Astro-particle Physics

1

1.1 The Non-Thermal Universe

Rendering of the southern CTA array. (© G. Pérez Diaz (IAC) / M.-A. Besel (CTAO) / ESO / N. Risinger (skysurvey.org))

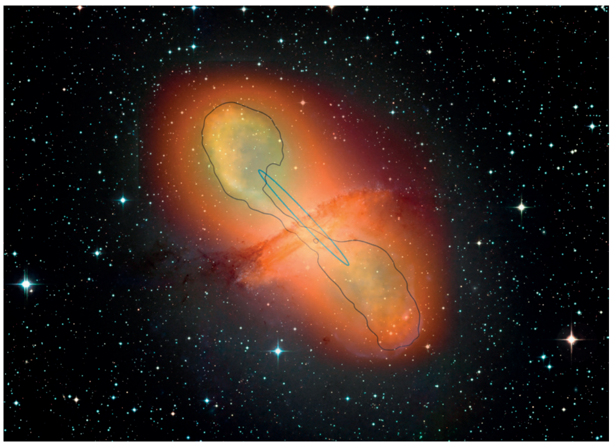
Cosmic Accelerators – Astronomy at the Highest Energies

High-energy astrophysics at MPIK is characterized by a close cooperation between experimentalists and 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 high enough temperatures were reached for a very short time. Charged particles, known as cosmic rays, 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 MPIK is going into the modelling and theoretical description of processes within the different cosmic accelerators, as well as into VHE observations.

VHE gamma radiation is produced when strongly accelerated charged particles interact with the interstellar gas or photon fields. In contrast to cosmic rays, 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.

H.E.S.S. has detected more than 100 VHE gamma-ray sources – each being a cosmic particle accelerator – arranged along the galactic equator. Many of these sources are connected with the remnants of exploded stars such as supernovae or pulsars and their winds. The supermassive black hole in the galactic centre turned out to be a cosmic "pevatron" that accelerates particles to tremendous energies. A hitherto unidentified galactic source was recently assigned to a massive young star cluster. In 2022, H.E.S.S. reported the first observation of a nova outburst in VHE gamma rays and was able to follow both its growth and subsequent fading. Beyond the Milky Way, H.E.S.S. identified several extraordinarily luminous sources in the Large Magellanic Cloud. In the last years, it could detect and spectrally analyse the afterglow of gamma-ray bursts over many hours. H.E.S.S. also showed that the VHE gamma-ray emission from galaxies with active nuclei extends over several thousand light-years along jets of plasma instead of being concentrated at the central black hole.



Composite image of Centaurus A, showing the jets emerging from the galaxy's central black hole, together with the associated gamma radiation (Image credits: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray), H.E.S.S. Collaboration (Gamma)).

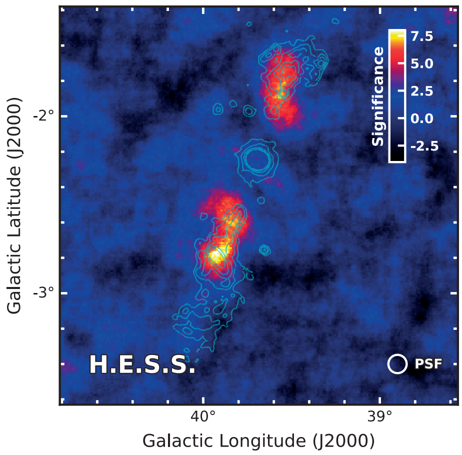
HAWC observations complement those of H.E.S.S., providing sensitivity to larger-scale emission and up to higher energies. Recently, HAWC has detected cosmic gamma rays with energies up to at least 200 TeV, (1 TeV = 10^{12} eV) from the direction of a superbubble surrounding the birthplace of massive stars.

The future instruments CTA and SWGO (see below) 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.

Spatially resolved gamma-ray emission from nearby jets

Since its detection in the mid 1970s, the microquasar SS 433 has emerged as one of the most intensively studied systems in the Galaxy. Microquasars, so-called due to their resemblance to the powerful large-scale jets observed emanating from the centres of other galaxies (quasars), offer powerful laboratories to resolve jet processes in our own Galaxy. In the case of SS 433, material from a ~10 solar-mass star is accreted onto a compact object, presumably a low-mass black hole, launching a pair of jets that move at ~25% the speed of light.

Out to distances of 0.1 parsecs from the binary, the inner jets have been resolved down to x-ray wavelengths. As the jets propagate further out, they remain dark until they abruptly reappear as bright x-ray sources at 25 parsecs. How and why this happens is still unclear, but the appearance of several bright x-ray knots, visible in the blue contours that follow the outer jets, suggest recent non-thermal particle acceleration far from the central binary, indicated by the central contours. The detection of the outer jets with the HAWC observatory confirm that electron acceleration to hundreds of TeVs is occurring.



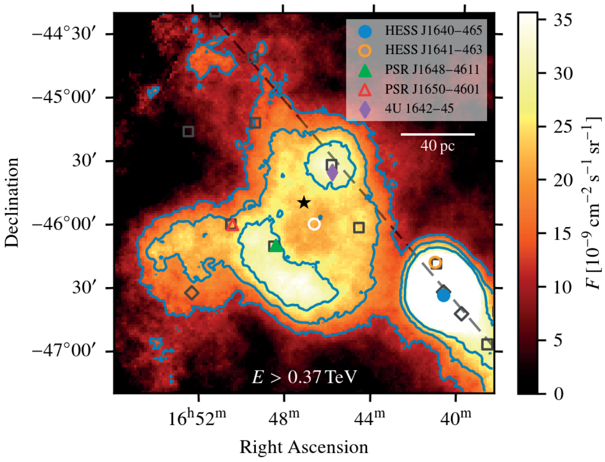
Following up on this discovery, the H.E.S.S. array of imaging atmospheric Cherenkov telescopes performed a deep observation campaign which resulted in the first ever detection of SS 433 by such an instrument. The colours in the figure show the emission detected by H.E.S.S., revealing a close correlation between the gamma-ray and x-ray emission in the outer jets. The superior resolution of H.E.S.S. allows for a detailed study of the morphology and spectral properties of the gamma-ray emission from the SS 433 jets.

In particular, the H.E.S.S. observations can be used to determine both the size and shape of the gamma-ray emission regions from the jets. The flux from each jet was also measured, with no indication of the flux tapering off at the highest energies. The jets are likely emitting gamma rays at even higher energies than those probed with H.E.S.S., a regime soon to be accessible to CTA or SWGO. In order to reach such high energies, the acceleration of particles in the jets of SS 433 must be relatively efficient, a fact which can, in turn, be extrapolated to the much more distant and larger jets launching from the centre of other galaxies.

Reference:
H.E.S.S. Collaboration, in preparation

Westerlund 1: a powerful cosmic-ray accelerator

Young massive star clusters have recently become popular as potential major contributors to the flux of the highest-energy Galactic cosmic rays – as competitors to isolated supernova remnants, the long-term "culprits". Westerlund 1 is the most massive known young star cluster in our Galaxy. Its total mass is about 10^5 solar masses, half of which is contained within a radius of ~1 pc. In 2012, the H.E.S.S. Collaboration reported the detection of an extended gamma-ray source called HESS J1646–458, coincident with Westerlund 1 [1]. However, due to the limited data set available at the time, the emission could not firmly be linked with Westerlund 1. With an increased data set, it was now possible to perform a more detailed analysis, which has recently been published [2].



Gamma-ray map of the HESS J1646−458 region. The position of Westerlund 1 is marked by the black star symbol; the grey, dashed line shows the Galactic plane. Coloured symbols indicate objects listed in the legend, and dark grey symbols indicate further objects detected by the Fermi satellite.

The gamma-ray emission of HESS J1646–458 extends over a region almost 2 degrees across, which corresponds to about 140 pc – much larger than the cluster itself, as shown in the map. Intriguingly, the gamma-ray emission seems to exhibit a shell-like structure, with several bright peaks in addition. A detailed investigation of possible counterparts has revealed that only cosmic rays accelerated by Westerlund 1 can explain the observed gamma-ray emission. The large spatial extent of the emission and its shell-like structure may indicate a connection with the collective wind of the cluster, which forms as a superposition of the stellar winds of the massive stars inside Westerlund 1. If confirmed, it would be the first time that the collective wind of a massive star cluster could be directly linked to high-energy gamma-ray emission, and thus be identified as a cosmic-ray acceleration site.

