HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Proposal for the Helmholtz Research Program

MATTER AND THE UNIVERSE

Research Field MATTER
Strategic Evaluation for the Fourth Period
of Program-oriented Funding, 2021 – 2027

A. PROGRAM *MATTER AND THE UNIVERSE*

Spokespersons

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Participating Helmholtz Centers

DESY Deutsches Elektronen-Synchrotron

GSI Helmholtzzentrum für Schwerionenforschung GmbH

HIM Helmholtz-Institut Mainz
TransFAIR (Forschungszentrum Jülich FZJ/GSI)

KIT Karlsruhe Institute of Technology

IPP Max-Planck-Institut für Plasmaphysik

CONTENTS

1. OVERVIEW

The Program *Matter and the Universe* (MU) bundles the Helmholtz Centers' research on the smallest building blocks of matter, on fundamental particle interactions and forces, on the complex behavior of hadronic and nuclear matter, and on the evolution of our universe from the Big Bang to the present day. The research within the Program MU helps to build the foundation of our understanding of the world. Hence, it is crucially relevant for society to pursue this kind of knowledge creation as part of our culture and to provide the textbook basis for other activities that are targeted more directly at applications.

Our current picture of the cosmos is based on two Standard Models – the one of elementary particle physics and the one of cosmology. These theoretical frameworks impressively describe the elementary building blocks of matter, the forces acting between them, the spatial structure of the universe, and many of its numerous fascinating objects. This view, however, is incomplete and partially inconsistent. Open questions are:

- What is the nature of dark matter, why does matter dominate over antimatter, and what is the role of the Higgs boson in the universe?
- How can the complex world of hadrons and nuclei be understood starting from basic Quantum Chromodynamics (QCD)? How did the elements form?
- What do high-energy particles from the universe with energies far beyond those reachable on Earth tell us about the most violent places in the universe, and what can we learn about the fundamental properties of these particles?

In this Program proposal, we describe a unified approach that will lead to significant progress on these fundamental questions. With the competences in the Helmholtz Centers DESY, GSI, IPP, and KIT and together with partners all over the world, we combine important elements of elementary particle physics, atomic and nuclear physics, astroparticle physics, astrophysics, and cosmology to advance our knowledge in an integral and structured way.

The Program MU is organized in three Topics, which are thematically and methodically complementary and tightly connected to each other:

- *Fundamental Particles and Forces* (MU-FPF) with DESY and KIT
- *Cosmic Matter in the Laboratory* (MU-CML) with GSI and TransFAIR (FZJ/GSI)
- *Matter and Radiation from the Universe* (MU-MRU) with DESY, IPP, and KIT

GSI is also the organizational home of the Helmholtz Institutes Mainz and Jena[1] (HIM, HIJ). TransFAIR denotes the activities of the FZJ Institut für Kernphysik (IKP), which are planned to be transferred to GSI during PoF IV. Parts of the IPP have moved from the Research Field *Energy* to the Research Field *Matter* and are now strengthening the Program MU. See Chapter 2.2 for more structural details.

The Program also comprises two large-scale user facilities (LK II): the Tier-1 data and computing center GridKa at KIT and the GSI-MU Ion Facilities (UNILAC and SIS18 accelerators including various experimental stations and compute facilities).

Typical "Helmholtz features" of the research within the Program MU arise from the fact that the conceptual foundation of our centers is complementary to those of universities and other research institutions in Germany. Helmholtz Centers are mission-based (see Volume I), they adhere to a well-defined strategy, and they are typically committed to a selected set of long-term projects using large-scale infrastructures.

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[1] HIJ participates in the Programs Matter and Technologies and From Matter to Materials and Life.

As a result, the Program MU offers a reliable framework and excellent opportunities for university groups to participate in large-scale projects that would otherwise be out of reach because no university would be able to host the required apparatus. An example is the KATRIN experiment at KIT for the measurement of the neutrino mass. Further examples are the DESY Test Beam Facility in Hamburg, the CTA Science Data Management Center and detector workshops at DESY in Zeuthen, the GridKa Tier-1 center at KIT, the scientific-technical laboratories and the Green-IT Cube at GSI, and the facilities for the Pierre Auger Observatory at KIT – i.e. infrastructures and long-term tasks requiring commitments that only Helmholtz Centers can make. Finally, the FAIR facility in Darmstadt will be an anchor point for many groups working on nuclear and hadron sciences, as is the case for GSI up to now.

The cooperation between the centers exploits complementary approaches and participation in different projects: In this way, we can avoid thematic gaps and double efforts while pursuing a broad research program. Astroparticle physics research done in our Program provides a nice example of work sharing: KIT focuses on cosmic rays and DESY on gamma rays, while both contribute to high-energy neutrinos and conduct a strong program in elementary particle physics. The creation and distribution of chemical elements in the universe, which are of common relevance, are investigated by GSI.

Last but not least, Helmholtz Centers offer excellent career opportunities and working conditions. Development and operation of large-scale infrastructures require more permanent positions than are typically available at universities. And, of course, there is a significant exchange of scientists between universities and Helmholtz Centers.

As a result, we provide comprehensive system approaches, critical key contributions, and support – if necessary – over decades.

The Program MU has a strong impact on broad-based international strategies. Our scientists are engaged in international policy bodies and roadmap processes, such as the CERN European strategy for particle physics, the ECFA and ICFA committees, the Astroparticle Physics European Consortium (APPEC), the Nuclear Physics European Collaboration Committee (NuPECC), and the European Strategy Forum on Research Infrastructures (ESFRI).

The Program *Matter and Technologies* (MT) was introduced in 2015 starting with the PoF III period. Naturally, there are strong links between MU and MT in terms of instrumentation, methods, and personnel. All three Programs of the Research Field *Matter* cooperate in many ways (see Chapter 5 in Volume I and Section 2.2 below).

1.1. Planned Resources

The following graphs show the costs of the Program MU by Topic and the expected distribution of personnel resources for activities in the Program in FTE. Please note the used notation which applies to the entire proposal: Costs are given in thousand euros (TEUR), and for all resource numbers the thousands separator is a dot, and the decimal separator is a comma.

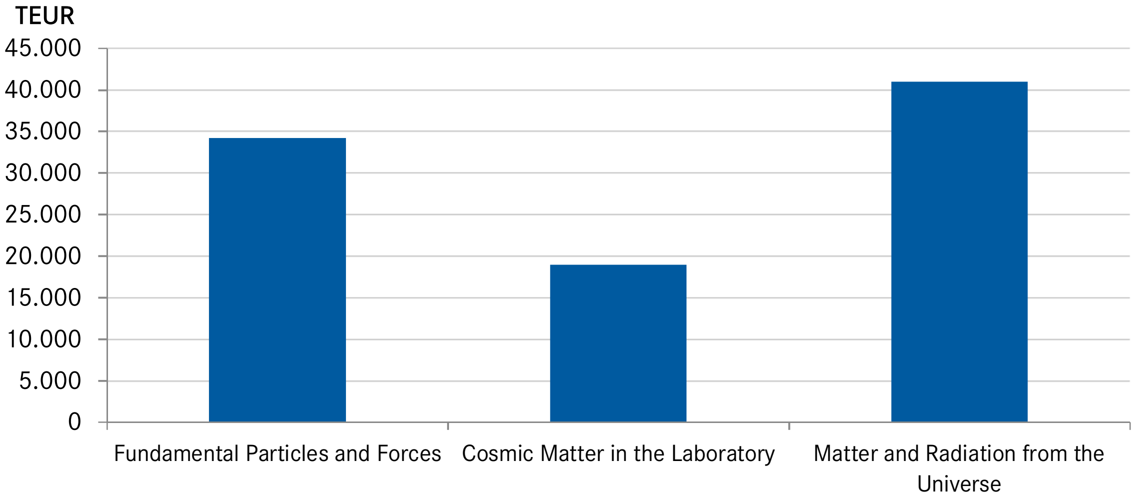

Figure 1: Program costs in 2021 by Topics. For details see Table 9.

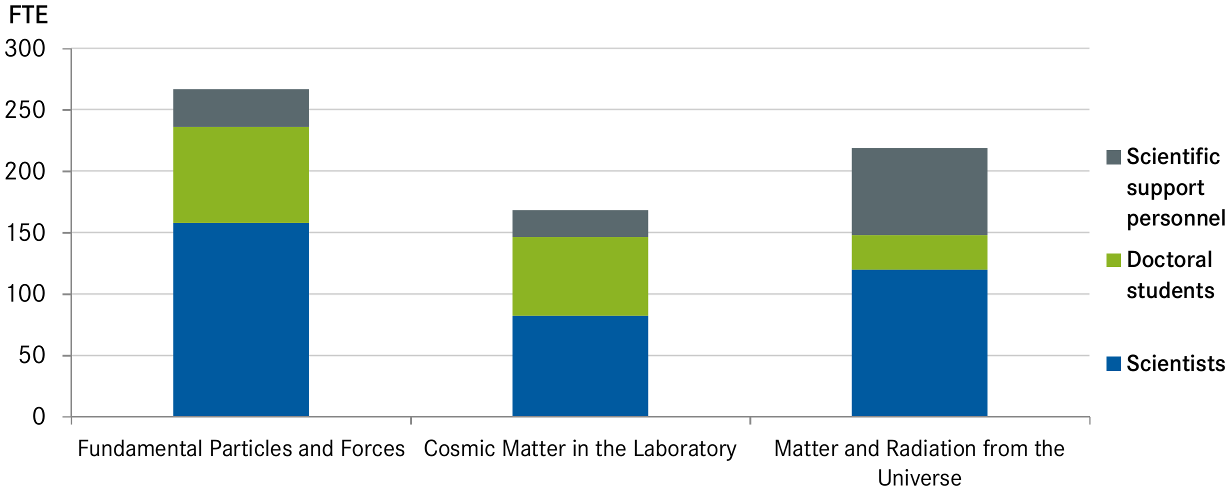

Figure 2: Foreseen personnel resource distribution in 2021 for activities in the Program. For details see Table 9.

2. RESEARCH PROGRAM

The scope of the Program MU is broad and deep. We will describe some aspects of the Program as a whole in Chapter 2.1 and turn to the three Topics in Chapter 2.2.

2.1. Objectives and Strategy

In this chapter, we describe some general challenges, the research environment, and the main objectives and deliverables of the Program and conclude with remarks concerning the recommendations that were made for the Program as a whole during the scientific evaluations of the participating centers.

2.1.1. Challenges

The overall advantage, but also the challenge of the Program is the breadth and depth of the coherent approach by which we intend to advance our understanding of the quantum cosmos, of the complex world of hadrons and nuclei, and of the universe at large. It is a joint effort comprising theory and experiment, modeling and observation, technological developments and operation of very large infrastructures, detector systems, or observatories, often at remote places on the globe.

We plan, develop, build, and operate large science instruments to conduct our research: accelerators, detectors, observatories, data and computing infrastructures. A continuous challenge is to secure the Helmholtz contribution to the operation of large-scale international projects, which is – in accordance with the Helmholtz mission – in most cases indispensable and critical. This requires the commitment of substantial resources over many years – an essential feature of the Program-oriented Funding scheme. At the same time, the science-driven evolution of such large infrastructures or observatories has to be managed.

The computing challenges in the Program MU are manifold and range from extreme data volumes and data rates to most computationally intensive simulations and the transmission of data from very remote locations. The Helmholtz Centers contribute significantly to mastering these challenges in the international collaborations and form the bridge to the Research Field *Information* and the Topic *Data Management and Analysis* in the Program MT (MT-DMA).

