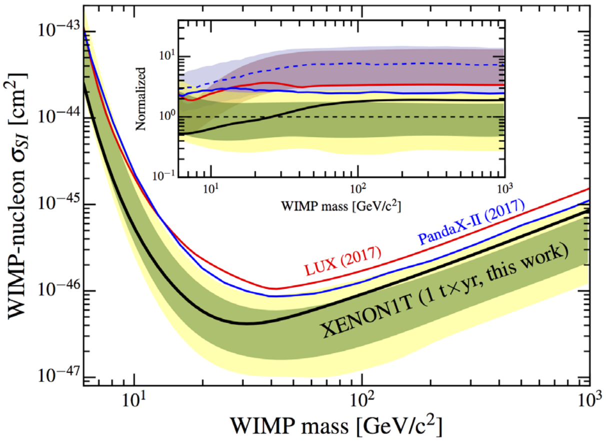
In addition, the H.E.S.S. telescopes look for high-energy gamma rays, produced by the annihilation of DM particles in the DM halo of the Milky Way. Despite the high sensitivity reached, none of the dark-matter detectors has so far seen a signal.



Composition of the Universe.

XENON1T probes dark matter with the world's best sensitivity





The direct detection of dark matter would constitute a great step in understanding the nature of this non-luminous component of our Universe. Data collected by the XENON1T detector with an unprecedented exposure of about 1 ton × year, agrees with the expected background and allows to place the most stringent exclusion limit on WIMP-induced spin-independent interactions for dark matter masses above a few GeV [1].

A key requirement to achieve the required sensitivity is a careful selection and control of the detector materials which determine the detector background. Gamma-ray spectroscopy, measurements of radon emanation with proportional counters and xenon purity control using rare-gas mass spectrometry are some of the tools that assure the lowest background levels ever measured. Such a low intrinsic activity allows the detector to search not only for dark matter interactions but also for other rare nuclear processes. The collaboration has been able to measure for the first time the double electron capture of ^{124}Xe. In this process, two electrons are absorbed in the nucleus simultaneously emitting two neutrinos. The signal in the liquid xenon originates from the relaxation of the electronic shell after the decay. The measurement in XENON1T has determined a lifetime of 1.8×10^{22} y for this process which is the longest half-life ever measured directly [2].

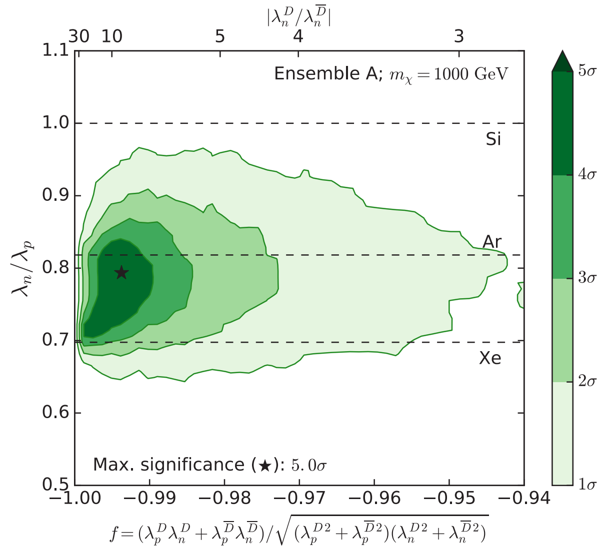
References:

[1] XENON Collaboration, Phys. Rev. Lett. 121 (2018) 111302, DOI: 10.1103/PhysRevLett.121.111302

[2] XENON Collaboration, Nature 568 (2019) 532, DOI: 10.1038/s41586-019-1124-4

Theory of dark matter

Improved direct detection limits on standard WIMP dark matter lead to increased interest in alternatives. A WIMP signal could, however, be around the corner in upcoming searches and combining direct searches with indirect and collider data one could learn about its properties (quantum numbers, spin, self-conjugate, etc.). Well-known simple models include the Higgs and the Z' portal, as well as dark photon models that require kinetic mixing. Many simple cases are essentially ruled out by a combination of different probes which allows to study which interactions, production mechanisms or non-standard masses are allowed.