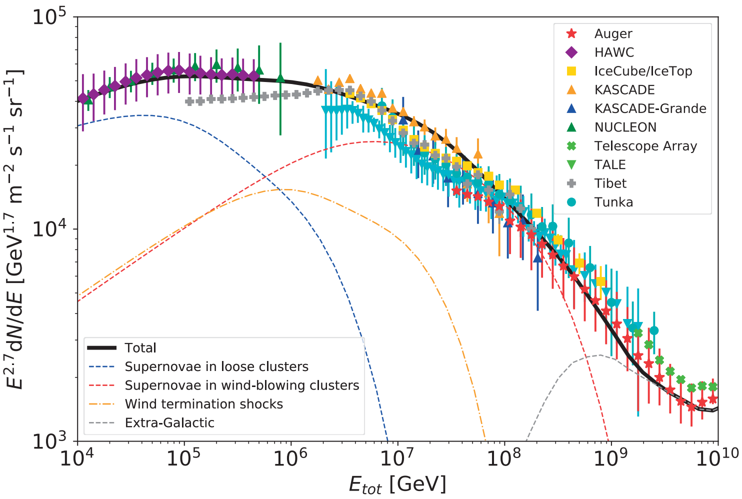
References:
[1] H.E.S.S. Collaboration, Astronomy & Astrophysics 537, A114 (2012), DOI: 10.1051/0004-6361/201117928
[2] H.E.S.S. Collaboration, Astronomy & Astrophysics 666, A124 (2022), DOI: 10.1051/0004-6361/202244323

A superbubble model for galactic cosmic-ray origins

Earth's atmosphere is continuously bombarded by energetic cosmic-ray particles. Their energy spectrum resembles a series of connected power-laws, covering more than eleven decades in energy. Two significant breaks in the particle spectrum are observed at a few PeV (10^{15} eV) and a few EeV (10^{18} eV), the cosmic-ray knee and ankle respectively.

Below the knee, cosmic rays are thought to be energized at supernova remnant shocks, though this theory currently lacks observational confirmation. Above the ankle particles are of extragalactic origin, though we still only speculate on their sources. Between the knee and ankle however, cosmic-ray sources, while Galactic in origin, have received scarce consideration. Recent gamma-ray observations hint that sources may be found in superbubbles: low density cavities blown in the interstellar medium by stellar clusters and their associated supernova explosions.

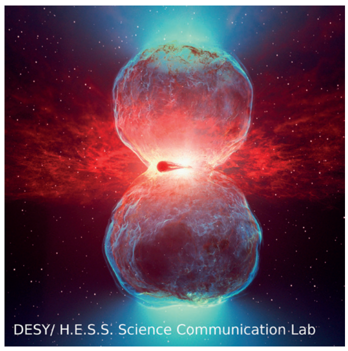
In work developed at MPIK, a promising mechanism to accelerate cosmic rays beyond the knee in young massive stellar clusters has been proposed. The compact clustering of strong winds from many massive stars drive turbulent magnetic field amplification in the core, which is carried out on the cluster's collective wind. After several million years, the supernovae from massive stars launch fast shocks into the magnetized wind, providing favourable conditions to accelerate particles to extreme energies. Using Gaia data, it is inferred that ~15% of massive stellar clusters can generate the winds needed to enable acceleration beyond the knee. Coupled with the expected supernova rate, a physically consistent model (see figure) of cosmic-ray production from Galactic stellar clusters can reproduce well current experimental data.



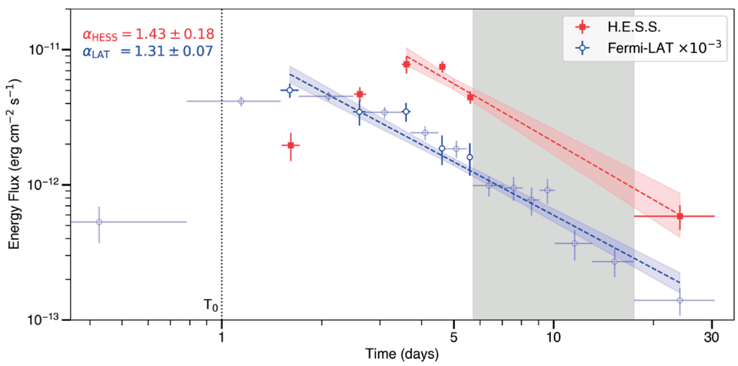
References:
[1] T. Vieu, B. Reville & F. Aharonian, MNRAS, 515, 2256 (2022), DOI:10.1093/mnras/stac1901
[2] T. Vieu & B. Reville, MNRAS in press (2022), arXiv:2211.11625 [astro-ph.HE], DOI: 10.48550/arXiv.2211.11625

Novae - a new class of very-high-energy transients

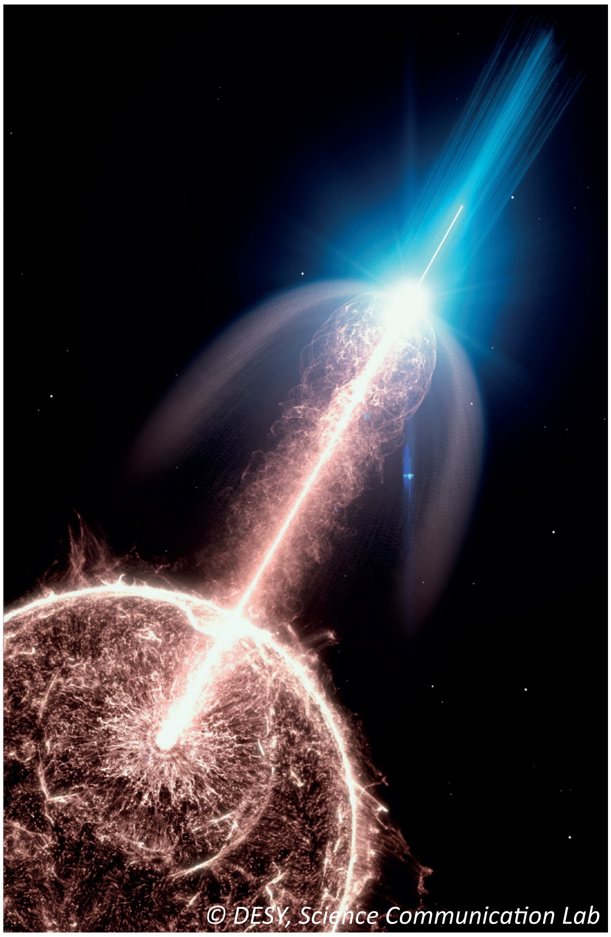
A nova is produced when a white dwarf accretes sufficient material from a stellar companion to ignite a thermonuclear explosion on its surface. Novae are well understood in optical light but the repeated detection by the Fermi LAT satellite confirms also their status as important high-energy astrophysical sources.



On August 8th 2021 an outburst was reported from the recurring nova RS Ophiuchi triggering H.E.S.S. follow-up observations. This yielded a highly significant detection over several weeks. Consequently, RS Ophiuchi not only established a new source class in TeV astronomy but the data set also allowed detailed time-resolved tracking of the gamma-ray emission. This is evident in the light curve (see figure) with the H.E.S.S emission peaking roughly 3 days after the peak seen in the optical (T0) and 2 days after the peak seen by Fermi LAT at slightly lower energies. The similar shape of the H.E.S.S. and Fermi light curves implies a common origin of the emission over the whole MeV to TeV regime, whereas the delay reflects the expected finite acceleration time. Modelling the combined gamma-ray data showed a clear preference for a hadronic origin of the emission. This demands efficient cosmic-ray acceleration to occur at the fast shock driven by the thermonuclear explosion as it propagates into the dense wind of the red giant companion. The maximum photon energy of ~1 TeV closely matches theoretical limits for such systems. This has important implications for its bigger and more powerful siblings, supernova explosions, strongly supporting the hypothesis, that the primary component of Galactic cosmic rays originates in core-collapse supernova remnants.