2.1.2. Research Environment

The research environment is first of all truly international. Scientists at the Helmholtz Centers DESY, GSI, TransFAIR (FZJ/GSI), IPP, and KIT cooperate with each other and with groups at large international laboratories. There is a backbone of international flagship accelerators and experiments: the LHC in Switzerland with the experiments ATLAS, CMS, and ALICE, SuperKEKB in Japan with Belle II, FAIR in Darmstadt with CBM, NUSTAR, and PANDA, and the Tritium Laboratory Karlsruhe and KATRIN experiment at KIT.

Furthermore, a number of extraordinary instruments that have the characteristics of an “observatory” establish a research site of their own, often in a remote location. These include the Pierre Auger Observatory in Argentina, the IceCube neutrino telescope in Antarctica, and the CTA gamma-ray observatory under construction in Chile and on La Palma. In all cases, the related Helmholtz Centers play an indispensable role in the development, operation, science exploitation, and evolution of these world-leading observatories. KIT hosts the Auger project office; the CTA data science center will be established at DESY in Zeuthen.

The Program MU acts as a strategic partner of universities and other institutions in Germany and all over the world. MU has been able to establish itself as a visible entity of its own and has successfully promoted the “Helmholtz” label to stand for coherent, large-scale, and long-term research efforts.

More details on the lively research environment with many excellent partners can be found in Chapter 3.1. The currently existing and planned infrastructures are listed in Chapter 3.2.

2.1.3. Objectives

For the next seven-year long funding period, we have set ourselves ambitious goals. In a joint effort of theory and experiment, we intend to shed light on the nature of dark matter, the excess of matter over antimatter, and the Higgs potential and its role in the universe. We want to understand how the complex world of hadrons and nuclei can be understood starting from basic QCD. Turning to the high-energy universe, we aim to fully exploit the multimessenger approach using photons, charged particles, high-energy gamma rays, neutrinos, and finally even gravitational waves in order to compose a picture of the universe from these messengers.

The objectives of the Program MU are manifold. The following list is rather a framework than an exhaustive enumeration:

- Searches for new particles and forces will help us to resolve major puzzles such as dark matter, the matter–antimatter asymmetry, or the hierarchy problem. We will set stringent constraints on many classes of new theories.
- We will get to know the fundamental particles and forces much more precisely, shedding light on issues such as how the Higgs boson interacts with other particles and itself or whether new particles contribute to decays of bottom and charm hadrons, and probing the electroweak and strong force with high-precision measurements.
- We will set world-best limits or determine values of important particle properties, e.g. the mass of the electron neutrino.
- We will unveil the phase structures of the QCD phase diagram and understand the properties of extreme and exotic matter much better.
- We will obtain a deeper understanding of the astrophysical origin of the chemical elements up to the heaviest nuclei.
- We will develop precise models of extreme cosmic objects, e.g. active galactic nuclei, neutron stars, and supernova explosions.

Some objectives are common to the Programs MU and MT, e.g. to develop advanced detectors with unprecedented capabilities in terms of energy resolution, time resolution, spatial resolution, allowable event rate and smallest deadtime, radiation tolerance, wide spectral range or energy range, sensitivity to many radiation types, etc.

For each Topic of the Program, there is a list of milestones, which may be used to monitor progress (see pages 16, 28, and 37).

2.1.4. Strategy

Basically, the strategy of the Program MU is to advance towards the goals described above, simultaneously in science, technology, and infrastructures, in complementary experimental and theoretical approaches, together within the participating centers, together with our partners, in particular in close cooperation with the German universities – and all of this in a coherent way.

The Helmholtz Centers involved take a complementary approach to answer the same basic science question with different methods. We avoid thematic gaps and redundant double efforts. An example is the work sharing in multimessenger astroparticle physics, in which charged cosmic rays, high-energy neutrinos, and gamma rays are being studied with the observatories Pierre Auger (KIT), IceCube (KIT, DESY) and H.E.S.S./MAGIC/VERITAS/CTA (DESY), respectively.

It is important to integrate the huge variety of activities in the Helmholtz Centers and the participating partner institutions involved in the Program MU into a science-oriented picture with a focus on the underlying basic questions that we address. Instead of breaking down the three Topics of the Program into independent Subtopics or similar, we chose a different approach. Figure 1 shows a collection of keywords that have been carefully positioned within a tripod made up by the Topics. The figure shows some of the key features of the Program MU: a huge intellectual challenge to "grasp it all", wide scientific overlaps, and complementary approaches.

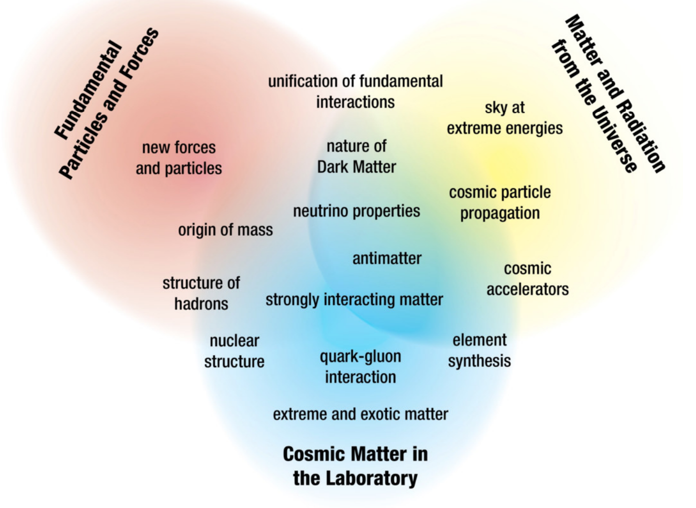

Figure 3: Topic map of the key scientific constituents of the Program MU.

The strategy of the Program has evolved over the years. Its effectiveness is demonstrated by the many scientific successes that we achieved together with our partners all over the world in the ongoing PoF III period:

- We observed the Higgs boson coupling to third-generation quarks and leptons, measured differential cross sections for the Higgs boson, and developed a novel framework for Higgs measurement interpretations.
- We significantly improved the sensitivity to dark matter particles at the LHC and developed new models for dark matter searches at the LHC and beyond.
- We took a leading role in electron–positron precision physics, i.e. in the preparation and start of physics operation of the Belle II experiment in Japan.
- The excellent and reliable performance of the GridKa Tier-1 data and computing center secured the efficient handling and storage of precious data from particle and astroparticle experiments and enabled thousands of physicists to analyze the data all over Germany and Europe.
- We took a leading role in the international discussions on the update of the European strategy for particle physics and in related studies of physics perspectives for future colliders.
- We advanced a dedicated axion physics program, in particular the preparation of the ALPS II experiment at DESY, which is about to start data taking soon.
- We explored the quark–gluon plasma as it existed after the big bang by studying collisions of heavy nuclei with the ALICE detector.
- The prediction and explanation of a kilonova light curve together with the observation of gravitational waves led to the identification of neutron star mergers as astrophysical sites for the production of the very heavy elements.
- We achieved a polarization lifetime for deuterons exceeding 1,000 s in a storage ring – a major step towards the measurement of the electric dipole moment of protons or deuterons.
- Multimessenger astroparticle physics made wide leaps forward with measurements of high-energy neutrinos (IceCube) and discoveries of an anisotropy and unexpectedly heavy composition of cosmic rays (Auger). Observatories for cosmic rays, neutrinos, gamma rays, and gravitational waves jointly published their results, and we found the first high-energy neutrino source (TXS 0506+056) in a multimessenger observation covering neutrinos and gamma rays.
- We discovered new high-energy gamma-ray source types.
- We successfully commissioned the neutrino mass experiment KATRIN in 2019 and completed pilot data taking, which already yielded the currently best neutrino mass limit.

The achievements of Helmholtz research were reviewed two years ago across all Research Fields. The scientific evaluation of the Program MU took place in a series of center-based evaluations at GSI, FZJ, DESY, and KIT from November 2017 to February 2018. Three specific recommendations from the reviewers related to the Program MU as a whole were derived from this process:

First, it was remarked that "the interplay between theory groups and experimentalists in all Program Topics should be strengthened". This is an ongoing process at DESY, GSI, IPP, and KIT. It must be noted that the group of IPP that will join the Program MU in PoF IV will particularly strengthen the interplay between theory and experiment. In addition, recruitments of professors of theoretical physics that are affiliated with MU are ongoing at many related universities, e.g. in Hamburg, Aachen, Munich, and – in an integrated way – in Karlsruhe[2].

Second, the Program proponents were encouraged to take a leading role in scientific computing in the Research Field *Matter* and to increase exposure of this work by more engagement with the broader international community. The role of the data and computing centers at KIT and DESY has been sharpened: The GridKa Tier-1 center is being prepared to cope with the forthcoming data flood from the High-Luminosity LHC (HL-LHC) not only by adding hardware but also by developing highly efficient computing services for novel data analysis techniques. The current Tier-2 center at DESY is being transformed into the Interdisciplinary Data and Analysis Facility (IDAF), which will be transferred to the Program MT. With their experience in scientific computing and in dialogue with the BMBF and the DFG, experts from all the participating Helmholtz Centers have helped to shape the upcoming national funding plans ErUM-Data[3] and NFDI[4] to meet the challenges ahead.

Third, we were encouraged to make good use of talented people, who in turn attract more good people. This recommendation is well received and is already being implemented in the participating centers. Targeted measures include, but are not limited to, science classes for schools, master classes for advanced pupils, summer student programs, Helmholtz International Research Schools, tenure track programs, young investigator group support, and individual recruitments of professors (see Chapter 3.3.1 for a detailed description).

2.2. Structure of the Program

The Helmholtz Centers DESY, GSI, TransFAIR (FZJ/GSI), IPP, and KIT participate in the Program MU, which is organized in three Topics:

- *Fundamental Particles and Forces* (MU-FPF) with DESY and KIT
- *Cosmic Matter in the Laboratory* (MU-CML) with GSI and TransFAIR (FZJ/GSI)
- *Matter and Radiation from the Universe* (MU-MRU) with DESY, KIT, and IPP

The Program also comprises two large-scale user facilities (LK II): the Tier-1 data and computing center GridKa at KIT and the GSI-MU Ion Facilities (UNILAC and SIS18 accelerators including various experimental stations and compute facilities). The Program structure and the respective representatives are shown in the organizational chart in Figure 2.

This Program structure has proven to be efficient and flexible; hence, it will be continued for the upcoming PoF IV period.

Parts of the IPP have moved from the Research Field *Energy* to the Research Field *Matter*. We welcome the new partner IPP, who brings in new expertise in plasma physics into MU.

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[2] KIT is "The Research University in the Helmholtz Association".

[3] ErUM-Data: Action plan of the BMBF to support the development of state-of-the-art computer and software technologies for basic scientific research.

[4] NFDI: National Research Data Infrastructure: https://www.dfg.de/en/research_funding/programmes/nfdi/index.html

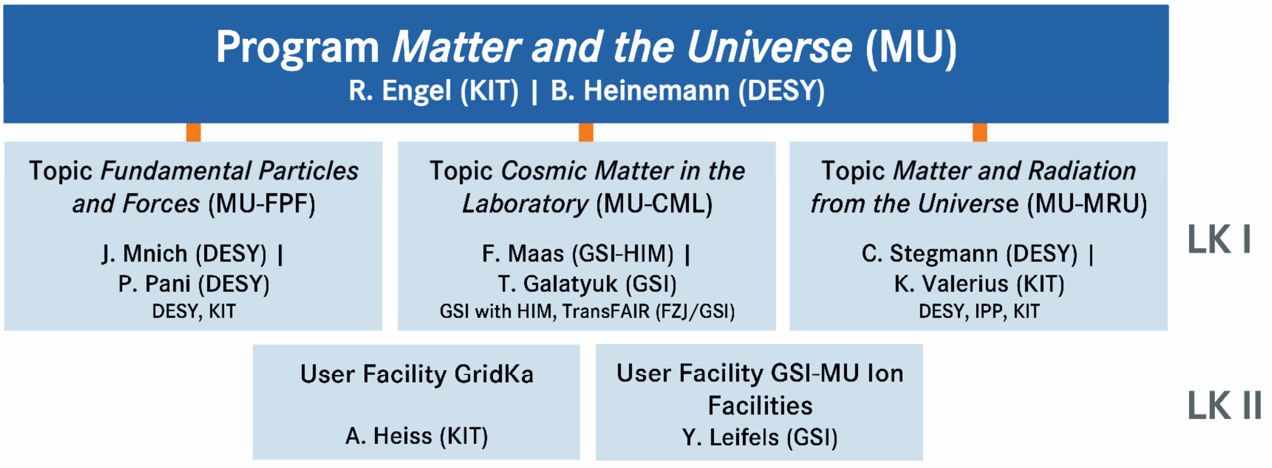


Figure 4: Organizational chart of the Program MU.