Various aspects of dark matter models and phenomenology were studied. For instance, new interactions on the evolution of keV sterile neutrino dark matter in the early Universe can thermalize the sterile neutrinos and resolve the tensions with structure formation and X-ray observations. Due to its highly suppressed cross section (fermionic) dark matter interacting via pseudoscalar mediators was expected to be unobservable in direct detection experiments. However, the leading one-loop contribution to the effective dark matter-nucleon interaction dominates the scattering rate and was found to be in the vicinity of the neutrino floor. Direct detection signals from at least three different targets may be used to determine whether the dark matter particle is different from its antiparticle. We have determined the significance with which the self-conjugate nature can be rejected, and found cases with up to 5-sigma discrimination potential.

References:

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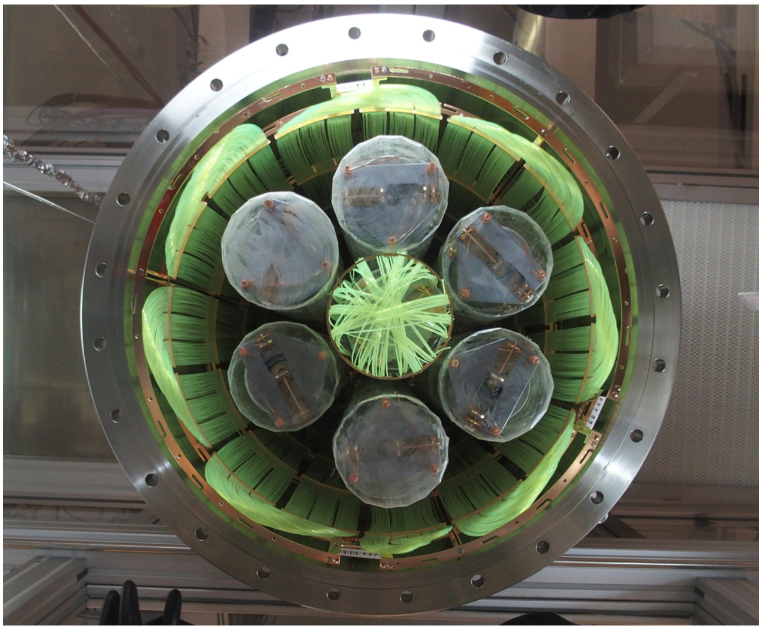
Neutrinos – Particles with Striking Properties

Neutrinos are electrically neutral elementary particles of tiny mass which occur as three different types, so-called flavours. Besides photons, they are the most abundant particles in the Universe, but we don't notice them as they interact only rarely with matter. Thus, sensitive detectors with excellent shielding against background signals are required to detect them.

A neutron inside a nucleus beta decays to a proton, an electron and an antineutrino leading to another element. Some atomic nuclei, one of them the germanium isotope ^{76}Ge, are not subject to the single but instead the double-beta decay: two neutrons are decaying at the same time with either two or possibly no neutrino. The GERDA experiment searches for the neutrinoless double-beta decay in pure germanium crystals enriched with ^{76}Ge. Neutrinoless double-beta decay, which is well motivated by theory, is an extremely rare event. Until now, no evidence for the decay was found – only that its half-life in ^{76}Ge must be at least 10^{26} years. The successor project LEGEND200 is based on GERDA with a significantly higher ^{76}Ge mass which will improve the sensitivity considerably. A signal would prove that neutrinos are their own antiparticles, so-called Majorana particles, making it possible to deduce their mass.



The germanium detectors of GERDA in their shielding.

For the rest mass of neutrinos only limits and differences are known to date. Other experiments to determine the neutrino mass rely on the capture of an electron by a proton in a nucleus. Therefore, the knowledge of the exact mass difference between mother and daughter nucleus is necessary. A group at the MPIK is performing such precision measurements.

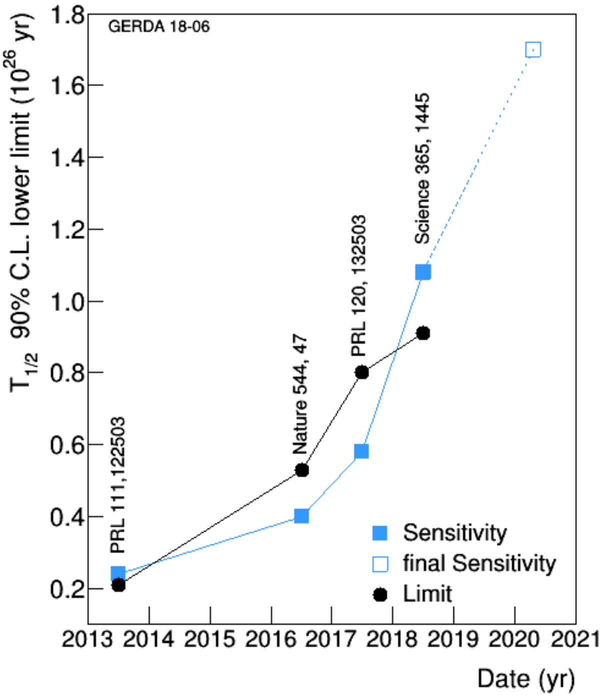
The periodic changeover between the three neutrino flavours electron, muon and tauon neutrino ("neutrino oscillations") is described by so-called mixing angles. The Double Chooz experiment used electron antineutrinos from a nuclear power plant in France to measure one of the three mixing angles. The two identically designed detectors with liquid gadolinium-containing scintillator at different distances from the reactors are sensitive only to electron antineutrinos, the number of which declines from the near to the far detector due to the oscillations. The results confirm that also this mixing angle has a non-zero value which means that all oscillations take place.