Reference:
H.E.S.S. Collaboration, Science 376, 77-80 (2022), DOI: 10.1126/science.abn0567



A nearby gamma-ray burst reveals striking features

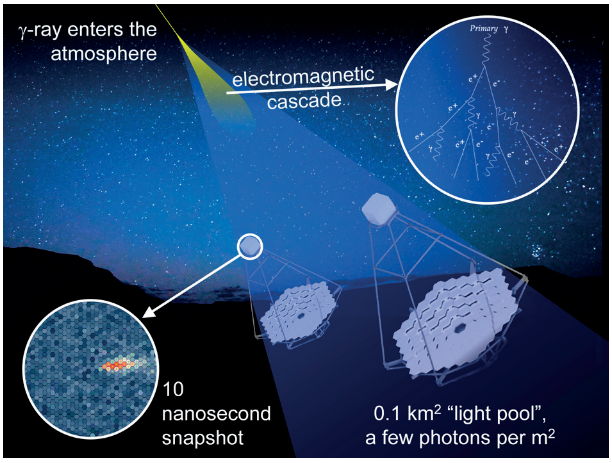
Gamma-ray bursts (GRBs) are extremely bright events associated to the death of massive stars or mergers of compact objects. These distant events briefly become the brightest objects in the Universe, principally emitting in the soft gamma-ray band. The radiation is produced within relativistic jets of matter that are beamed towards Earth. This initial bright episode is followed by a longer-lasting decay period in their emission, as the propagating jet decelerates and the luminosity decreases.

In 2019, the H.E.S.S. telescopes detected at TeV energies the gamma-ray emission from GRB190829A, one of the nearest GRBs ever observed, at a redshift of 0.0785; more commonly, GRBs are seen at redshifts close to 1. Observations with H.E.S.S. were performed 4 hours after the beginning of the burst, when the GRB was visible in the night sky of Namibia and continued for a second and a third night in which, strikingly, TeV emission was still detected. This late-time detection was possible thanks to the proximity of this GRB to Earth, which allowed the TeV photons to travel without being greatly absorbed by the extragalactic background light. This enabled an unprecedented study of the TeV spectrum from a GRB afterglow. Observations in the x-ray band with the Swift satellite are found to have striking similarities in the temporal evolution and spectral features with the H.E.S.S. observations. This reveals an acceleration and emission mechanism that connects eight orders of magnitude in photon energy and challenges well-known theories of TeV emission in GRBs.

Reference:

H.E.S.S. Collaboration, Science 372, 1081 (2021), DOI: 10.1126/science.abe8560

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 specialized cameras. To determine accurately the direction of the incoming gamma ray, the shower is observed stereoscopically by several of these telescopes.

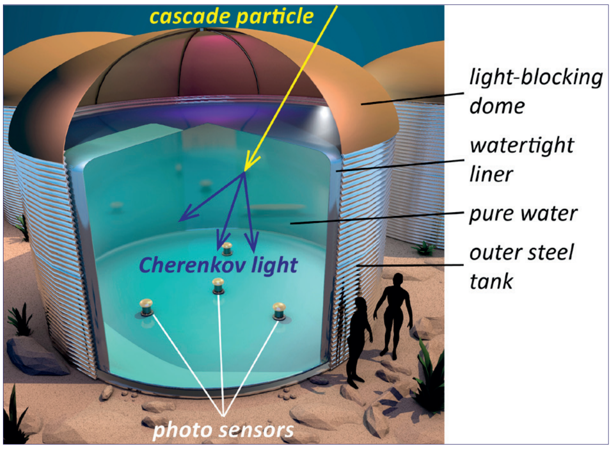
The High Energy Stereoscopic System H.E.S.S. consists of five telescopes, four of them each with 107 m^2 mirror area deployed in a square of side length 120 m. A camera composed of 960 photomultiplier sensors is placed at the focus of each mirror. H.E.S.S. was the first instrument that was able to produce true images of astrophysical gamma-ray sources. In the centre of the array, a fifth, huge telescope with 614 m^2 mirror area has been operational since 2012, enhancing the sensitivity of the system and extending observations to lower energies. In 2019, it has been upgraded using the camera technology developed at MPIK for CTA. The new camera provides increased sensitivity for transient phenomena.

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 La Palma, with – in a first step – 64 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 the small- and medium-sized telescopes.

A key milestone towards establishing the CTA Observatory has been reached in 2022 with the submission of the formal request to the European Commission to establish a European Research Infrastructure Consortium.

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 in Mexico. 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 also playing a major role in the development of a next-generation gamma-ray survey observatory in the southern hemisphere, the Southern Wide-field Gamma-ray Observatory (SWGO). SWGO will make use of the same detection principle as HAWC, but cover a much larger area and a wider range of gamma-ray energies.



How a HAWC tank works as a water Cherenkov counter.

Progress towards SWGO

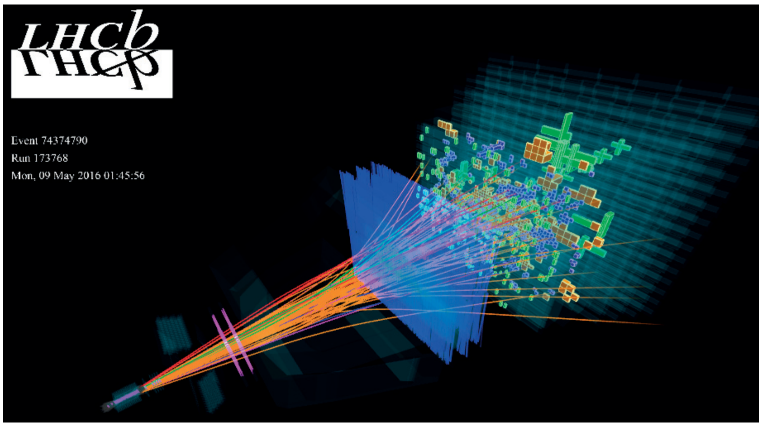
The Southern Wide-field-of-view Gamma-ray Observatory (SWGO) is currently in a design study phase, with the MPIK group strongly involved in the development of the detector design. SWGO will make use of large water-filled units equipped with sensitive light detectors, to measure the Cherenkov light produced by shower particles high in Andes in South America.

A fake lake or Gewässersimulationstank was built at the institute to explore the option of deployment of detector units directly in to a natural or artificial lake (see picture, with MPIK members Hazal Göksu and Fabian Haist). Most aspects of this approach are now demonstrated and it is looking promising in terms of cost and performance. After a decision on site and technology for SWGO, which is planned for 2023, we plan to build an engineering array at the final site. As the first such instrument in the southern hemisphere this will already be extremely exciting in unveiling large-scale emission in the central parts of our own Galaxy.

References:
[1] SWGO website: http://www.swgo.org/
[2] J. Hinton (for the SWGO Collaboration), arXiv:2111.13158 [astro-ph.IM], DOI: 10.48550/arXiv.2111.13158

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.



Visualisation of particle tracks from a collision inside the LHCb detector.

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). It is currently 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 give access to collective phenomena in extended systems consisting of free quarks and gluons, so-called quark-gluon plasmas.

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.

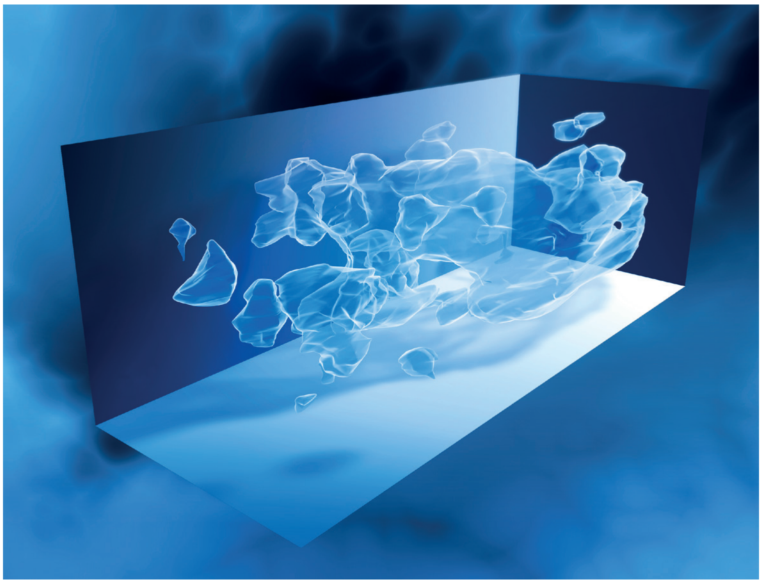
1.2 Dark Matter and Neutrinos

Theoretical proposals to explain dark matter: (clockwise) weak interaction, neutrinos, light bosons, other particles gravitation, and macroscopic objects. Background: Hubble ultra-deep field.