The Helmholtz Institute Mainz (HIM) at the Johannes Gutenberg-Universität Mainz belongs to GSI. HIM contributes hadron, nuclear, and fundamental physics, as well as accelerator and detector developments within the programs MU and MT and the FAIR pillars PANDA and NUSTAR. Further foci are the chemistry and physics of superheavy elements and tests of fundamental symmetries with low-energy antiprotons. HIM is in the cluster of excellence PRISMA.

It is planned to organizationally transfer the Institut für Kernphysik (without IKP3) from FZJ to GSI, focusing on the realization of the high-energy storage ring HESR and major components of PANDA (“TransFAIR”). Moreover, IKP will pursue precision physics experiments, in particular with polarized particles. These activities are embedded in MU and MT in close cooperation with the universities of Aachen, Bochum, Bonn, Cologne, Düsseldorf, Mainz, and Münster. The competences of IKP will therefore be fully retained within the Helmholtz Association.

It should be noted that KIT contributes significantly to the CMS experiment at CERN. In fact, the KIT group is the largest university group in the CMS collaboration. KIT is also a major partner in the Belle II experiment at KEK in Japan. Although both CMS and Belle II are flagship experiments within the Topic MU-FPF, the KIT contributions are not referenced in this proposal: They are rooted in the university domain of KIT and funded through the BMBF ErUM framework program. Of course, at the scientific level, this difference is not noticeable. In the Helmholtz sector, KIT contributes to MU-FPF in particle physics theory and phenomenology and by operating the GridKa Tier-1 data and computing center.

In the following three chapters, the competences, strategies, objectives, and approaches of the three Topics within MU for the upcoming PoF IV funding period are described in detail. The expected goals are referred to in the texts and listed in the milestone tables of the Topics (Tables 1–3).

2.2.1. Topic Fundamental Particles and Forces

Executive Summary

Elementary particle physics has provided deep insights into the fundamental building blocks of matter, their interactions, and the evolution of the universe. Over the past decades, the Standard Model of particle physics has been developed in a common effort of experiment and theory. However, the Standard Model is known to be incomplete, leaving many fundamental questions open. The Higgs boson, which was discovered in 2012, is generally believed to be a key to gaining further insight.

Particle physics is a central pillar of the Helmholtz scientific portfolio. In the Topic *Fundamental Particles and Forces* (MU-FPF), we cover the complete lifecycle of particle physics experiments and their interpretation, with expertise found only in a very few places worldwide. We lead global projects, addressing some of the most profound questions of nature. We are also a key player in the development of future international projects, and we maintain and develop an attractive portfolio of on-site particle physics experiments in the important fields of dark matter and axion searches. Our research in particle physics theory is at a globally leading level. The breadth of our particle physics theory portfolio guarantees cross-fertilization with mathematics, computer science, condensed-matter physics, cosmology, and modern theories of gravity. Theory provides high-precision predictions for the relevant observables, interpretation of experimental results, development of new methods and concepts, as well as guidance for experimental activities.

Strategy

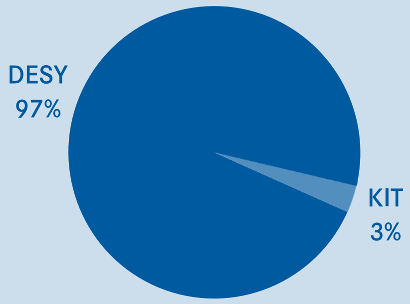
The future particle physics program of the Topic MU-FPF is guided by three science drivers: Higgs properties and fundamental interactions at high precision, searches for new particles and phenomena, and cosmology and the dark sector of the universe. In close interaction between experiment and theory, we will concentrate on the full exploitation of the LHC experiments ATLAS and CMS and of the Belle II experiment, complemented by an attractive program of smaller-scale on-site experiments to search for axions and dark matter. Members of the Topic play an active role in all national, European, and international strategy boards and processes and thus contribute very visibly to the overall strategy of particle physics. As the national laboratory and hub for particle physics, DESY is a facilitator for large-scale contributions to international flagship projects.

Facts and Figures

Participating centers:
DESY, KIT

Spokespersons:
Joachim Mnich, DESY
Priscilla Pani, DESY

Core-funded scientists: 158 FTE (2021)
Core-financed costs: 34,2 Mio.EUR (2021)



Contributions of the centers to Topic MU-FPF:
Total core-funded personnel in 2021

Strategic Goal of the Topic

The mission and strategic goal of the Topic MU-FPF is to identify the basic constituents of nature and the fundamental laws governing their interactions and to apply this knowledge to understand the intricate connection between the physics at the smallest scales with the evolution and characteristics of the universe.

It is firm knowledge today that the extremely successful Standard Model (SM) of particle physics can at best be an effective theory that is expected to be embedded in a more comprehensive, richer theory providing answers to the fundamental questions left open by the SM. These are e.g. the nature of the dark matter and dark energy observed in the universe, the unexplained asymmetry between matter and antimatter, the dynamics of electroweak symmetry breaking, and the related question of stabilization of the huge gaps between the fundamental scales of physics.

The precise exploration of the properties of the Higgs boson discovered at the LHC in 2012 will provide access to the mechanism of mass generation and lead to enormous progress in our understanding of the fundamental interactions of nature. Great advancements in studying the properties of this particle have already been made, experimentally at the LHC and also in theory. Further detailed investigation of this unique particle – the only spinless fundamental particle observed to date – is a top priority for future runs of the LHC. There are intrinsic limits, however, to what can be learned at the LHC. These provide a strong motivation for a dedicated electron–positron Higgs factory as the next international large-scale collider project.

The strategic goals and science drivers of the Topic MU-FPF are i) to explore the properties of the Higgs boson and the fundamental interactions at high precision and ii) to search for new particles and new phenomena. These two lines of research will have a large impact on and will be closely linked to iii) the exploration of cosmology and of the dark sector of the universe. All these goals will be pursued in a coherent approach between experiment and theory in close interaction with our worldwide partners and in line with the global strategy of the field. In this context, Helmholtz scientists play an active role in shaping the current update of the European strategy for particle physics, ensuring that the Helmholtz strategy in particle physics will be aligned will the priorities defined therein.

Competences

DESY and KIT have a long tradition and vast experience in particle physics. As a large international lab for particle physics, DESY is one of the few places in the world providing leadership competence over the full lifecycle of complex particle physics facilities, with experience covering the complete path from the conception and design of new detectors and accelerators through their construction and operation to the scientific exploitation, interpretation, and publication of results. This ability – which involves experimental, theoretical, and technical expertise – makes Helmholtz a key partner on the national and international level. It also underlines the importance of the Helmholtz Association for the realization of German contributions to international projects. Our particular competences in this context are:

- We have the ability to develop and deploy cutting-edge technologies to construct large particle physics detectors and accelerators. In our detector development projects, we profit from the close collaboration with the often more generic R&D activities within the Topic *Detector Technologies and Systems* of the Program *Matter and Technologies* (MT-DTS). We also collaborate closely with the accelerator R&D activities in the MT Topic *Accelerator Research and Development* (MT-ARD).
- We have an undisputedly successful track record in data analysis and interpretation at previous and current experiments. The competences of our scientists result in many high-level management positions in collaborations and make us a key player in the definition of future directions [1–6].
- For many years, the Topic has cultivated an intense collaboration between theory and experiment (see e.g. [5–8]), a feature that was highly regarded in the awarding of the new cluster of excellence Quantum Universe to Universität Hamburg and of the new Collaborative Research Center SFB 257 Particle Physics Phenomenology after the Higgs Discovery to KIT. Our theorists provide high-precision predictions for observables using perturbative and non-perturbative methods, guidance for new experimental directions, and interpretation of the data. They devise new models and develop new methods, algorithms, and concepts (e.g. [9, 10]).

- We have world-leading expertise in data analytics, big-data handling, and complex algorithms. With the computing centers at KIT (GridKa) and DESY (Tier-2 center, NAF), we provide world-class computing resources and services as well as leading software contributions. This helps us to make optimal use of data from existing facilities, and it prepares us well for the computing challenges posed by future experiments such as those at the HL-LHC, which will start in the middle of the next decade. In collaboration with the Topic MT-DMA and in close exchange with the neighboring communities of astroparticle physics and photon science, we will expand our expertise in data analytics (e.g. machine learning) as well as in large-scale and high-performance computing. We are a partner of numerous German and EU scientific computing projects.

In recent years, we have also acquired new competences fostering our leadership roles:

- We have significantly strengthened our theory portfolio, in particular in the field of cosmology, with high-quality recruitments. We have established the Wolfgang Pauli Center at DESY and interdisciplinary centers for mathematical physics in Berlin and Hamburg. KIT has established a strong theory group working on Higgs properties, dark matter searches at colliders, physics beyond the Standard Model and on precision calculations.
- We have become a key partner for the HL-LHC upgrades of the ATLAS and CMS experiments and assumed major responsibilities for the construction of silicon tracker end-caps for both of them (see Figure 5 left). We have also provided key contributions to the Belle II detector and in particular to the new vertex detector realized in novel technology (see Figure 5 right). The Detector Assembly Facility (DAF) at DESY, which began operation in 2018, is an important asset also for future projects.
- The field of dedicated experiments for searches for axions, WIMPs/WISPs and dark matter is flourishing [11, 12]. Astrophysical hints for axions and axion-like particles are a strong motivation for ALPS II and similar experiments. The previous ALPS experiment, a “light shining through the wall” experiment, has built up significant expertise in this field. We have also played a key role in the CERN-based Physics Beyond Colliders study. With the ongoing construction of the ALPS II experiment and the preparatory work for future axion and dark matter search experiments, we have taken a lead in this flourishing field.

Scientists of the Topic MU-FPF are represented in all important committees (KET on the national level, ECFA on the European level, and ICFA[5] on the international level). This ensures that the Helmholtz Association has a high impact and large influence on the field.

Objectives and Approach

Our work program for PoF IV is organized along the three science drivers defined above:

- **Higgs properties and fundamental interactions at high precision**: The precise investigation of the properties of the Higgs boson and of the electroweak and strong interactions will be one of the main objectives of the Topic. The study of the strong force also establishes natural connections to hadron and nuclear physics (Topic MU-CML).
- **Searches for new particles and phenomena**: The manifest incompleteness of the Standard Model places this theme at the center of many of our experimental and theoretical priorities. This also includes the developing program to discover axions.
- **Cosmology and the dark sector of the universe**: Building on the previous two points, these activities are set to shed light on the dark sector of the universe. The aim is in particular to unravel the nature of dark matter and to explore the origin and dynamics of the universe. These efforts also provide a link to astroparticle physics (Topic MU-MRU).