Indeed, many experiments in the vicinity of nuclear power plants detect about 6% less neutrinos than expected. The STEREO detector tries to find out whether sterile, i. e. non-interacting, neutrinos might be responsible for this reactor neutrino anomaly.

The CONUS experiment also uses reactor neutrinos to investigate the coherent neutrino-nucleus scattering – scattering of neutrinos at the nucleus as a whole. Highly pure germanium detectors with very low energy threshold measure the tiny energy transfer due to this scattering process, which, however, is significantly more probable than the interaction of neutrinos with electrons.

Record sensitivity for the search of neutrinoless double beta decay

The sensitivity of an experiment for a rare decay search depends on the number of background events in the search window. For GERDA, the expected number is about 0.4 for the design exposure – the exposure is the product of active detector mass and measurement time. This value is exceptionally low in comparison to all competing experiments. For values smaller than about 1, the sensitivity for setting a limit on the half-life improves linearly with the exposure rather than with the square root. Such an experiment can therefore be called "background-free" [1].



With the recent publication [2] the low background was confirmed with more statistics. For the first time, a double-beta decay experiment surpassed the threshold of 10^{26} years for the sensitivity of setting a 90% C.L. limit on the half-life – in our case for the isotope ^{76}Ge.

The history of half-life limits and the sensitivity are plotted in the figure. Since 2015, the second phase of GERDA is running stable with the above-mentioned low background. In November 2019 the design exposure was reached and we expect an improvement of the sensitivity by 50%.

The extremely good performance of GERDA in terms of background suppression – but also energy resolution – lead to the formation of the new LEGEND collaboration that adopted the experimental concept of operating germanium detectors in liquid argon. Starting in 2020, our existing infrastructure will be modified by LEGEND to boost the half-life sensitivity for setting a limit to 10^{27} years.

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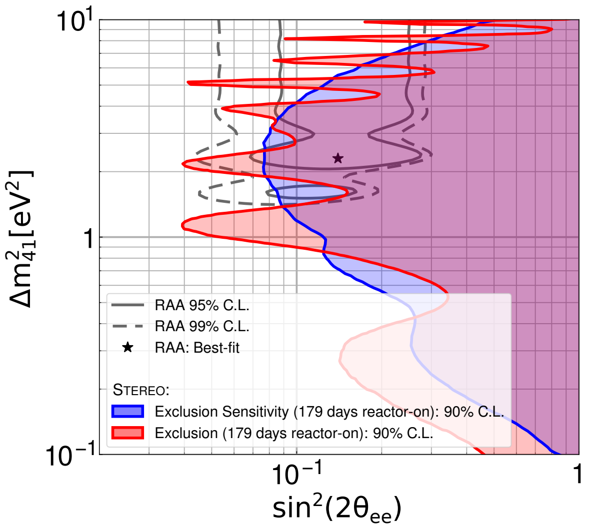
Constraints on the existence of sterile neutrinos

The search for light sterile neutrinos with the Stereo detector [1] started after the installation at the 58 MW_{th} research reactor of ILL Grenoble in November 2016. A first analysis in the phase-I of the experiment using 66 days of data with the reactor turned on already allowed to exclude a large fraction of the parameter region of interest [2]. A very good agreement between experimental data and the simulated antineutrino signal in the Stereo detector could be achieved using FIFRELIN, a Monte Carlo code developed at CEA/DEN Cadarache, France. This code is capable of modelling the emission cascade of gammas and electrons resulting from the de-excitation of the excited nuclei created by neutron capture after the neutrino interactions in the Stereo detector. In this way, the description of the energy measured after selected neutron captures and the understanding of the efficiency for neutrino detection improved notably [3]. With additional optimizations in the neutrino analysis and an extended data taking period including about 180 days of reactor turned on and 230 days of reactor turned off even stronger constraints on the existence of sterile neutrinos are set [4]. The figure shows the excluded combinations of neutrino mass splitting and mixing angle. The Stereo experiment will also deliver a leading precision result on the absolute comparison between the predicted and measured total neutrino rate for a highly enriched ^{235}U reactor. Finally, the extensive calibration of the energy scale allows for an accurate study of the reactor anti-neutrino spectral shape which is currently under heavy discussion in the field of reactor physics.