Dark Matter – Structure Forming Agent in the Universe

Based on cosmological observations such as galactic rotation curves, gravitational lensing by galaxy clusters or the cosmic microwave background, it was shown that the Universe consists to about 26.8% of dark matter, while the fraction of ordinary matter is 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 the most promising candidates for dark matter. They are motivated by the so-called WIMP miracle saying that the right amount of dark matter automatically emerges in the hot early Universe, and that they are in addition expected to exist in many extensions of the Standard Model of particle physics. Further solutions studied by researchers are motivated by other theoretical aspects. Examples are ‘axions’, ‘sterile neutrinos’ or particles only interacting gravitationally. Combined analyses and interpretation of different particle and astroparticle experiments aim at testing different proposed explanations for dark matter. Furthermore, candidates must fit into consistent theoretical models.



3D map of the large-scale distribution of dark matter, reconstructed from measurements of weak gravitational lensing with the Hubble Space Telescope. (Image: NASA/ESA/Richard Massey (California Institute of Technology))

MPIK is involved in the direct search for WIMPs with the XENON experiments at the Gran Sasso underground laboratory in Italy. The detector uses ultra-pure liquid xenon as detector medium and observes the combination of scintillation light and ionization charge emerging from the rare interactions of WIMPs with Xe atoms. XENON1T reached in 2018 the highest sensitivity of such experiments, deeply probing the most plausible parameter regions where WIMPs and other dark matter candidates are expected. The upgrade to XENONnT is taking data since 2021 and will lead to a ten-fold sensitivity increase. First results using electron recoils instead of the more standard nucleon recoil data set allowed to set world-leading limits on neutrino magnetic moments, solar axions, axion-like particles and dark photons, demonstrating the broad physics potential of dark matter direct detection experiments.

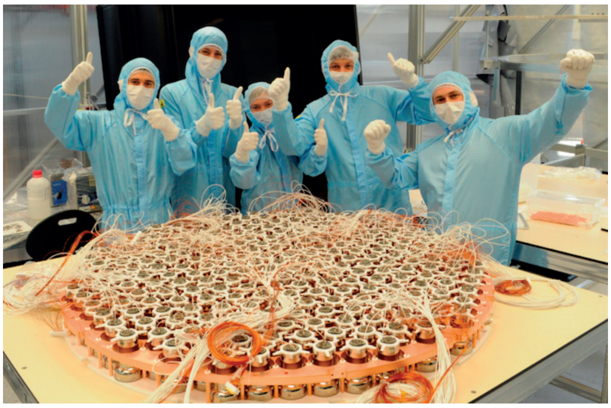
In addition, the H.E.S.S. telescopes look for high-energy gamma rays, produced by the possible annihilation of dark matter particles in the dark matter halo of the Milky Way. CTA and SWGO will reach the critical sensitivity to detect or exclude a WIMP produced under certain assumptions as a thermal relic from the Big Bang. This will lead to a complementary discovery potential about as large as that of XENONnT and related experiments.

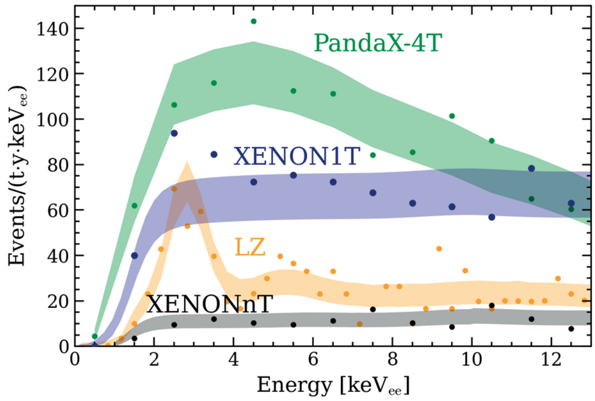
First XENONnT results with the lowest ever achieved background

Understanding the nature of dark matter is one of the most important questions in physics nowadays. The currently running XENONnT detector is the largest and cleanest of the successful series of XENON experiments. Its construction was finished in 2020 (see picture) and it is hunting, since then, for dark matter particles gravitationally bound in our Milky Way.

To unambiguously identify dark matter interactions, an extremely low experimental background is required. Besides a careful selection of detector materials with trace analysis techniques, the purity of the xenon target itself is of great importance [1]. In the last years, radon has become the dominant background in all liquid xenon experiments. In the framework of XENONnT various strategies to avoid, mitigate and remove radon were pursued, which is one of the important contributions of MPIK. The success of this combined approach is visible in the first XENONnT data, which demonstrate the lowest background rate ever achieved in any dark matter experiment [2].

With the data, world-leading limits on new science channels like solar axions, an enhanced neutrino magnetic moment and bosonic dark matter [2] could be derived. Currently, the search for weakly-interacting massive dark matter is ongoing and exciting results are expected in the next years.



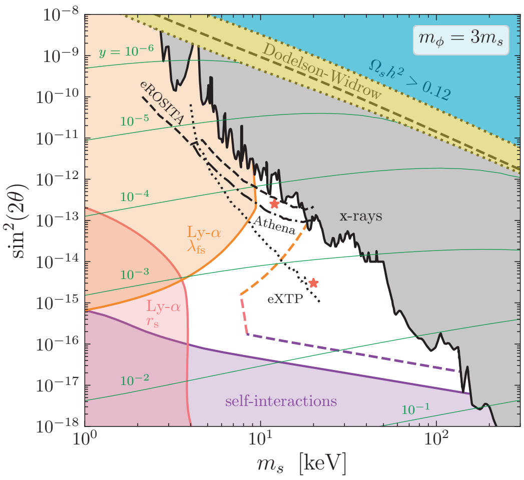


References:
[1] XENON Collaboration, Eur. Phys. J. C 82 (2022) 7, 599, DOI: 10.1140/epjc/s10052-022-10345-6
[2] XENON Collaboration, Phys. Rev. Lett. 129 (2022) 161805, DOI: 10.1103/PhysRevLett.129.161805

Theory of dark matter

In recent years improved limits on WIMP dark matter (DM) from direct and indirect detection as well as collider searches have motivated the exploration of alternative dark matter scenarios. In particular, models with dark matter mass much smaller or larger than the usual WIMP mass of O(100) GeV have been considered. For example, unusually light WIMPs have been shown to be possible using a light second Higgs mediator [1]. Dark matter production mechanisms beyond thermal freeze-out have been studied, e. g. making very heavy DM possible through freeze-in [2].

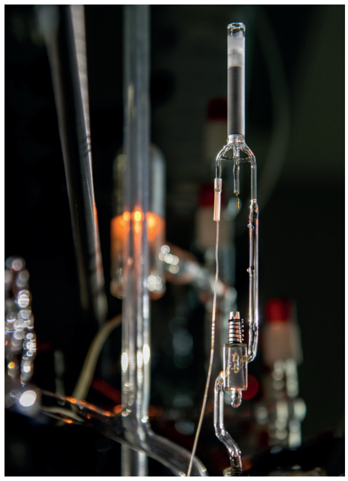
New production mechanisms for sterile neutrino dark matter are reviving interest in this DM candidate. It was shown in [3] that self-interacting sterile neutrino dark matter can be exponentially produced by converting the Standard Model neutrinos into sterile neutrinos in the early Universe. This model opens up significant parameter space which can be probed by structure formation, astrophysical, and x-ray observations as demonstrated in the figure. In [4] it was shown that varying the Yukawa coupling in the early Universe can lead to keV sterile-neutrino dark matter consistent with current observations.