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[5] *KET – Komitee für Elementarteilchenphysik (Committee for Elementary Particle Physics): http://www.ketweb.de; ECFA – European Committee for Future Accelerators: https://ecfa.web.cern.ch; ICFA – International Committee for Future Accelerators: https://icfa.fnal.gov*

These themes complement each other, while sharing a significant number of instruments and methods. They are pursued across the full range of our current and planned collider experiments as well as at dedicated experiments on the DESY site. Specifically considering the physics program of the LHC, we will pursue in particular the following subjects:

- In the field of Higgs physics, we will explore the electroweak symmetry breaking mechanism and the structure of the vacuum through the properties of the Higgs boson discovered at 125 GeV, and we will search for additional Higgs states [milestone FPF-2][6]. This involves for example the determination of Higgs couplings with a precision at the 5–10% level [FPF-12]. The measurement of differential distributions, together with the theoretical formalism of simplified template cross sections, will allow better access to the dynamics of electroweak symmetry breaking and provide more detailed probes of new physics [FPF-2, FPF-5]. We also aim at reducing the theoretical uncertainties to below 1 GeV for the mass of the SM-like Higgs in supersymmetric models [FPF-4].
- We will perform precision measurements of quantities relevant to the electroweak interaction, such as the properties of the top quark and the W boson, which are of critical importance to understand the consistency of the Standard Model. Small deviations could hint at contributions from new physics from a high scale. An important related subject is the study of diboson processes and top-quark processes. Diboson processes are closely linked to the Higgs boson and electroweak symmetry breaking. With high precision, measurements based on the LHC data will test the consistency of the electroweak interaction in a profound way. Similarly, anomalies in top-quark production processes at high energies may provide indications for new physics [FPF-3]. The theoretical physicists will perform a thorough study of the implications of the precision electroweak and Higgs data within an effective field theory framework in order to guide the experimental analyses.
- We will pursue an extensive search for new physics signatures and new symmetries, often reaching far beyond 1 TeV, e.g. for dark matter particles. In particular, we aim for an improvement in sensitivity by using machine-learning concepts [FPF-8]. Figure 6 left shows a comparison of the projected HL-LHC reach (broken lines) with the current limit (grey shaded area).

We will construct, deploy, and commission ATLAS and CMS tracker end-caps for the HL-LHC (see Figure 5 left) at DESY. These endeavors are carried out by a consortium of DESY and German universities together with international partners. Around 2025, these end-caps will be delivered to CERN for installation in ATLAS and CMS [FPF-1].

The efficient exploitation of the expected LHC data, in particular from the HL-LHC phase, requires the continuous development of tools and methods for data taking, data monitoring, and detector calibration, as well as a continuous analysis optimization. DESY has particular expertise in tracker alignment, luminosity calibration, triggering, heavy-quark tagging, and electron and photon reconstruction, which we will continue to develop further. These abilities are vital for the efficient operation and scientific exploitation of the experiments [FPF-6].

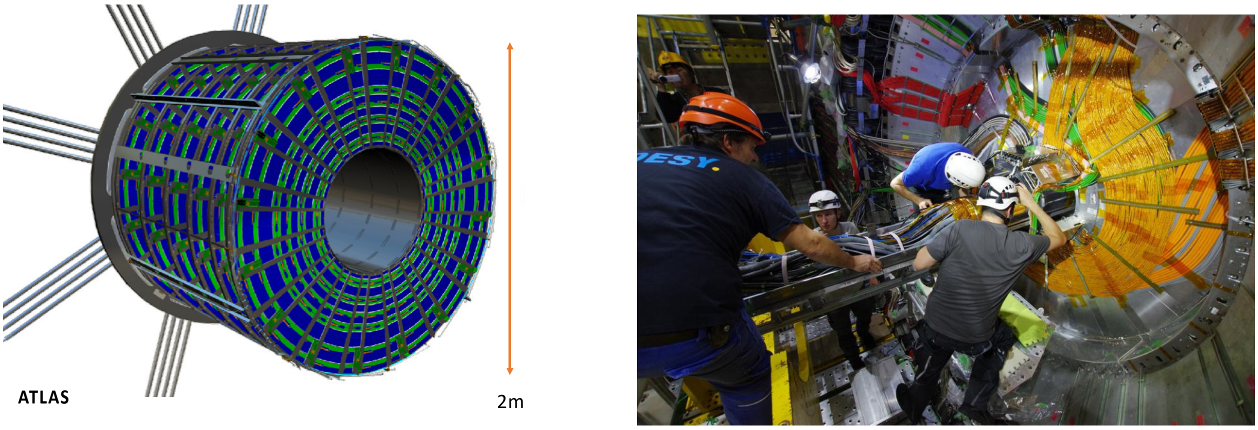

Figure 5: Left: Technical drawing of the ATLAS tracker end-cap for the HL-LHC. Right: Insertion of the Belle II vertex detector into the experiment in November 2018.

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[6] *See Table 1 for an overview of the Topic's milestones.*

Precision measurements at collider experiments provide important guidance for the future development of the field. The ultimate goal of the Belle II experiment, which has just started data taking, is to accumulate an integrated luminosity of 50 ab^{-1} until 2027 [FPF-13]. This represents a 50-fold increase with respect to the existing Belle data set, allowing unprecedented precision tests of many observables sensitive to new physics and sensitivity to new physics at mass scales up to 100 TeV or more, depending on the scenario [FPF-7,10].

Regarding the Belle II detector, the DESY group has major responsibilities in the areas of tracking and vertexing, calorimetry, and analysis software. DESY is heavily involved in the construction, testing, integration, and commissioning of the novel pixel vertex detector (see Figure 5 right), which is one of the key components of Belle II.

We are already involved in the analysis of the first Belle II physics data and currently preparing analyses in the following fields:

- We will perform unique tests of lepton flavor universality (LFU) using rare exclusive B decays, where several hints of anomalies have been reported in recent years. In addition, DESY researchers will exploit the world's largest sample of tau-lepton pairs to search for lepton flavor or lepton number violation (LFV/LNV) in tau decays [FPF-7]. Complementary theoretical research at KIT covers precision predictions and new-physics interpretation of flavor anomalies at Belle II [FPF-2].
- Our experimentalists and theorists are carrying out a global analysis of inclusive B decays to obtain a robust determination of the CKM matrix element $|V_{ub}|$, the b-quark mass, and parameters sensitive to physics "Beyond the Standard Model" (BSM). This will help to shed light on the long-standing discrepancies between different $|V_{ub}|$ results [esp. FPF-10].
- Belle II has unique sensitivity for probing light vector mediators ("dark photons") and axion-like particles (ALPs) that decay into light dark matter [7] [FPF-7]. DESY physicists are optimizing analysis techniques to yield optimal sensitivities in so far unexplored regions of dark-sector particle masses and coupling constants. The parameter region accessible by Belle II is complementary to that of the ALPS II experiment, which is sensitive to very light and feebly interacting axion-like particles.

Preparations at DESY for the ALPS II experiment are accelerating. ALPS II has the sensitivity to improve existing axion and ALP limits from laboratory experiments by about a factor of 1,000 (Figure 6 right). Searches using helioscopes have produced more stringent but model-dependent results. Even here, ALPS II can improve existing helioscope limits by a factor of 3. This represents a significant discovery potential. Data taking with ALPS II is expected to start in 2020, with first results available in 2021 [FPF-1].

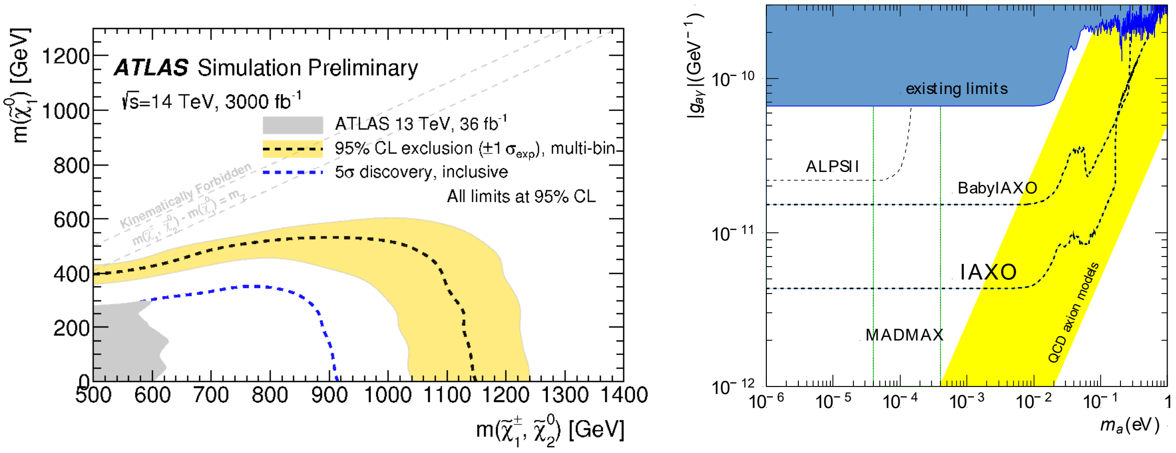

Figure 6: Left: Example for the reach of SUSY searches at the HL-LHC. Right: Reach of future axion/ALP experiments with DESY involvement.

Studies for the realization of the future axion experiments IAXO (searching for solar axions) and MADMAX (searching for axions as dark matter particles) are also proceeding; Figure 6 right shows their expected reach for axions and ALPs together with the existing limits. DESY is a member of both collaborations and intends to host the experiments.

Prototypes for MADMAX and IAXO (precursor experiment babyIAXO) are expected to be set up within the PoF IV period [13, 14].

Following the update of the European strategy for particle physics expected by early 2020, we will further sharpen the case and prepare for a future global collider project in the CERN context. Currently, a broad consensus is emerging that an electron–positron Higgs factory should be the next global collider project, allowing the determination of the properties of the Higgs boson with exquisite precision and thus shedding light on many of the open questions of particle physics. Various proposals are being discussed[7], and Helmholtz scientists have great influence on all these projects (e.g. [4]). Once a decision is taken, we aim to contribute at a level commensurate with the size and expertise of the Helmholtz particle physics activities.

With our broad and innovative theory program, we will play a leading role in the interpretation of experimental results and the discrimination between different underlying physics models. We will provide guidance for current and future experimental activities and explore the interplay between Higgs physics and cosmology, using gravitational waves as a window to cosmological phase transitions and for testing string cosmology. To these ends, we develop and apply perturbative and non-perturbative methods and mathematical concepts [FPF-9].

Our theory program will be further strengthened by a new strategic initiative, the Wolfgang Pauli Center (WPC), a world-leading center for theoretical physics at DESY that will facilitate interdisciplinary research in order to address fundamental challenges in matter, materials, and the universe in a single organization. Profiting from being embedded in a large-scale research center, the WPC will foster international cooperation and dialogue between theory and experiment. The WPC proposal foresees the construction of a new building, providing state-of-the-art co-working and discussion areas and catalyzing collaborations both locally and internationally.

The research directions in theory follow the three science drivers defined above:

- Higgs properties and fundamental interactions at high precision: We will continue to develop coherent interfaces between theory and experiment, such as the Higgs simplified template cross section framework (developed with key contributions from DESY scientists) [FPF-5,12]. This framework is an important step for the interpretation of experimental data in different theoretical models [FPF-2] and the separation of experimental from theoretical uncertainties [FPF-4]. We will work towards a better understanding of the implications of the Higgs sector on cosmology, exploring for instance its role in the inflationary expansion of the universe and in generating the observed matter–antimatter asymmetry.
- Searches for new particles and phenomena: We will produce precise phenomenological predictions using perturbation theory and lattice QCD simulations [FPF-9], where the latter provide crucial input e.g. for the determination of the strong coupling constant or on weak matrix elements of B mesons relevant to Belle II. We will explore string theory-motivated fundamental models of physics beyond the Standard Model, with emphasis on their quantum dynamics and non-perturbative effects. The predictions will be tested in global fits to all available data [FPF-2].
- Cosmology and the dark sector of the universe: In connection with the Topic MU-MRU, DESY will lead initiatives such as the Dark Matter Forum and the LPCC[8] Dark Matter working group to catalyze cooperation between theorists and experimentalists. Gravitational waves will be explored as a unique window on phenomena on which the history of the early universe is imprinted.