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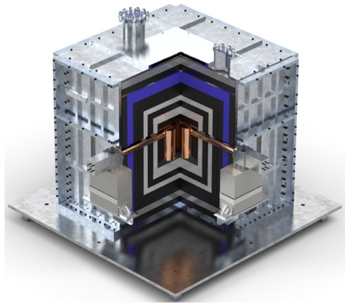
Neutrinos scattering on atomic nuclei

The Standard Model of particle physics predicts six ways of interacting with matter for the tiniest and most elusive particles: the neutrinos. The most intriguing and till 2017 undetected [1] channel is a scattering process of neutrinos with the constituents of atomic nuclei. Due to quantum-mechanical coherency the respective cross section can scale with the squared number of neutrons in the nucleus and thus be enhanced by several orders of magnitude compared to the other interaction channels. This enhancement allows for the first time to build kg-sized neutrino detectors which, however, need the ability to register extremely small nuclear recoils induced by the momentum transfer of the neutrinos.

To this end, we initiated the CONUS experiment, aiming at detecting neutrinos at the nuclear power plant in Brokdorf, Germany. With its 3.9 GW thermal power it is one of the most powerful single reactor neutrino sources world-wide. At the detector site 17 m from the reactor core, the immense neutrino flux is still 10^{13} per second/cm^2. There, we set up 4 specifically designed low-energy-threshold germanium detectors inside an elaborated passive and active shield, and started the operation in April 2018. Since then, data have been collected including few short reactor-off periods. A preliminary analysis of the count rates during reactor on vs. off periods has already provided a first hint of observation of this coherent neutrino-nucleus scattering process [2].

Ongoing activities focus on optimization of the detector operation under extraordinary laboratory conditions, the background understanding [3] and quantifying systematics effects, as prerequisites to a final spectral shape analysis.



Three-quarters portrait of the CONUS setup including the germanium detectors, the passive and active shields.

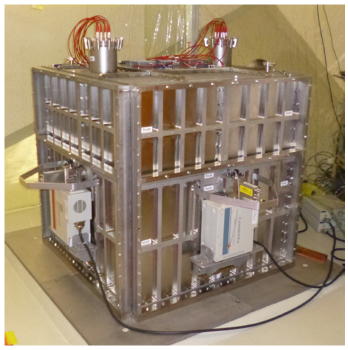


Photo of the CONUS setup after its successful installation at the nuclear power plant in Brokdorf.

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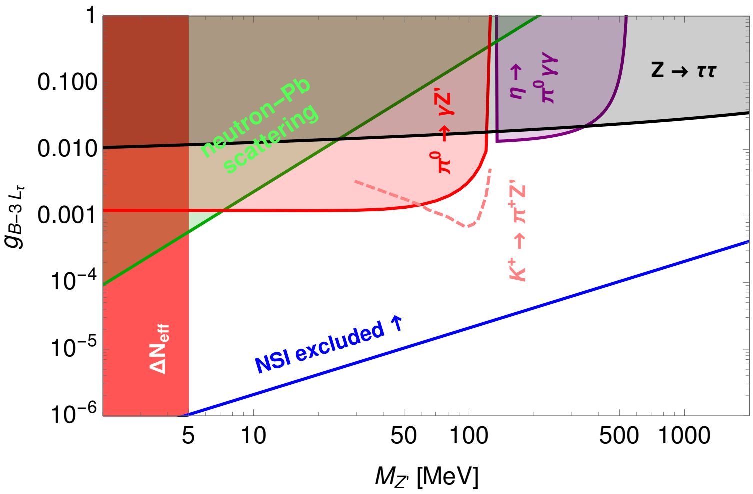
Neutrinos and physics beyond the Standard Model