The phenomenology of various dark matter models has been studied, considering both conventional direct/indirect/collider WIMP signatures, as well as implications for early Universe cosmology and phase transitions. Moreover, generic dark matter signatures have been considered in the effective field theory framework which can be mapped to UV complete dark matter models. In connection to astrophysics, calculations for dark matter capture in neutron stars [5] and constraints from core-collapse supernovae [6] have been improved.

References:
[1] J. Herms et al., Phys. Rev. Lett. 129, 091803 (2022), DOI:10.1103/PhysRevLett.129.091803
[2] A. Ahmed et al., Phys. Lett. B 831, 137201 (2022), DOI:10.1016/j.physletb.2022.137201
[3] T. Bringmann et al., arXiv:2206.10630, DOI:10.48550/arXiv.2206.10630
[4] C. Jaramillo, JCAP 10, 093 (2022), DOI:10.1088/1475-7516/2022/10/093
[5] N. F. Bell et al., JCAP 09, 028 (2020), DOI:10.1088/1475-7516/2020/09/028
[6] Y. M. Chen et al., JCAP 11, 014 (2022), DOI:10.1088/1475-7516/2022/11/014

Low Level Techniques



A miniaturised quartz proportional counter tube used to perform highly sensitive radon emanation measurements.

Extremely sensitive low-level techniques are essential for neutrino experiments and dark matter searches which look for very rare events, where identification and reduction of the background plays a key role. At the MPIK, there is a long tradition and internationally recognised 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 are used to check the radiopurity of materials. They are the heart of very sensitive assay techniques for concentrations of radioisotopes which are many orders of magnitude below natural radioactivity in the environment.

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.

Neutrinos – Particles with Striking Properties

Neutrinos are electrically neutral elementary particles with tiny masses which occur in 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 very rarely with matter. Sensitive detectors with excellent shielding against background signals are therefore required to detect them.

Unlike all other elementary particles like electrons or quarks, neutrinos might be identical to their own antiparticles. They would then be so-called Majorana particles which may be related to their tiny masses and which might explain why our Universe is dominated by matter. The best way to establish the Majorana nature – or more generally lepton number violation – is to search for a process called neutrinoless double beta decay. In this decay two neutrons inside a nucleus decay to two protons and two electrons. The electrons leave the new nucleus and their energies are measured. If the sum agrees with the expectation and other environmental processes that mimic neutrinoless double beta decay can be sufficiently suppressed, the Majorana nature is established. MPIK initiated the GERDA experiment that searched for this decay mode using ^{76}Ge. The first phase of the successor experiment, LEGEND, is currently under commissioning at the Laboratori Nazionali del Gran Sasso in Italy.

Topics of neutrino research.

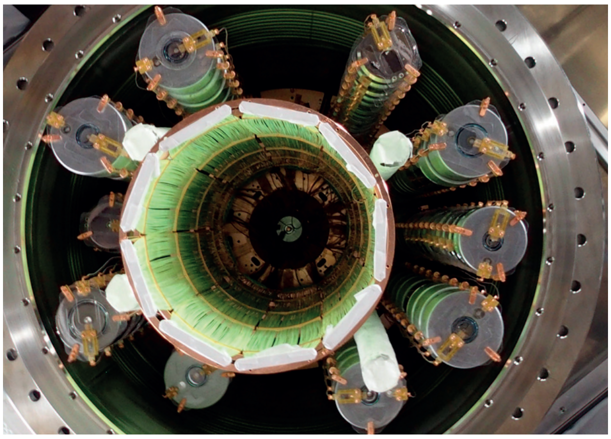
For the masses of neutrinos only limits and differences are known to date. Other experiments to determine the neutrino mass rely on the capture of an electron by a proton in a nucleus. Therefore, the knowledge of the exact mass difference between mother and daughter nucleus is necessary. Penning traps (see section 2.1) are particularly suitable tools for such precision measurements.

Various experiments in the vicinity of nuclear power plants detected about 6% less antineutrinos than expected. This could have been the consequence of oscillations into so-called sterile neutrinos. The `Stereo` experiment tested the sterile neutrino hypothesis and the results disfavour most of the allowed parameter space. The experiment also clarified another anomaly in the observed neutrino spectrum.

The CONUS experiment uses a very intense flux of reactor antineutrinos close to the core of power reactors to investigate the coherent neutrino-nucleus scattering – scattering of neutrinos with the nucleus as a whole. Highly pure germanium detectors with very low energy threshold were developed to measure the tiny energy transfer due to this scattering process, which, however, is significantly more probable than the interaction of neutrinos with electrons. A very powerful shielding had to be developed to create close to a reactor radio-pure conditions which are usually only achieved in deep underground laboratories with special methods. Strong limits on coherent scattering and world-leading limits on neutrino physics beyond the Standard Model were obtained. An upgrade of CONUS with further improved detectors, even better shielding and more detector mass is being prepared.

The riddle of the neutrino nature: search for neutrinoless double beta decay with ^{76}Ge

The GERDA experiment searched for neutrinoless double beta decay of ^{76}Ge by operating germanium detectors made from material enriched to about 88% in ^{76}Ge. The total mass was 35-40 kg. The detectors were operated in a 64 m^3 cryostat filled with liquid argon. The argon acted as shield against environmental background radiation and – by the detection of scintillation light – also allowed to veto most of the radioactive backgrounds since they typically deposit energy not only in the germanium but also in the argon. The cryostat was inside a 660 m^3 water tank to further suppress environmental backgrounds. The entire setup was located underground to shield against cosmic radiation at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Reducing or identifying events from environmental sources that mimic double beta decay is a key to improve the sensitivity of the search. GERDA was a European collaboration founded in 2003 by MPIK. It stopped data taking in 2020. No hint for neutrinoless double beta decay of ^{76}Ge was found and a 90% C.L. lower half-life limit of 1.8×10^{26} yr was extracted. All design goals were met.

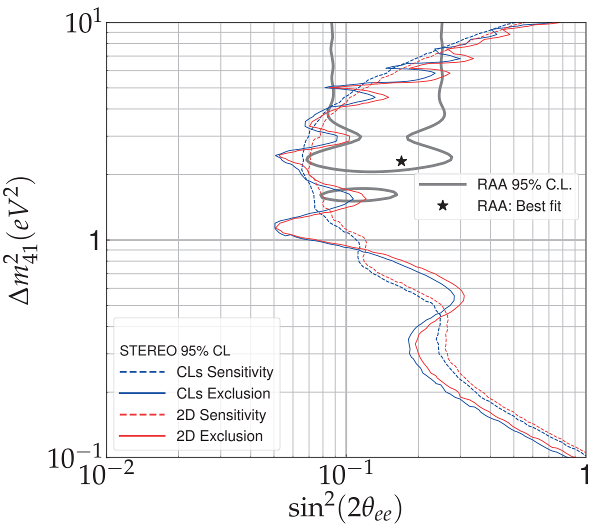


LEGEND-200 germanium detector assembly with fibre argon veto.

The background level achieved by GERDA is the lowest in the field. This motivated to continue the search using the same technique. A new collaboration called LEGEND formed. Institutions from GERDA, the American Majorana experiment and others joined. In a first step, LEGEND will deploy close to 200 kg of germanium detectors in the previous GERDA setup at LNGS. This phase is currently in commissioning. Physics data taking is expected to start by the end of 2022. Several improvements are in place that should allow to reduce the background level relative to GERDA. The sensitivity of this phase called LEGEND-200 is expected to reach 10^{27} yr. Another phase with 1000 kg of germanium detectors in a new setup has been proposed. Its sensitivity will reach 10^{28} yr. Last year the US Department of Energy performed a review of three proposals. LEGEND was rated favourably. Construction could start in a few years from now.