Following the recent development by Helmholtz Centers of a roadmap for quantum computing, we are exploring applications of this emerging technology. First results have already been published. Cooperation with TRIUMF and other Canadian institutes has been established[9].

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7 See the “Briefing Book” of the update process for the European strategy for particle physics.

8 The LHC Physics Center at CERN collects a set of initiatives in support of the LHC physics program. These include, among other things, the coordination of joint LHC working groups between experimentalists and theorists and the organization of workshops.

9 See e.g. https://datascience.triumf.ca.

Expected Results

The sketched work program translates into a number of milestones that are well suited for monitoring the progress of the Topic. These are shown in the following table.

Table 1: Overview of milestones for the Topic MU-FPF.

Number	Year	Milestone
FPF-1	2021	First scientific results from the ALPS II experiment
FPF-2	2022	Interpretation of LHC results, electroweak precision measurements, and results from flavor physics in global fits
FPF-3	2022	First observation of four-top process by ATLAS/CMS; use of this channel for searches for new physics
FPF-4	2022	Reduction of the theoretical uncertainty for the mass of the SM-like Higgs in supersymmetric models to below 1 GeV
FPF-5	2022	Determination of cross sections for all accessible Higgs production and decay channels in the simplified template cross section framework
FPF-6	2023	Collection of 300 fb^{-1} of high-quality LHC data with both ATLAS and CMS
FPF-7	2023	With approx. 10 ab^{-1} of Belle II data, coverage of a new regime in coupling strength for dark photons and ALPs in the mass range of around 100 MeV – 10 GeV; factor 5–10 improvement on branching ratio limits on various LFV and LNV tau decay channels
FPF-8	2024	Extension of the discovery reach on dark matter at the LHC by a factor 3 to 5 (depending on the specific model) compared to present limits based on 2016 data, employing modern analysis methods such as machine learning
FPF-9	2024	Precise phenomenological predictions using perturbation theory (below 1% theory uncertainty) and lattice field theory (reduction of uncertainty by a factor of 2) for the strong coupling
FPF-10	2024	With approx. 15 ab^{-1} of Belle II data, establishment of first combined fit results for $\lvert V_{ub}\rvert$ and m_b based on inclusive B decays using improved theoretical predictions
FPF-11	2025	Completion of system-tested silicon tracker end-caps for ATLAS and CMS
FPF-12	2026	Increase of the precision of Higgs couplings determined from combined ATLAS/CMS data by a factor of 2 (compared to today) using high-precision theory predictions
FPF-13	2027	Collection of 50 ab^{-1} with the Belle II experiment

Synergies and Collaboration

Collaboration and cooperation extend from the local areas in Hamburg, Berlin, and Karlsruhe over the national landscape to the European and global scale. There is also intense collaboration between different Topics in the Program MU and between the other Programs in the Research Field *Matter*.

As the center responsible for the greatest share of the Topic's resources, DESY is its natural center of gravity of this Topic. The MU-FPF activities at KIT are dedicated especially to collider phenomenology. Close collaboration in particular between theorists from DESY and KIT is well established. Important events for the Topic are the annual meetings of the Program MU or the cross-topical activities described above, to which our university partners are also invited.

Locally at DESY and KIT, strong collaboration exists between the various physics groups. Examples are the intense discussions between physicists from ATLAS and CMS and theorists on Higgs physics and the regular LHC Physics Meeting at DESY, which brings together all involved colleagues. The close collaboration between theorists and experimentalists is demonstrated by jointly supervised Ph.D. theses and joint publications [5-8].

Close contact between colleagues from different experiments also manifests itself in the construction of the tracker end-caps for ATLAS and CMS. Sharing of technical personnel and infrastructure between ATLAS and CMS is the norm.

Close collaboration also exists within the Program MU between particle, astroparticle, and hadron and nuclear physics. In PoF III, several cross-topical working groups were created that are constantly developing their activities according to scientific needs (Figure 3). Among these groups are the following:

- Neutrinos are of high interest to all research areas within the Program MU. Already now, IceCube is measuring mass differences and mixing angles based on atmospheric neutrinos, and KATRIN will be sensitive to the absolute mass scale of the electron neutrino. At the DUNE experiment in the USA, neutrinos produced by the LBNF accelerator beamline at Fermilab will be used to perform high-precision measurements of neutrino mixing and to probe CP violation. The DUNE program also has synergies and complementarities to IceCube and KATRIN. In addition, the neutrino platform at CERN brings together the European contributions to neutrino physics.
- Understanding the nature and properties of dark matter is an inherently interdisciplinary challenge. All three Topics of the Program MU address this scientific goal in different and complementary ways. The Topic MU-FPF focuses on identifying potential dark matter candidates at colliders and elsewhere and on studying their properties. An electric dipole moment (EDM) storage ring as proposed by FZJ would also probe the very low-mass region for axion-like particles with oscillating EDMs.
- Strongly interacting matter plays a prominent role for many investigations in all three Topics of the Program MU. The quark–gluon structure of hadrons will be probed in complementary ways by PANDA at FAIR and at the LHC. A wide range of questions regarding the strong interaction is addressed within both MU-FPF and MU-CML using lattice computations [FPF-9]. Methods from string theory can provide new insights into QCD, including its phase diagram, which will be studied experimentally at ALICE and CBM. The study of high-energy hadron scattering at the LHC is of prime importance for understanding cosmic-ray interactions with the atmosphere.
- Strong collaboration with other Topics exists in the field of flavor physics, in particular regarding the question of the observed matter–antimatter asymmetry in the universe and of CP violation. This issue is pursued in MU-FPF by Belle II and in our theory groups, as well as in MU-MRU and in the search for electric dipole moments of charged particles in MU-CML.

The connections to other Programs in the Research Field *Matter* are numerous and fruitful:

- With the Program MT, we share in particular expertise for the development and employment of detector technologies and systems. While the more generic R&D aspects are typically worked out within the Topic MT-DTS, the application of these detectors and technologies to concrete experiments is performed in the Topic MU-FPF. This ensures that the detector components that end up in the experiments are designed and built by the same people who will later be responsible both for the operation of the devices and for the understanding and interpretation of the data obtained with them. In addition, many scientists and technical staff are active in both Programs.
- Collaboration between detector developers from the Programs MU and MML is facilitated through the Topic MT-DTS. Two examples of common interests are the development of new CMOS-based pixel detectors and the field of microchannel cooling.
- Particle physics has always been a driver of scientific computing, and installations such as the Tier-1 and Tier-2 centers at KIT and DESY or the NAF at DESY have set standards from which other communities such as photon science profit. While in PoF IV scientific computing for the Programs in the Research Field *Matter* will be bundled in MT-DMA, there will by close collaboration with MU-FPF e.g. in the development of modern machine-learning algorithms.
- The LUXE (Laser Und XFEL Experiment) collaboration is an excellent example for cooperation among the Programs MU, MT and MML. LUXE aims to pioneer the study of Quantum Electrodynamics (QED) in the strong-field regime by causing laser photons from a multi-TW laser to interact with high-energy electrons and photons from the European XFEL beam. Particle and accelerator physicists of DESY and laser physicists of HI Jena and Helmholtz-Zentrum Dresden-Rossendorf HZDR collaborate on LUXE together with ten other institutes from Germany, Israel, and the UK.

At the local and regional level, the participating Helmholtz Centers collaborate closely with the local universities. This collaboration takes many shapes: In Karlsruhe, KIT is a merger between a Helmholtz Center and a university. Another form of collaboration exists between DESY and Universität Hamburg: the Partnership for Innovation, Education and Research (PIER), of which particle physics is a central pillar. Since the beginning of 2019, the cluster of excellence Quantum Universe and the Collaborative Research Center SFB Particle Physics Phenomenology after the Higgs Discovery have been operating in Hamburg and Karlsruhe, respectively. Both proposals have profited from the participation of scientists from DESY and the Helmholtz part of KIT, who now play active roles in the respective research programs.

The participating Helmholtz Centers have many joint professorships with local and other universities. As an example, DESY currently maintains 12 joint professorships in the field of particle physics with the universities in Aachen, Bonn, Berlin, Freiburg, Hamburg, and Wuppertal. In Germany, DESY assumes the role of the national lab for particle physics, acting as a hub and facilitator for the participation of German institutes in international collaborations. DESY hosts many workshops, schools, and other events for the German community. The center also takes over managerial and administrative tasks for the German community, for example the controlling and reporting of federal funds allocated to universities for the HL-LHC upgrade. KIT and DESY offer significant infrastructure to the German community and beyond (see below).

At the European level, DESY is represented in ECFA and in the European Particle Physics Lab Directors' Group. DESY scientists are members of the European Strategy Group and the Physics Preparatory Group, which are central to the update of the European strategy for particle physics. On a global scale, DESY is represented in ICFA and involved in the important strategic discussions. One important example with strong DESY representation is the update process for the European strategy for particle physics, which is expected to be completed by May 2020. DESY and KIT will further strengthen strategic partnerships, particularly with other large particle physics laboratories (CERN, Fermilab, KEK, SLAC), with the aim of advancing particle physics at a global level.

In addition to the cooperation activities described above, we would like to mention a case of synergy with Fermilab. The LBNF/DUNE neutrino experiment in the USA has been approved to investigate neutrino properties with a long-baseline experiment, featuring a "near" and a "far" neutrino detector exposed to the same beam. Data taking is expected to start in the second half of the 2020s. The lively interest within the German community[10] is supported by Helmholtz scientists, who could contribute their expertise in neutrino physics and detector technology to the near detector, a high-granularity calorimeter originally developed for a future electron–positron linear collider.

Infrastructures

- GridKa (LK II), the LHC Tier-1 center, will be further developed as a data center optimized for the requirements of particle physics computing. The technological development will be driven by particle physics and in particular by the requirements for the HL-LHC era. There will be a close exchange of expertise with the Topic MT-DMA and the Research Field *Information* to develop and apply cutting-edge technologies for scientific computing at GridKa. GridKa will also continue to support other (astro-)particle physics experiments.
- Tier-2/NAF at DESY (LK II in MT): In PoF IV, this facility will be expanded into the Interdisciplinary Data and Analysis Facility (IDAF) and integrated into the Program MT in order to serve a broader scientific community. It will remain an important infrastructure for particle physics, e.g. for the HL-LHC, where new computing challenges have to be faced.
- The DESY Test Beam Facility has become an increasingly important asset for detector development. It has attracted strongly increasing numbers of users over the past few years, working on projects not only from particle physics, but also from astroparticle physics as well as hadron and nuclear physics. Currently, test beam upgrades are being discussed, together with plans for a new injector for the PETRA IV light source (see Volume II B on the Program MT).