Neutrinos are a window to physics beyond the Standard Model. Mechanisms to generate neutrino mass have a variety of new features such as new particles, new energy scales, new interactions, etc. Within such mechanisms the baryon asymmetry of the Universe can be generated, and connections to dark matter are also very frequent. Other consequences include observable effects in running and future experiments that probe neutrino parameters. The properties of neutrinos also influence several interesting astrophysical objects such as Supernovae. The physics behind neutrino mass may also be related to interesting ideas related to conformal symmetry, or classically scale-invariant theories, that may solve the hierarchy problem. A broad program investigates consequences of neutrino mass and mixing theoretically and phenomenologically. This includes proposing and studying new physics effects in neutrinoless double beta decay or direct mass experiments. The particles related to those new effects would show up at colliders or in rare decays, which provides a way to distinguish the new from standard neutrino physics. Features of supernova neutrino spectra and the possibility to triangulate the position of a supernova via different neutrino arrival times in different detectors was investigated. Additional interactions of neutrinos (NSI) can cause an observable effect in neutrino oscillations. The current constraints were shown by us to be often better than the ones of other probes for such new interactions.



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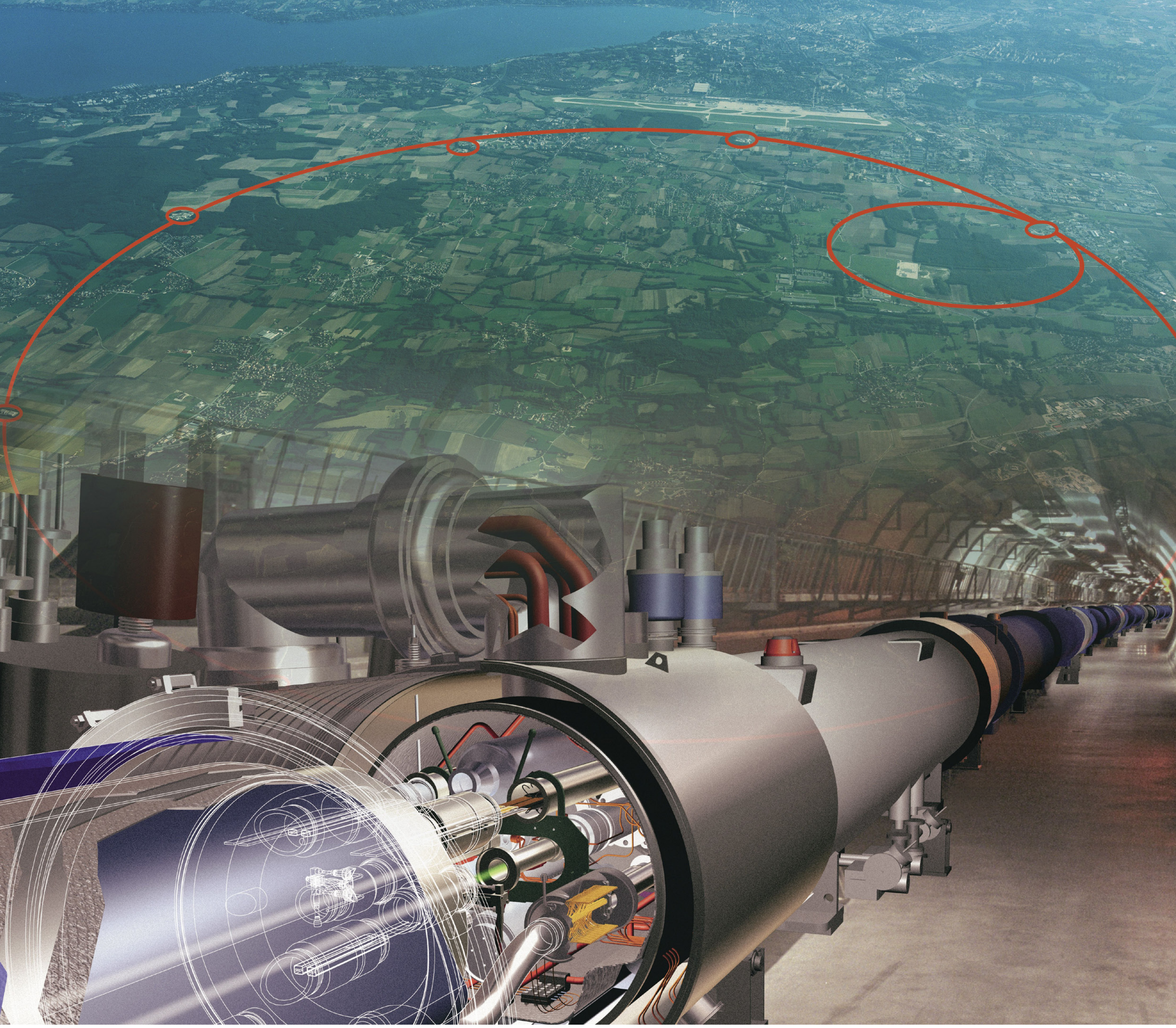