Reference:
M. Agostini et al. (GERDA collaboration), PRL 125, 252502 (2020), DOI: 10.1103/PhysRevLett.125.252502

Constraints on the existence of sterile neutrinos



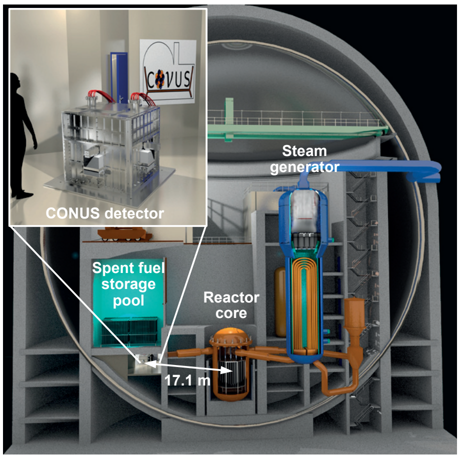
Exclusion contour (solid red) and exclusion sensitivity contour (dashed red) in sterile neutrino parameter plane.

An observed anomaly in the measured neutrino rate emitted by nuclear reactors has triggered the hypothesis of the existence of an additional sterile neutrino state on top of the three known active neutrino flavours. Such a particle would not participate in weak interaction reactions and its existence would require extensions of the Standard Model of particle physics. The Stereo experiment was searching for light sterile neutrinos at the 58 MW research reactor of ILL Grenoble at a distance of only 10 m to the reactor core. Flavour conversion into sterile neutrinos would induce distortions in the measured energy spectrum as a function of the distance to the reactor core. Therefore, the Stereo detector was segmented into 6 identical cells and the sterile neutrino hypothesis tested by the comparison of the 6 measured spectra. This way the analysis is independent of predictions on the emitted spectrum.

Based on the measurement of more than 100 000 antineutrinos detected from 2017 to 2020 including 273 days with the reactor turned on and 520 days with the reactor off, Stereo rejected the hypothesis of a light sterile neutrino [1]. The experiment also delivered leading precision results on the absolute comparison between the predicted and measured total neutrino rate for a highly enriched ^{235}U reactor [1,2]. Furthermore, Stereo established a new reference for the ^{235}U antineutrino energy spectrum. In this way, another anomaly related to the spectral shape could be confirmed. The sensitivity of the shape measurement was further improved by combing the data of the Stereo and Prospect experiments in a joint analysis [3]. In summary, the Stereo results suggest biases in the nuclear data used for the predictions as origin of the anomalies in contrast to explanations based on new neutrino physics.

References:
[1] Stereo Collaboration, arXiv:2210.07664v2 [hep-ex] (2022), DOI: 10.48550/arXiv.2210.07664
[2] Stereo Collaboration, Phys.Rev.Lett. 125 (2020) 20, 201801, DOI: 10.1103/PhysRevLett.125.201801
[3] Stereo and Prospect Collaborations, Phys.Rev.Lett. 128 (2022) 8, 081802, DOI: 10.1103/PhysRevLett.128.081802

Neutrinos scattering on atomic nuclei



CONUS detector set-up within the building of the nuclear power plant at Brokdorf.

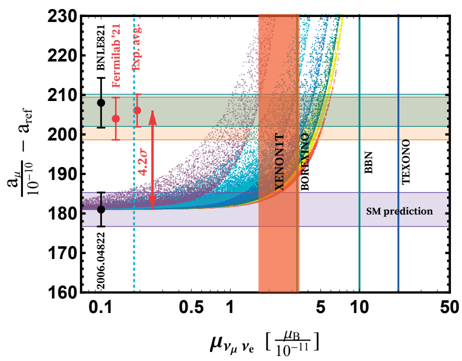
The Standard Model of particle physics predicts a process in which neutrinos, the tiniest and most elusive of the known elementary particles, scatter with the constituents of atomic nuclei. Due to quantum-mechanical coherency the respective cross section is enhanced by several orders of magnitude compared to more commonly applied interaction channels. This enhancement allows in principle 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.

The CONUS experiment aims at detecting neutrinos at the nuclear power plant in Brokdorf, Germany with its 3.9 GW thermal power. The immense neutrino flux was monitored at a distance of 17 m from the reactor core using 4 specifically designed low-energy-threshold germanium detectors inside an elaborated passive and active shield. It would be the first time that this type of interaction is measured for low-energy reactor neutrinos. A new very precise measurement of the ionization quenching in the germanium crystals revealed an unfavourable material parameter, which further challenges the neutrino detection with this technique [1].

So far, with the first analysed CONUS dataset, a strong upper limit on the number of neutrino-nucleus interactions was determined [2]. Moreover, the low background levels in the experiment allowed to constrain neutrino physics beyond the Standard Model of elementary particle physics and to partly set world's best limits on those [3]. In particular, competitive constraints on electromagnetic properties of neutrinos, i. e., upper limits on an effective neutrino magnetic moment and an effective neutrino millicharge were achieved [4]. The Brokdorf reactor stopped operation by the end of 2021. The long period with the reactor turned off in 2022 allows for the precise determination of background events. An analysis update with improved low-energy threshold is in preparation.

References:
[1] A. Bonhomme et al., Eur.Phys.J.C 82 (2022) 9, 815, DOI: 10.1140/epjc/s10052-022-10768-1
[2] CONUS collaboration, Phys.Rev.Lett. 126 (2021) 4, 041804, DOI: 10.1103/PhysRevLett.126.041804
[3] CONUS collaboration, JHEP 05 (2022) 085, DOI: 10.1007/JHEP05(2022)085
[4] CONUS collaboration, Eur.Phys.J.C 82 (2022) 9, 813, DOI: 10.1140/epjc/s10052-022-10722-1

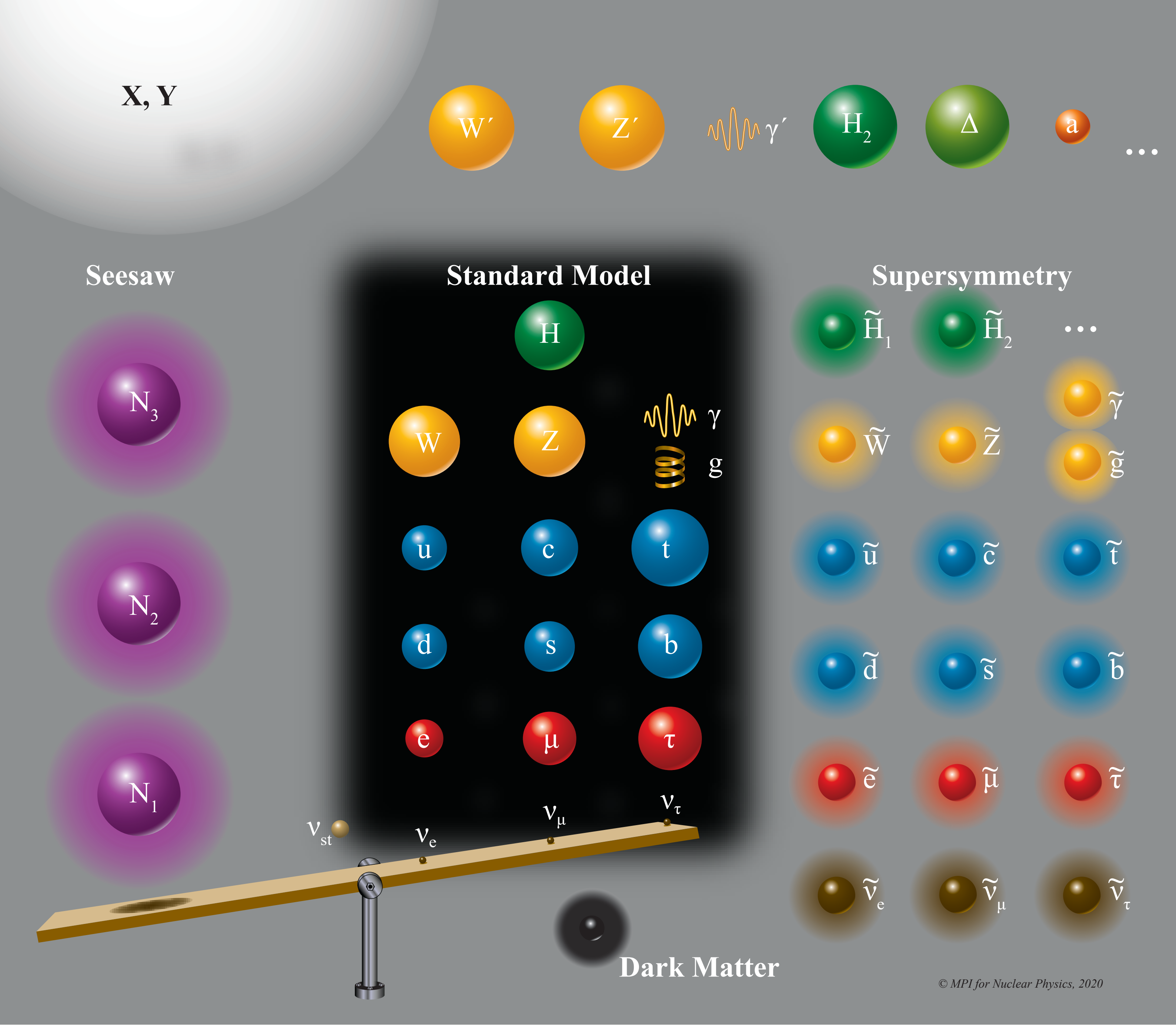
Neutrinos and physics beyond the Standard Model



Correlated theoretical predictions and experimental measurements of the muon anomalous magnetic moment and the neutrino transition magnetic moment.