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[10] See the KET statement as input for the update of the European strategy for particle physics from November 2018, http://www.ketweb.de/stellungnahmen/e298526/KET_ESPP_Statement_2018.pdf

- The Detector Assembly Facility (DAF) at DESY is currently used for the production, assembly, and testing of ATLAS and CMS tracker end-caps for the HL-LHC. In future, the DAF will serve other large-scale detector projects in particle physics and continue to be a vital asset for DESY's role as the national particle physics laboratory.
- The COoler SYnchrotron (COSY) at the IKP of FZJ is the world's only storage ring for polarized proton and deuterium beams. It is the ideal development facility for the Charge and Parity violating Electric Dipole Moment (CPEDM) project to measure electric dipole moments of charged particles with high sensitivity ($\sim 10^{-29}$ e cm). Currently, a precursor experiment is running at COSY. In the future, the synchrotron may be used as an injector for a prototype ring without magnetic steering elements – as one step towards a purely electric precision storage ring.

Opportunities and Risks

Accelerator-based particle physics can be characterized by a small number of long-term global projects with guaranteed physics output for many years to come. The LHC/HL-LHC has a well-defined physics program until about 2037. Data taking with the Belle II experiment is foreseen to last at least until the end of the PoF IV period in 2027, and discussions on possible upgrades of this facility have started. We also initiate and take prominent roles in smaller-scale experiments, e.g. searches for axions or ALPs. At the same time, we explore new opportunities together with our national and international partners. Through the high quality and influence of its staff, the Helmholtz Association has a significant impact on the decision process for the next large collider project at CERN or elsewhere.

The Helmholtz Association offers a very impressive program in particle physics, covering mass scales from below neV to over TeV. The projects suggested in this proposal will produce world-leading results, with potentially revolutionary consequences on our understanding of the universe around us. The Helmholtz Association is a reliable and valued partner with key responsibilities in large-scale projects extending over several decades, and we often play the role of a national or even European hub within these projects. In addition to first-class science, this program will produce important developments in modern technologies in particle detection and scientific computing, with major benefits for science and society.

2.2.2. Topic Cosmic Matter in the Laboratory

Executive Summary

The Topic *Cosmic Matter in the Laboratory* (MU-CML) explores the formation of matter from its elementary building blocks and the many facets and role of the strong force in this process. Extreme forms of matter are recreated in the laboratory. These resemble cosmic forms of matter such as the primordial matter from which protons and neutrons emerged, the dense baryonic matter occurring in compact stellar objects, and nuclei with extreme isospin playing a pivotal role in stellar nucleosynthesis. The Topic is complemented by studying hadrons and their excitation spectrum to provide important experimental information for developing a complete understanding of Quantum Chromodynamics in the non-perturbative regime. FAIR, with its capability to provide high-intensity, high-energy, stored and cooled ion and antiproton beams, is a unique facility to explore the Topic in its full breadth. The investigation of the strong force in this Topic impacts searches for physics beyond the Standard Model, including searches for dark matter, the exploration of matter–antimatter asymmetry, and other tests of fundamental symmetries.

Strategy

Our principal strategy is the completion and commissioning of the FAIR accelerator and experimental facility (within the scope of the modularized start version) by 2025/26, together with a staged approach to FAIR science that has started already in 2018 and will continue during PoF IV. Besides the construction and preparation of the FAIR experiments APPA, CBM, NUSTAR, and PANDA, our strategy therefore includes performing a comprehensive research program (FAIR Phase 0) by operating and exploiting existing research infrastructures at GSI and FZJ and participating in selected international experiment collaborations at other institutions. Whenever possible and advantageous, the FAIR Phase 0 experiments include testing and usage of novel FAIR detectors as well as advanced FAIR data acquisition and analysis concepts. FAIR Phase 0 thus serves several important ends: (i) gradual commissioning of FAIR accelerators and detectors; (ii) early FAIR science employing newly developed FAIR instrumentation and techniques; (iii) education and training of young scientists for FAIR; (iv) preserving and extending technical skills and expertise for FAIR, and – last but not least – (v) serving and further building the GSI/FAIR community.

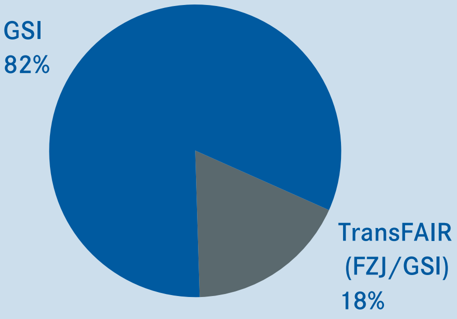
We will also continue our strong engagement in the ALICE collaboration at the LHC, both with major contributions to the ALICE detector upgrade and with participation in the LHC Runs 3 and 4. Further R&D activities include fundamental physics studies addressing the search for EDMs (for deuterons and protons) in storage ring experiments and precise measurements of the solar neutrino spectrum. A strong theory activity supports our experimental program. It includes lattice gauge QCD approaches, hadron theory, transport models and experiment simulations, theoretical predictions of nuclear properties and reactions, as well as theoretical nuclear astrophysics and explosive-nucleosynthesis models.

Facts and Figures

Participating centers:
GSI, TransFAIR (FZJ/GSI)

Spokespersons:
Frank Maas, GSI-HIM
Tetyana Galatyuk, GSI

Core-funded scientists: 82 FTE (2021)
Core-financed costs: 18,9 Mio.EUR (2021)



Contributions of the centers to Topic MU-CML:
Total core-funded personnel in 2021

Strategic Goal of the Topic

QCD is the generally established theory of the strong interaction, which describes how hadrons – and any form of matter built hereof – emerge from quarks as fundamental building blocks and their interactions via gluons. Although it has been realized that the mass of the hadrons is mainly generated by QCD dynamics rather than by the sum of their quark constituents, many of the details underlying this counterintuitive but fascinating aspect are not well understood. As of today, fundamental features such as confinement and chiral symmetry breaking cannot be derived from first principles. Likewise, the limits of nuclear existence and the structure of nuclei with extreme isospin are only vaguely known. We will contribute to unraveling these remaining secrets by exploring, with novel experimental approaches, the excitation spectrum of QCD, the structure of (strange, charm) hadrons, the properties of exotic nuclei, and, in general, the properties of QCD matter under extreme conditions of temperature and density, where matter is expected to exist in the form of quarks and gluons (quark–gluon plasma, QGP) or in some other yet-unobserved exotic form such as quarkyonic matter. In addition, we will test the limits of QCD theory by searching for beyond-the-Standard-Model (BSM) particles and effects such as axions or the charged-particle electric dipole moments, using novel and unique techniques connecting the Topic MU-CML with the Topics MU-MRU and MU-FPF.

Protons and neutrons are the most important hadrons, because as building blocks of nuclei they shape the world around us. The overarching goal of nuclear structure and reaction physics is to develop a global and unified model that describes the many facets and phenomena observed in nuclei and nuclear matter. This quest is currently experiencing an exciting renaissance thanks to new radioactive ion beam facilities for the study of short-lived nuclei in important, yet unexplored territories of the nuclear chart. Facilities with intense stable beams have led not only to the discovery of new chemical elements up to $Z = 118$, but also, at CERN and BNL, to the discovery and exploration of the QGP at high temperatures and vanishing baryon density. New microscopic nuclear models, based on the symmetries of QCD, have been developed and successfully applied to nuclear structure and reactions.

Hadrons and nuclei and bulk matter built hereof are genuine cosmic forms of matter, which shape the structure and evolution of stars during their long life in hydrostatic equilibrium. The properties of such bulk matter are important for stellar dynamics once steady nuclear burning comes to an end and black holes or neutron stars are formed. Strongly interacting matter existed in the form of the QGP in the early universe and was the primordial soup from which protons and neutrons emerged. Similar forms of matter might exist in the interior of neutron stars or be created in events such as supernovae or mergers of heavy star remnants. Short-lived nuclei play an essential role for the origin of the elements in the universe and for the astrophysical objects in which they are created. This is in particular true for the r-process as the astrophysical origin of heavy elements such as gold. This process has been listed among the big unsolved problems in astrophysics and put center-stage by the observation of the gravitational and electromagnetic (kilonova) signals of the neutron star merger event GW170817 in 2017, which for the first time gave evidence for heavy-element production in an astrophysical object. The activities in this Topic include the search for BSM physics and have important implications for the search for dark matter candidates or the understanding of the matter–antimatter asymmetry in the universe; both are forefront questions in astrophysics today.

The groups contributing to the Topic MU-CML have access to facilities that allow the creation of cosmic matter in the laboratory, and they play a leading role in exploring its properties. They study hot and dense strongly interacting matter in relativistic heavy-ion collisions at the LHC (ALICE experiment) and GSI (HADES experiment), exploring the QCD phase diagram in two quite distinct regimes. They study hadron structure and dynamics programs at BESIII in China and JLab in the USA, and explore short-lived and super-heavy nuclei at GSI and at other facilities such as RIKEN in Japan and TRIUMF in Canada. Decisive experimental progress on all the different facets of the research program is expected from FAIR. Owing to the unique combination of high-energy, high-intensity primary beams, the high-momentum-resolution superconducting fragment separator (Super-FRS), storage rings for studying nuclear reactions of astrophysical relevance, and the large variety of novel detectors and instrumentation, FAIR will give unrivaled access to a large, unexplored variety of cosmic matter on an unprecedented scale. This includes high-resolution studies of the QCD spectrum and of exotica created by proton–antiproton collisions (PANDA experiment), the investigation of the QCD phase diagram in previously inaccessible temperature/density regimes in relativistic heavy-ion collisions with unprecedented event rates (CBM experiment), and the production and study of short-lived nuclei. These include for the first time heavy nuclei with large neutron excess, the study of which is crucial to unravel the physics of kilonovae and the r-process (NUSTAR experiment). Besides the design and construction of the facilities and detectors, which will allow optimal use of the FAIR facility, our main focus during the PoF IV period will be the development of the physics program to be explored once FAIR is operational. To reach this goal, we will follow a stepwise process, performing a unique and exciting science program (FAIR Phase 0) that exploits the upgraded GSI accelerator chain and fully or partly available FAIR experimental instrumentation. This is supplemented by the participation in the experimental programs at the LHC, where scientists of the Topic MU-CML have played an important role in the upgrade of the ALICE detector in preparation for the upcoming high-luminosity runs as well as for selected other facilities. Last but not least, scientists involved in MU-CML are actively pursuing a proof-of-principle experiment to search for an electric dipole moment (EDM) of charged-particles by using storage rings and to detect axion-like particles in the ultralight mass range as potential dark matter candidates. Moreover, we are engaged in experiments studying neutrino characteristics.

Unraveling these fascinating questions in hadron and nuclear physics is the main focus of the Topic MU-CML, which will be addressed in four research areas:

- Properties of hadrons and their excitation spectrum
- QCD phase structure and understanding the microscopic properties of QCD matter
- Nuclear structure, nuclear reactions, and superheavy elements (SHE)
- Origin of the matter–antimatter symmetry and test of fundamental symmetries

Competences

As one of the leading accelerator facilities in subatomic physics, GSI has a wide-spanned experimental, theoretical, and technical expertise in accelerator science and in the many subfields defining modern hadron and nuclear physics. Due to this broad competence, GSI serves as the host laboratory for the FAIR facility, which will open up unprecedented new avenues in fundamental and applied science and ensure Europe's competitiveness in these basic fields of science for the next decades. Scientists of FZJ and HIM make major contributions within this Topic to the construction of FAIR and to the definition of its science program. The importance of FAIR for European science has been impressively confirmed by the recent long-range plan of NuPECC, which listed FAIR as its top priority and included FAIR in the recommendation of all research areas owing to the facility's wide-ranging relevance for science. The report also stressed the essential importance of the intermediate research program at GSI (FAIR Phase 0) for the science community in Europe.