1.3 Beyond the Standard Model

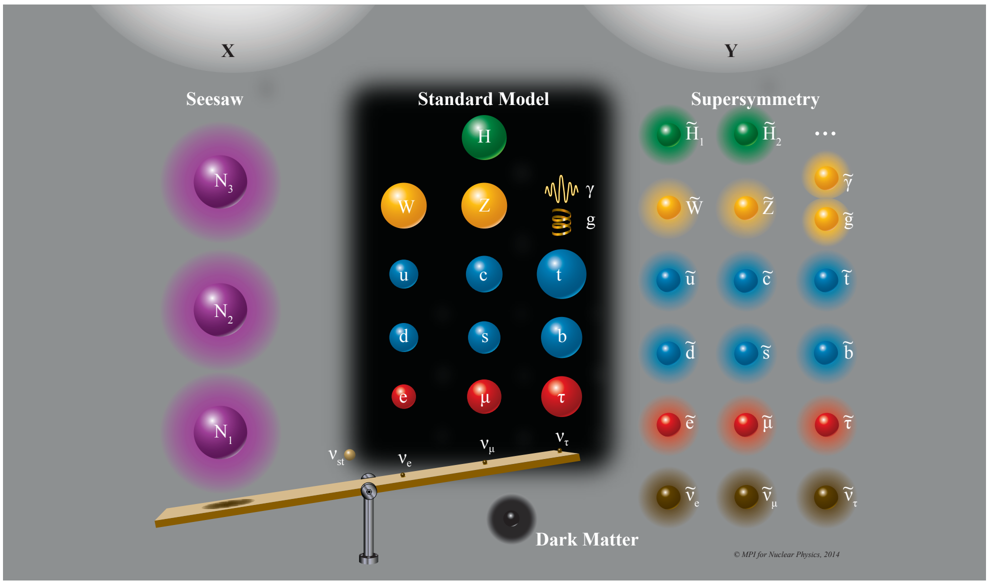
An upgrade of the Large Hadron Collider may detect physics beyond the Standard Model. (Image: CERN)

The Origin of Mass – Physics Beyond the Standard Model

The Standard Model of elementary particle physics successfully describes all known elementary particles (and corresponding antiparticles): each 6 quarks and leptons. In addition, there are gauge bosons mediating the particle's interactions, and the Higgs boson. Its discovery on 2012 opened a number of fundamental questions that are addressed by theoreticians at the MPIK.

Both dark matter and the proof of non-zero neutrino masses as well as some further theoretical deficiencies require an extension of the Standard Model of elementary particle physics which seems to be valid only up to a certain energy, from which on so-called new physics comes into play. Theoreticians of the MPIK are studying supersymmetry and Grand Unified Theory as promising extensions of the Standard Model in connection to present and future particle physics experiments, and cosmology.

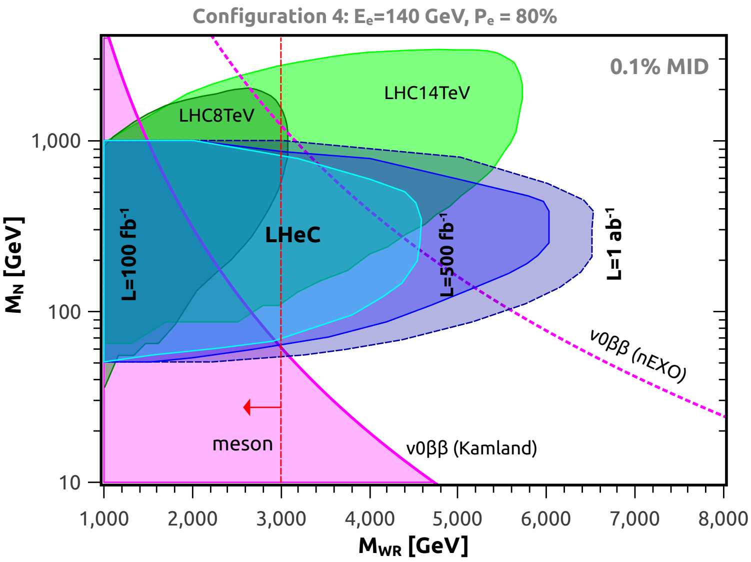
A lot of theoretical work is done at MPIK on the origin of neutrino masses and mixings via basic and phenomenological studies. The so-called seesaw mechanism is a way to explain the smallness of neutrino masses based on the presence of new heavy particles, which are in fact predicted by many theories beyond the Standard Model. Neutrino masses and dark matter may have a common origin. The overall aim is a deeper understanding of the fundamental laws of nature.