Neutrinos are one of the most abundant of all known particles in the Universe, but yet the least understood ones. In the Standard Model, neutrinos are massless and interact only via the weak force. However, the discovery of neutrino oscillations implies that neutrinos are massive and mixed. Therefore, the Standard Model must be extended to account for the tiny neutrino masses, and that opens up a gateway to new physics beyond the Standard Model. In these extensions, neutrinos also acquire electromagnetic properties through quantum loop effects. The theoretical and experimental investigation of neutrino electromagnetic interactions can therefore serve as a powerful tool in searching for the fundamental theory behind the neutrino mass generation mechanism [1]. The models that induce neutrino magnetic moments while maintaining their small masses naturally also predict observable shifts in the charged lepton anomalous magnetic moments [2], thereby linking properties of neutral and charged leptons. This shift is of the right magnitude to be consistent with the Brookhaven measurement as well as the recent Fermilab measurement of the muon *g*-2. A broad program investigates the consequences of it in ongoing neutrino and dark matter experiments. The electromagnetic properties of neutrinos also influence several interesting astrophysical objects, such as supernovae [3,4], and can thus be probed by observing a future galactic supernova. It could also lead to testable consequences in future neutrino telescopes, which are designed for EeV cosmogenic neutrino detection [5,6]. Furthermore, the particles related to those new effects would show up at upcoming collider experiments or in rare decays, and moreover generate additional interactions of neutrinos (NSI), which cause observable effects in neutrino oscillations and scattering experiments.

References:
[1] K.S. Babu, Sudip Jana, Manfred Lindner; JHEP 10 (2020) 040, DOI: 10.1007/JHEP10(2020)040
[2] K.S. Babu, Sudip Jana, Manfred Lindner, Vishnu P.K.; JHEP 10 (2021) 240, DOI: 10.1007/JHEP10(2021)240
[3] Sudip Jana, Yago P. Porto-Silva, Manibrata Sen; JCAP 09 (2022) 079, DOI: 10.1088/1475-7516/2022/09/079
[4] Evgeny Akhmedov, Pablo Martínez-Miravé; JHEP 10 (2022) 144, DOI: 10.1007/JHEP10(2022)144
[5] Guo-yuan Huang, Sudip Jana, Manfred Lindner, Werner Rodejohann, arXiv: 2204.10347 [hep.ph]
[6] Alexei Y. Smirnov, Andreas Trautner, arXiv: 2211.00634 [hep-ph]



1.3 Beyond the Standard Model

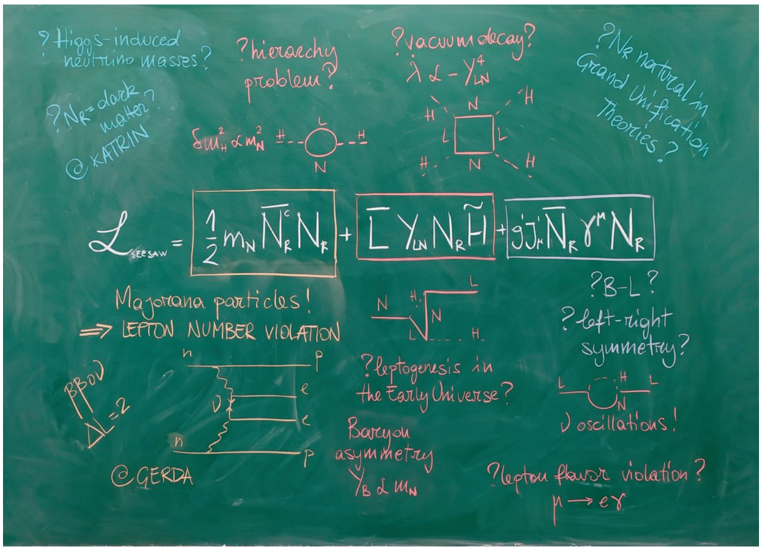
Elementary particles of the Standard Model (black background) and hypothetical particles.

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 in 2012 opened a number of fundamental questions that are addressed by theoreticians at the MPIK.

An extension of the Standard Model of elementary particle physics is required by dark matter, non-zero neutrino masses, the baryon asymmetry of the Universe and other experimental facts. Furthermore, there exist theoretical deficiencies which also require an extension. This leads to new physics which could either show up at high energies or at precision measurements testing so-called hidden sectors. Theoreticians of the MPIK are studying such extensions which can explain the experimental effects beyond the Standard Model or the theoretical shortcomings. Examples are based on extended symmetries such as conformal or 'grand unified' theories.

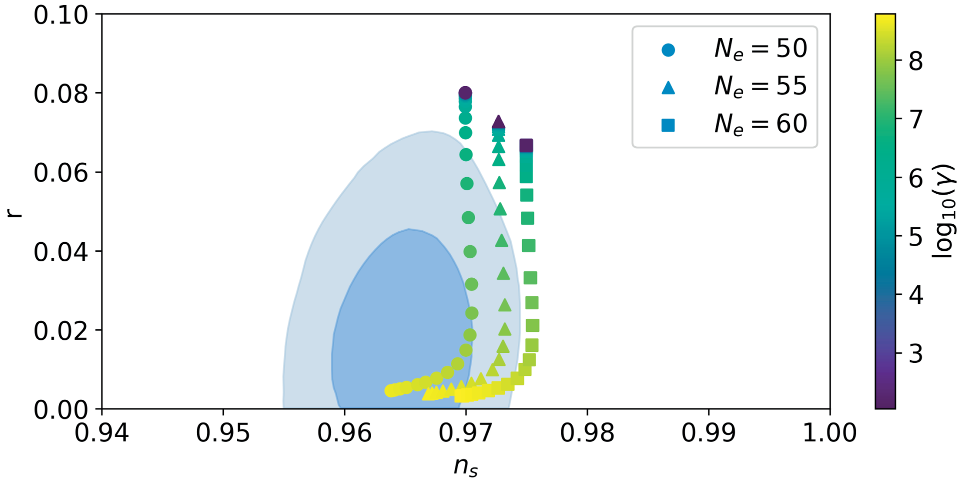
A lot of theoretical work is done on the origin of neutrino masses and mixings via basic and phenomenological studies. The so-called seesaw mechanism is a way to explain the smallness of neutrino masses based on the presence of new heavy particles, which are in fact predicted by many theories beyond the Standard Model. Another focus topic are theories and the phenomenology of various dark matter candidates and interconnections to the other problems of the Standard Model. Neutrino masses and dark matter may, for example, have a common origin. Similarly, alternative electro-weak symmetry breaking mechanisms or the thermal history of the Universe often lead to constraints or connections between the various topics. The overall aim is a deeper understanding of the fundamental laws of nature by including all available experimental facts and hints for new physics of laboratory experiments, cosmology and astronomy.



Blackboard sketch of a theorist's discussion about the various implications of new elementary particles, in the case, massive right-handed neutrinos.