The scientific expertise at GSI and FZJ covers the broad range of modern hadron and nuclear physics. This includes experimental and theoretical activities in hadron structure and dynamics, in nuclear structure and reaction physics, in nuclear astrophysics, and in accelerator physics. The competence of our scientists is reflected by their assignments to high-level positions in international collaborations and committees. Our research benefits from very close collaboration between experimental and theory groups, and from strong support from and synergies with activities at neighboring universities. In PoF III, the HIM has strengthened our science program in hadron and accelerator physics as well as in the physics and chemistry of superheavy elements and added a program on fundamental symmetries in particle, nuclear, and atomic physics to our portfolio. The latter is one of the pillars for an extended collaboration with scientists of the Johannes Gutenberg-Universität Mainz within the cluster of excellence PRISMA+.

Our competences are also reflected in the important role we play in the design and construction of state-of-the-art detector technology and readout electronics that will be used at FAIR and for the ALICE experiment at the LHC. Respective ongoing projects include the STS tracking system for CBM, the ALICE TPC readout chambers, the TRB3-based data acquisition architecture for HADES, and key detector components for PANDA, such as the inner (silicon-based) and outer (gas-detector-based) charged-particle tracking system, the particle identification system DIRC (based on the internal reflection of Cherenkov light) and the electromagnetic calorimeter. These efforts are strongly supported by the scientific-technical infrastructure departments existing at FZJ and GSI.

Data analysis, handling of big data, development of complex algorithms, and simulations of detectors are a prerequisite for the design and operation of the FAIR detectors, but also for the ongoing research program at GSI within FAIR Phase 0. We have extensive expertise in all these aspects as well as in theory efforts requiring large-scale computing, such as lattice QCD and astrophysical simulations. These activities benefit from our access to the computing facilities on the GSI campus in Darmstadt (Green IT Cube), the dedicated computer cluster at HIM, and the supercomputers at FZJ.

A special asset of our Topic is the extensive competence in the acceleration, deceleration, storage, and cooling of ion beams. With UNILAC, SIS18, ESR, and COSY, we have designed and operated leading accelerator facilities. Today, we are the leading laboratories for the construction of the major accelerator systems at FAIR, with the SIS100 as the heart of the future facility and the high-energy storage ring HESR for proton–antiproton annihilation experiments at PANDA as well as for unmatched experiments in nuclear and atomic physics. In addition, the Super-FRS will give worldwide unrivaled access to brilliant secondary beams of heavy exotic nuclei. The currently available accelerators and rings are the basis for the FAIR Phase 0 research program and for testing FAIR accelerator and detector components. Such tests are also performed at the Mainz Microtron MAMI, at CERN, and at other accelerator facilities.

All experimental activities profit from our substantial and broad expertise in theoretical physics, including nuclear effective theory, hadron phenomenology, perturbative QCD, chiral and soft collinear effective field theory, many-body models for nuclear structure and reactions, simulation models for astrophysical objects, lattice QCD, studies into the nature of the transition to the plasma phase, and investigations of transport properties by means of relativistic hydrodynamics.

Objectives and Approach

We study strong interaction at all length scales, in nuclear physics and in hadronic and quark matter, within the four research areas defined above:

Understanding the properties of hadrons and their excitation spectrum

The main tasks regarding the investigation of hadron structure and dynamics during PoF IV will be the continuous development of the PANDA physics program, the completion of the construction of the PANDA experiment, and the commissioning of the PANDA detector. Besides being primarily responsible for the main PANDA detector subsystems, the MU-CML groups also provide major contributions to the software framework and to the high-level data reconstruction and analysis methods.

Our scientific interest in the study of antiproton annihilation reactions in the PANDA experiment focuses on the spectroscopy of hyperons, light and heavy exotics up to the charmonium region (see Figure 7), hypernuclear physics, and nucleon structure observables. Important contributions to all those fields will be possible within the early experimental program of PANDA, the construction phase of which will be complemented by the preparation of analysis tools and feasibility studies [15]. This planned experimental program will be accompanied by extensive activities in theoretical physics. Nucleon structure observables, such as form factors and generalized parton distributions, will be studied in the framework of QCD factorization, soft collinear effective field theory, and lattice QCD calculations. Phenomenological analyses, supplemented by perturbative QCD, effective field theory, and lattice QCD will allow for a detailed interpretation of the hadronic spectrum and of the properties of resonances in the charm sector. Lattice simulations and nuclear

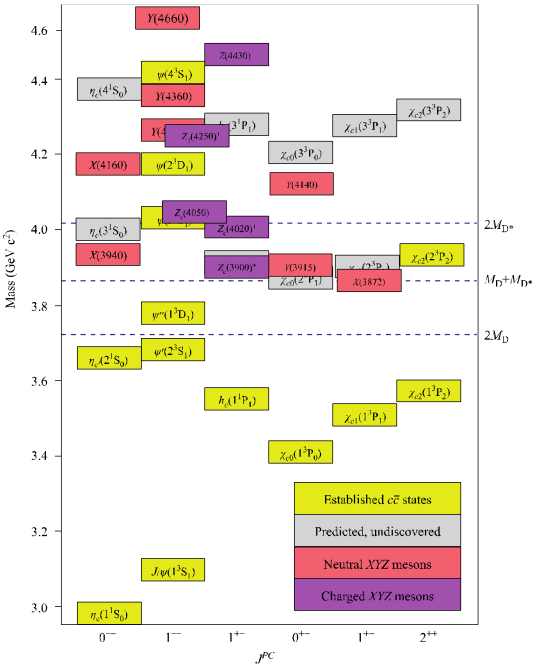


Figure 7: Spectrum of X, Y, and Z states.

effective field theory are the primary tools to study light nuclei and hypernuclear systems.

The extremely well defined antiproton beam will be a unique asset of this research area as it provides the only experimental possibility to measure line shapes and to gain a systematic understanding of the structure of the recently detected candidates for four-quark and five-quark states. Moreover, the antiproton beam makes PANDA a hyperon factory for the *terra incognita* of the excitation spectrum of hyperons, extremely interesting for hadron theory with medium-mass strange quarks. Time-like nucleon structure can for the first time be systematically studied with high statistics in differential cross sections. The antiproton beam is particularly well suited for the production of double-strange hypernuclei.

While this exciting physics program can be explored once the FAIR antiproton beam is available, we have four different FAIR Phase 0 projects that include PANDA subdetector systems being used for physics measurements at running facilities:

- Four PANDA tracking stations using 1.700 straw tubes of the PANDA forward tracking system design will be installed at HADES. These new detectors will greatly enhance the acceptance for the decay baryon from hyperon Dalitz decays. Together with HADES, a program to investigate radiative decays of excited (multistrange) hyperons will be carried out. This includes measurements of the real photon and dilepton decay of the $\Sigma^*(1385)$, the transition form factor of the $\Lambda(1520)$, and production measurements of cascade baryons [milestone CML-8][11].
- In the framework of the PANDA DIRC detector for particle identification, special algorithms have been developed for identification of the Cherenkov photons, corrections for their time of flight in the optical system of the DIRC, identification of the ring structure of the Cherenkov light, and application of the combination of all signals to achieve a new level of efficient particle identification capabilities. The GlueX experiment at JLab uses a recently commissioned DIRC for particle identification [CML-5]. The application of the full set of the PANDA DIRC analysis and particle identification algorithms for pions and kaons will allow for a unique test of these new particle identification algorithms and, at the same time, substantially improve the performance of the GlueX apparatus for the important pion/kaon separation.
- The PANDA backward end-cap calorimeter, which is important for the detection of hadronic radiative decays and nucleon structure observables at backward angles, offers a unique opportunity to measure the pion transition form factor at the 1.6 GeV electron accelerator MAMI in Mainz. This measurement requires the coincident detection of the photons from a neutral pion decay with the scattered electron. They provide perfect conditions for testing the streaming readout system, with first online analysis by the front-end electronics, as well as the reconstruction algorithms of the PANDA electromagnetic calorimeter. In addition, the measurement of the pion transition form factor using the Primakoff effect at MAMI will allow for a substantial reduction of the theory error from light-by-light scattering to the anomalous magnetic moment of the muon, which will complement ongoing measurements of this kind in gamma-gamma scattering at BESIII.
- The PANDA luminosity detector will be used in a dedicated setup for the hypernuclear physics program.

Moreover, radiative decays of hadrons are studied by analyzing the existing and upcoming data sets from Halls B and D at JLab. This will allow us to apply the PANDA partial-wave analysis (PWA) algorithms to experimental data [CML-10]. Photoproduction of mesons is a complementary production method of light and strange mesons, which is investigated at GlueX in Hall D at JLab with special emphasis on states with gluonic degrees of freedom [CML-10]. Experiments on e.g. exotic strangeonium states will complement the plans and results on exotic charmonium at BESIII [16] and later at PANDA. Exotics and non-exotic charmonium production and decays are being studied at BESIII [CML-10]. The Y(4260) region and the potential Z_c multiquark states are of particular interest and are being investigated. The discovery of complementary states and decay channels as well as a clarification of the nature of vector resonances are of utmost importance for the interpretation of the charmonium spectrum, which requires input from phenomenological analyses and lattice calculations.

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[11] See Table 2 for an overview of the Topic's milestones.

Establishing the QCD phase structure and understanding the microscopic properties of QCD matter at vanishing and high net baryon densities

By studying matter at extremes of temperature and density, produced in heavy-ion collisions at (ultra-)relativistic energies, we will understand and test how QCD gives rise to hadronic and nuclear matter and explore matter as it existed in the early universe and as it occurs in supernovae and in neutron star mergers. The investigation of the QCD phase diagram is in the focus of several facilities worldwide. With HADES, CBM, and our participation in ALICE, we have a unique possibility to understand the QCD phase structure over the full range of temperatures and baryochemical potentials, as shown in Figure 8.

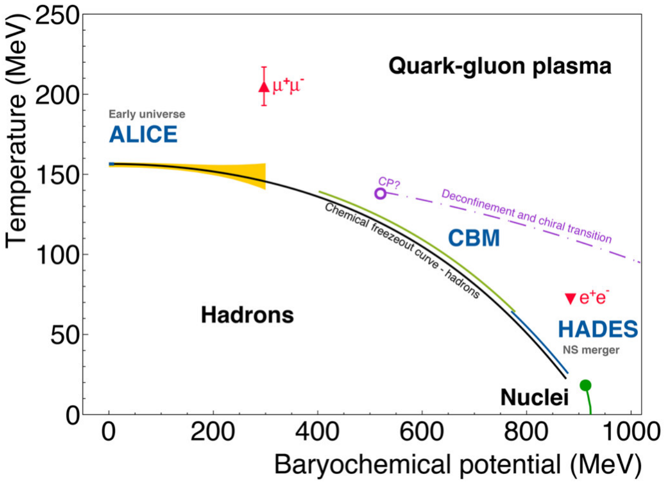


Figure 8: The conjectured phases of strongly interacting matter, their boundaries, and a critical point (CP) in a diagram of temperature versus baryochemical potential.

The ALICE experiment at the LHC addresses fundamental questions related to the nature of the produced QGP as well as to the nature of the transition to the hadronic phase [17], which according to lattice QCD predictions should happen via a crossover (yellow band in Figure 8). The HADES and CBM experiments at SIS18/SIS100 focus on the exploration of unknown territory of the QCD phase diagram in the baryon-rich domain, where theory predicts deconfinement, a chiral phase transition between hadronic and partonic matter (magenta dashed-dotted curve in Figure 8), the QCD critical point (magenta circle), and new (i.e. quarkyonic) forms of matter [18, 19]. The discovery of these landmarks requires a detailed theoretical understanding of the dynamics of heavy-ion collisions. Theoretical approaches based on hydrodynamics and microscopic transport models being developed within MU-CML are appropriate tools to achieve this goal [20].