Elementary particles of the Standard Model (black background) and their hypothetical supersymmetric and seesaw partners.

Lepton number violation at high and low energy

Essentially all theories beyond the Standard Model predict lepton number violation (LNV). In this case, neutrinoless double beta decay occurs at some level. If the particles mediating LNV are at the TeV scale, present and future colliders can produce them, and half-lifes for neutrinoless double beta decay are generated at a level that is testable in upcoming and running searches [1]. Hence, both approaches are complementary, and allow for tests of the underlying mechanism of LNV if it is observed in one of them.



The LHC might however be blind to certain parameter combinations, leading to a gap in sensitivity that other colliders may close. In particular, we have analysed how a future electron-proton collider, called LHeC, can probe the parameter space and how this would compare to LHC and double beta decay [2]. The chosen framework applied left-right symmetric theories. In the analysis one needs to take into account different values for the polarization of the electrons or the rate of charge misidentification, which are currently not known.

Nevertheless, a sizable part of the reachable parameter space is beyond the expected reach of the LHC and of future neutrinoless double beta decay experiments.

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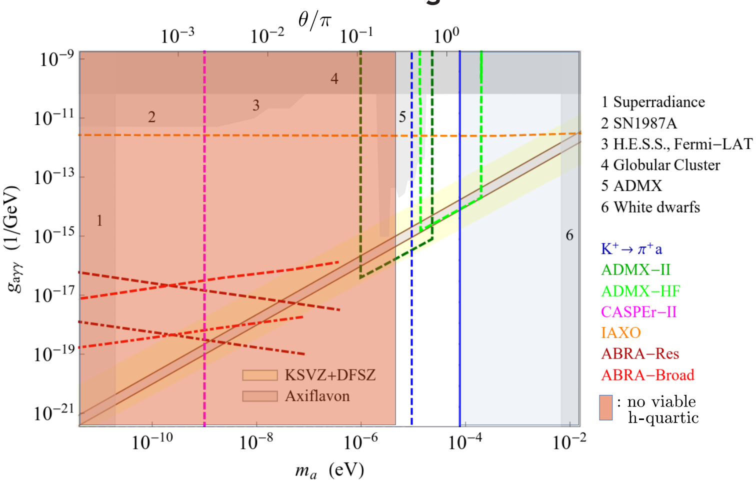
Unified solutions to shortcomings of the Standard Model of particle physics



Four of the biggest mysteries in fundamental physics are: the origin of the huge hierarchies in fermion masses, the seemingly fine-tuned vanishing of CP violation in strong interactions, the nature of dark matter (DM), and the dynamics behind electroweak symmetry breaking. A simple and unified solution to these puzzles has been proposed by extending the Standard Model of particle physics with a single scalar multiplet whose vacuum expectation value addresses all these issues. This unified picture makes the model very predictive, such that this “Axiflavon”-Higgs can be fully tested at near-future *axion* and *flavour* experiments, see the Figure, where solid (dashed) lines correspond to current (projected) bounds [1]. In a similar spirit, recently an *effective* DM scenario has been proposed, which explains the smallness of light-quark masses, evades direct detection limits, and features new collider signatures to be searched for [2].

Finally, since standard ideas for realizing the Higgs Boson as a composite particle, which in addition to some of the issues above elegantly solves the famous ‘gauge hierarchy problem’, got in increasingly pressing tension with missing signals of predicted light partner particles of the top quark at the LHC, threatening the idea of a natural composite Higgs, the recent model-building efforts were also focused on exploring ways out of this. In fact, an elegant means to save such models resulted, entertaining a new, softened, way of global-symmetry breaking by completing fermion multiplets to full SO(5) representations, which lifts the anomalously light partners. This allows to construct setups that solve the hierarchy problem, while being in full agreement with current LHC limits on top partners, yet detectable at the LHC upgrade or a future 100 TeV collider [3].