Conformal models of inflation

Two of the most puzzling unresolved issues in high-energy physics today are the hierarchy problem and the scale-invariant nature of the primordial power spectrum. A gravitational model based on global conformal symmetry has been proposed that addresses both issues by dynamically generating the Planck scale, electroweak scale, and inflationary potential. When scale-invariant quadratic gravity is coupled to an external scalar field (the inflation), it has been shown that quantum effects arising from the Coleman-Weinberg potential give rise to the very notion of mass, relate the two of most important mass scales in physics, and lead to inflationary predictions that satisfy the most stringent modern experimental constraints. This model is also able to generate masses for both Standard Model and additional right-handed neutrinos, the latter of which were shown to produce a satisfactory dark matter abundance.



Predictions for the scalar spectral index n_s and the tensor-to-scalar ratio r with varying number of e-folds N_e. The value of the Ricci scalar squared coupling γ is indicated by the colour scale. Experimental constraints from Planck collaboration are given by the shaded blue regions at 68% and 95% confidence levels.

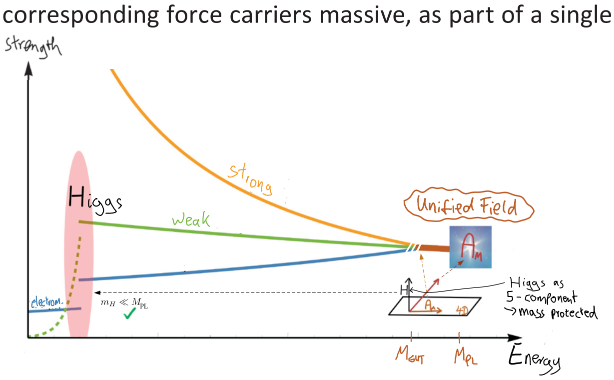
Reference:
Kubo, J.; Kuntz, J.; Lindner, M.; Rezacek, J.; Saake, P.; Trautner, A., JHEP 16 (2021), DOI:10.1007/JHEP08(2021)016

Constructing a viable theory that unifies the fundamental interactions of nature

The fundamental interactions observed in nature – the electromagnetic interaction, the weak and the strong nuclear force, as well as gravity – can be described in terms of 'gauge' symmetries in a mathematical language. It is a long-standing dream of fundamental physics to unify these basic interactions in a single fundamental structure at high energies. For the first three forces, this has been achieved in a so-called 'grand unified theory' (GUT), based on a single symmetry group with the prominent minimal example of a special unitary SU(5) group. Such straightforward realisations, however, come with various problems, some of which include too fast proton decay and the so-called hierarchy problem.

The latter denotes the fact that the scale suppressing the weak interactions (i. e., the Higgs scale) receives large quantum corrections that pull it towards the (way too large) scale of grand unification or the Planck scale MPL, which would make the corresponding interaction strength by many magnitudes smaller than it is found to be.

In [1,2,3] we presented a novel GUT that solves the mentioned problems (and more), by taking the concept of unification one step further. The proposed model describes (unified) gauge interactions and the famous 'Higgs' sector, which makes the corresponding force carriers massive, as part of a single structure – namely a five-dimensional gauge field AM (see figure).



By employing a warped extra dimension and a novel symmetry pattern, all problems of earlier attempts are solved, the Higgs gets naturally much lighter than MPL and also a successful model of flavour is presented [3] – predicting a viable hierarchical pattern of fermion masses and quark mixings.

Exciting signatures of the setup would be new resonances at the teraelectronvolt scale, in reach of future colliders, unveiling the unified structure. Moreover, the extended scalar sector could help to address further puzzles, like the emergence of a Universe full of baryons, which we will explore connecting to the analysis we recently completed in a related context [4].

References:
[1] Angelescu, Bally, Blasi, Goertz, Phys. Rev. D 105, 035026 (2022), DOI: 10.1103/PhysRevD.105.035026
[2] Angelescu, Bally, Blasi, Goertz, PoS 398 ((EPS-HEP2021)698 (2022), DOI: 10.22323/1.398.0698
[3] Angelescu, Bally, Goertz, Weber, arXiv:2208.13782 [hep-ph], DOI: 10.48550/arXiv.2208.13782
[4] Angelescu, Goertz, Tada, J. High Energy Phys. (2022), DOI: 10.1007/JHEP10(2022)019

Matter and Antimatter – Search for a Crucial Difference

There is no indication that anywhere in the visible Universe considerable amounts of antimatter exist. This is a problem since particles and antiparticles are expected to be created in equal amounts in the Big Bang and they should have completely annihilated, leaving a Universe filled only with radiation. Today's Universe requires therefore a new mechanism able to explain the so-called baryon asymmetry.

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 will test this puzzle more stringent.

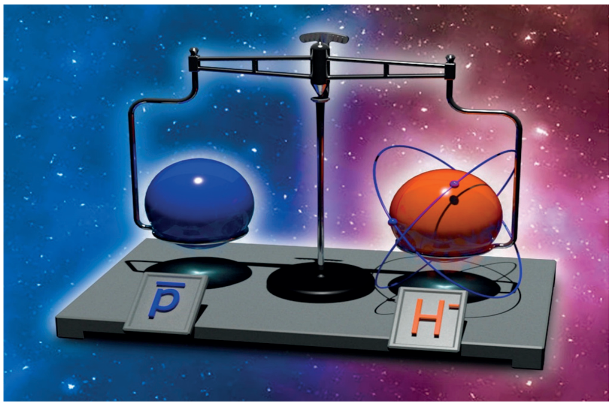
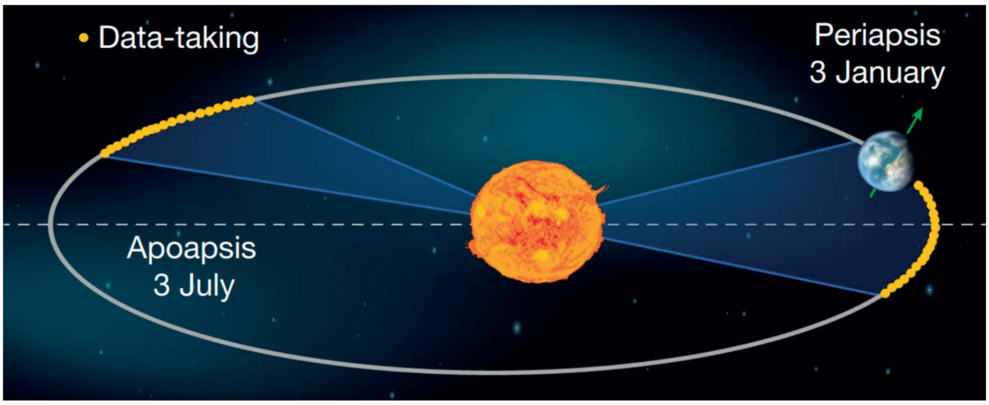


Illustration of the experimental comparison of the mass-to-charge ratios of the antiproton and the negative hydrogen ion. (Graphics: BASE collaboration)

Record measurement of antiproton charge-to-mass ratio constrains anomalous antiparticle gravitation

The striking imbalance between matter and antimatter in our Universe is one of the mysteries in modern physics, since we expect to find equal amounts of matter and antimatter from our theory. Moreover, we also expect that matter and antimatter experience the same gravitational force – a hypothesis that has however never been experimentally observed so far.

Researchers of the MPIK and the BASE collaboration reported in 2022 on the most precise comparison of the charge-to-mass ratio of protons and antiprotons with 16 parts per trillion uncertainty and a factor of four times more precise than before. This measurement also provided constraints on the anomalous gravitational behaviour of the antiproton because the measurement consists in total of about 24 000 proton and antiproton cyclotron frequency measurements, taken over the course of 1.5 years. During this period the antiproton was placed in a different gravitational potential due to the elliptic orbit of the Earth around the Sun. Since we did not find any deviation in the cyclotron frequency of proton and antiproton along the orbit of the Sun, we concluded that the difference in the gravitational force must be smaller than 3%. This study constitutes the first differential test of the weak equivalence principle for baryonic matter/antimatter clocks.



Positions along the elliptic orbit of the Sun where the antiproton and proton charge-to-mass ratio was measured.

Reference:
M. J. Borchert, J. A. Devlin, S. R. Erlewein et al., Nature 601, 53–57 (2022), DOI: 10.1038/s41586-021-04203-w