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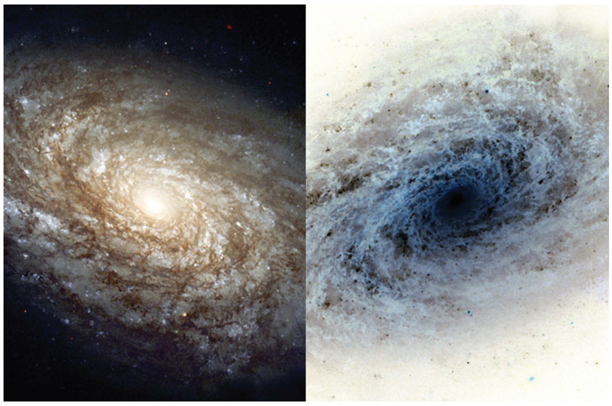
Matter and Antimatter – Search for the Crucial Difference

There is no indication that anywhere in the visible Universe considerable amounts of antimatter exist. Since particles and antiparticles must have been created in equal amounts in the Big Bang, there must be a fundamental difference between them. Else, they would have completely annihilated, leaving a Universe filled with pure radiation.

This symmetry violation must have occurred in the early Universe, but the Standard Model of elementary particle physics can't explain the observed asymmetry. A scenario for this, in which neutrinos play a crucial role, is the so-called leptogenesis which is explored by MPIK theorists. Here, the asymmetry of light particles subsequently induces the observed asymmetry of heavy particles.

The LHCb experiment at the Large Hadron Collider (LHC) of CERN in Geneva searches for matter/antimatter differences. Besides many other particles, in proton-proton collisions so-called B mesons are created, heavy particles consisting of each a light quark and a heavy antiquark; and reversely for their antiparticles. Measurements of their decays that lead to equal amounts of matter and antimatter showed that there are processes in which antimatter disappears faster than matter – however as predicted by the Standard Model of elementary particle physics.

Measurements of the masses as well as of the magnetic moments of the antiproton and the proton in Penning traps didn't yet reveal any differences despite the highest precision. But further advanced measurement techniques may resolve the puzzle.

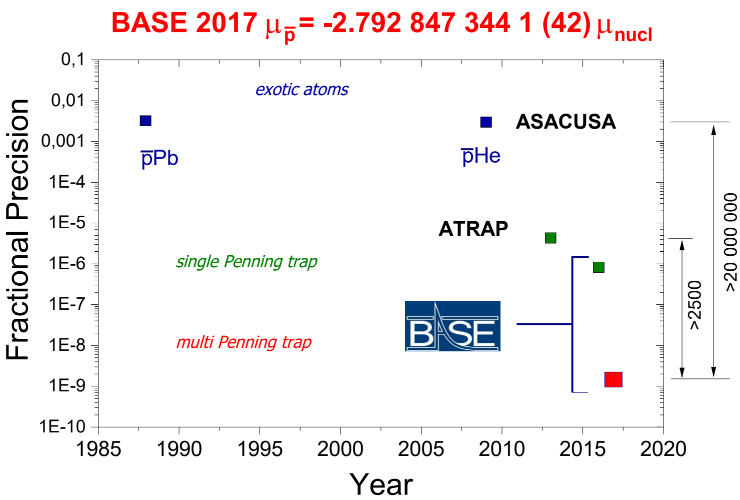


Despite intensive searches, astronomical observations have not provided any evidence of the existence of antigalaxies.

Protons and antiprotons under the microscope

Within the Standard Model of particle physics interactions are believed to be invariant under the combined CPT transformation. Consequently, particle-antiparticle pairs are expected to be created and annihilated in equal amounts and to have identical properties except for signs. This theoretical understanding is, however, in conflict to our astronomical observations, which indicate that our Universe consists almost exclusively of matter. The Standard Model can neither explain this matter-antimatter asymmetry in our Universe, nor reproduce the observed matter excess by any other means. Searching for an additional symmetry breaking or interaction may provide important hints to improve our understanding and explain the matter-antimatter asymmetry.

To this end, we operate several experiments within the BASE collaboration to compare the charge-to-mass ratios and magnetic moments of protons and antiprotons with ultra-high precision. Using single- and multi-Penning traps, we were able to outperform early spectroscopic experiments on exotic atoms. Our results verify that the magnetic moments are equal at the parts-per-billion level and that the charge-to-mass ratios are equal at the 70 parts-per-trillion level. However deviations, that explain the matter-antimatter asymmetry, might be observed at higher measurement precision. Thus, in future novel techniques like sympathetic laser cooling using a common endcap technique and phase-sensitive detection methods will be employed to improve upon the constraints even further.



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