The precise determination of the properties of the QGP at vanishing baryochemical potential is the ultimate goal of the ALICE physics program [CML-1]. Heavy quarkonia, i.e. bound states of charm or beauty quarks and antiquarks, can give key insight into the physics of deconfinement. Measurements of the quarkonium dissociation and (re-)generation pattern will also provide crucial information about the phase structure of QCD matter [17]. The thermalization of partons in the QGP will be studied via open heavy-flavor hadrons, i.e. hadrons carrying single charm or beauty quarks. Measurements of their phase space distributions and azimuthal anisotropies can put strong constraints on the transport coefficients of the QGP. Directed flow of charm mesons is sensitive to the primordial electromagnetic field generated in the collision and the related quantum effects. Measurements of heavy-flavor baryons will help to clarify the contribution of recombination with light quarks to the hadronization process. In the light-quark sector, hadronization can be studied, and limits of thermal production and nucleon coalescence models can be tested with measurements of loosely bound nuclear states, i.e. light nuclei, antinuclei, and light hyper-nuclei. Measurements with unprecedented precision of azimuthal anisotropies in identified-particle production with respect to the symmetry planes of the collisions will become possible. This is a promising and unique tool to access the dynamical evolution of the QGP.

The HADES activities aim to achieve a comprehensive understanding of the microscopic structure of the hot and dense collision zone [CML-11] with particular focus on dilepton signals (red triangle in Figure 8). For the interpretation of the heavy-ion data, it is essential to study the production of resonances and their structure in elementary proton- or pion-induced reactions. The combination of the HADES detector with a pion beam at GSI is a unique chance to study electromagnetic transition form factors (eTFF) of baryons in the time-like region and the role of far-off-shell ρ propagation for this quantity. The pioneering successful pion beam run with HADES demonstrated an exciting perspective for studies of a much larger range of nucleonic excitation reaching the third resonance region [21]. Moreover, using proton beams, the production of hyperons and the study of their eTFF are also within reach [CML-8], which will be done in collaboration with PANDA and CBM. These research activities will be extended at SIS100 after HADES has been moved to the CBM cave [CML-11].

The fundamental question whether a phase transition to a chirally restored phase exists can be explored for the first time with the novel CBM detector system using rare and penetrating probes. The detector system has the capability to provide excitation functions of rare probes with unprecedented precision, which is necessary to spot the discontinuities that are expected if a phase boundary is crossed during the evolution of the fireball. The high-rate capability will allow us to search for exotic multistrange objects or other forms of hyper-matter. The project planning is such that the CBM detector will be available for operation with the first beam extracted from SIS100 [CML-13]. The addition of an end-cap time-of-flight (eTOF) detector based on CBM TOF modules to the STAR experiment at RHIC in the USA strengthens the physics potential of the experiments during the RHIC Beam Energy Scan Phase II campaign. The installation of the eTOF was completed in November 2018. In the 2019 run of RHIC, it was demonstrated that the eTOF detector crucially complements the particle identification capabilities at forward-to-mid rapidities for collider and fixed-target experiments at STAR. Four detector stations equipped with double-sided silicon microstrip sensors will be installed in the BM@N experiment at JINR in Russia in order to upgrade the existing detector system for the measurement of Au–Au collisions up to kinetic energies of 4,5 GeV per nucleon.

mCBM@SIS18 (“mini”-CBM) is an experimental site to test CBM (and other) detectors with high-intensity heavy ion-beams. The mCBM experiment consists of full-size prototype CBM detectors, a free-streaming data readout chain, and optical-fiber connections to the Green IT Cube of GSI, where the online event reconstruction is performed. The benchmark experiment will be the online reconstruction of Λ hyperons [CML-9].

The experimental programs are accompanied by efforts to develop theoretical approaches that are able to describe HADES, CBM, and ALICE observables in order to exploit synergies between the different kinematic regimes. In particular, for the experiments in the CBM energy regime, transport codes will be extended to include effects of medium modifications and off-shell dynamics as well as a non-equilibrium phase transition. In particular, electromagnetic probes will be explored, including a detailed microscopic description of the dynamical evolution. We will work on understanding the origin of fluctuations in heavy-ion collisions, the role of the production of clusters and light nuclei, as well as the production mechanism of (multi-)strange particles.

Understanding nuclear structure, nuclear reactions, and superheavy elements as well as their relevance for nuclear astrophysics

During the stepwise completion of the NUSTAR at FAIR instrumentation, we plan to run a competitive experimental program [CML-8] that takes advantage of the intensity upgrade of the existing accelerator complex and already operational detection systems, thus providing unique science opportunities already during FAIR Phase 0. Once the FAIR experimental sites are ready, the equipment will be moved to the new premises [CML-14].

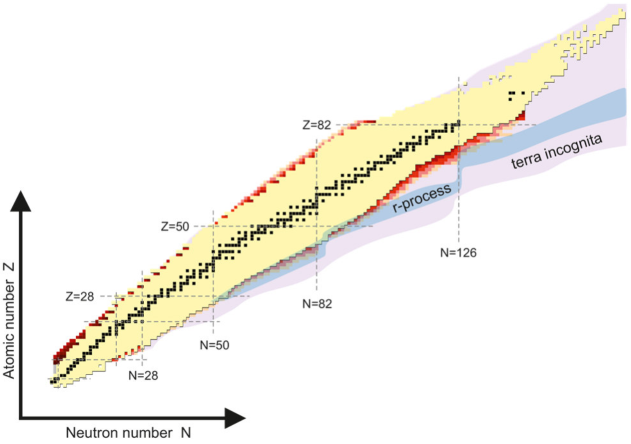


Figure 9: Chart of nuclei showing the known stable (black) and unstable (yellow) nuclei as well as the “unknown nuclei” (violet), whose existence is predicted by nuclear models. The nuclei that will be accessible with Super-FRS at FAIR for the first time are shown in dark red.

The planned program aims at advancing our general understanding of nuclei and is of high relevance for nuclear astrophysics. The high-energy, high-intensity beams from SIS18 in combination with the separation strength of the FRS allow us to further extend the nuclear chart in the $Z > 60$ region through the discovery of new isotopes and to study their gross properties (as indicated in Figure 9). For the first time, we will reach r-process nuclei at the $N = 126$ shell closure and measure their half-lives, which are crucial for the mass flow to the very heavy nuclei in the r-process operating in neutron star mergers. Nuclear spectroscopy experiments making use of the FAIR HISPEC/DESPEC detectors will focus on measurements of collective effects and the evolution of single-particle and shell structure far off stability. The results will serve as fundamental input to microscopic model calculations. We will study kinematically complete reactions at relativistic energies with radioactive beams with the R3B setup to constrain the symmetry energy in the nuclear equation of state in order to investigate short-range correlations in nuclei and the structure and exotic decay modes of dripline nuclei. R3B will pursue an active program in search for collective excitations in neutron-rich nuclei and study astrophysically important reactions in inverse kinematics via Coulomb dissociation. The EXL experiment will study such reactions in inverse kinematics in a storage ring. In experiments at the borderline of nuclear and hadron physics (e.g. search for mesonic atoms), hypernuclei production and properties (e.g. life times, structure) will be studied with detector setups at the FRS [CML-14].

GSI including HIM has a long-standing history in the study of superheavy elements (SHE) at the SHIP/SHIPTRAP and TASCA setups, which were recently upgraded with new detectors and will continue operation [CML-15]. The continuation of this traditional program will focus on reaction studies to find the optimum production conditions for SHE, laser spectroscopy to determine the atomic properties at SHIPTRAP [22], and probing their chemical properties in experiments with single atoms. This program would benefit from a superconducting continuous-wave (CW) linear accelerator, the development of which is actively pursued at HIM.

The NUSTAR theory activities aim at the description of exotic nuclei and their role in nuclear astrophysics. A particular focus will be on r-process simulations in neutron star mergers with improved nuclear reaction rates coupled to the appropriate astrophysical trajectories. For this purpose, we will develop a consistent set of astrophysical reaction rates for neutron captures, beta decays, and nuclear fission based on microscopic models. This will allow us to identify signatures of the r-process in kilonova light curves and determine their sensitivity to nuclear physics [23]. We will develop the nuclear equation of states for modeling supernovae and neutron star mergers [24]. Constraints on the nuclear equation of state will be derived from experimental studies probing the large range of densities achieved in various types of heavy-ion reactions. Such an improved nuclear equation of state will be applied in neutron star merger simulations to study the impact of such mergers on the gravitational-wave signal and the nucleosynthesis yields.

Understanding the origin of the matter–antimatter asymmetry and testing fundamental symmetries

We exploit our expertise in the design and construction of storage rings and high-precision experiments to test fundamental symmetries and interactions in close collaboration with the Topic MU-FPF. The experiments use neutrinos and electron beams as well as laser spectroscopy.

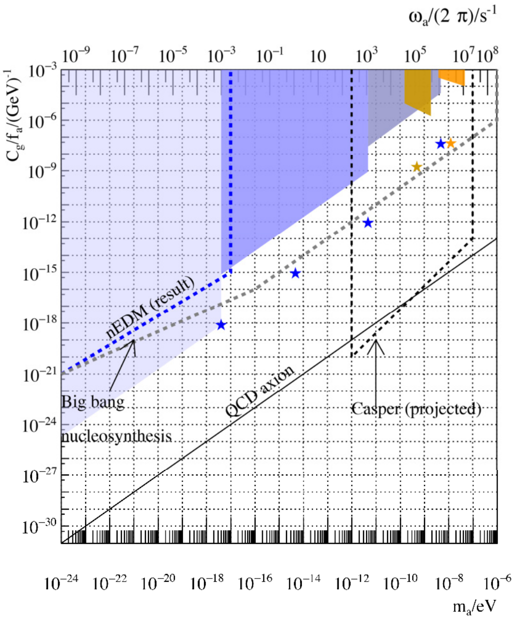


Figure 10: Axion–gluon coupling as a function of axion mass (frequency): nEDM and big bang nucleosynthesis are experimental results, others are projected limits.

The detection of an electric dipole moment (EDM) of the neutron or proton is a promising way to explore CP violation in the strong-interaction sector and bears fundamental importance for understanding the matter–antimatter asymmetry in the universe [25]. To supplement the worldwide search for an EDM of the neutron, we develop a strategy and pursue a pioneering experiment at a storage ring to search for an EDM of charged particles (proton, deuteron) with unprecedented sensitivity. This experiment, which is performed at COSY, will be completed at the beginning of the PoF IV period [CML-2, CML-12]. Based on this experience, we will further elaborate our strategy for a two-step approach towards a dedicated all-electric storage ring experiment achieving a sensitivity that competes or even surpasses the capabilities of state-of-the-art experiments for neutrons [CML-6].

Axions and axion-like particles (ALPs) are promising candidates for dark matter particles. In the framework of the Cosmic Axion Spin Precession Experiment (CASPEr), we search for ALPs in the ultralight mass range [CML-7]. Oscillating EDMs induced by ALPs will also be searched for in the COSY storage rings in a wide mass range (see Figure 10, nEDM experiment). The CASPEr program is part of the cluster of excellence PRISMA+ at the Johannes Gutenberg-Universität Mainz [26, 27].

Also in close collaboration with PRISMA+, we perform high-precision parity violation experiments in electron scattering to determine the weak mixing angle. In addition, we resolve the effects of neutron skin and the nuclear anapole moment in parity-violating laser spectroscopy of ytterbium [28] [CML-16]. We continue our involvement in studies of the exotic Th-229m isomer, which holds promise for a high-precision nuclear clock [29]. In the neutrino sector, we continue the precision measurements of the solar spectrum with Borexino [CML-3] and contribute to the next-generation experiment JUNO [CML-4] with the final aim to study the neutrino mass hierarchy and possible leptonic CP violation.

Expected Results

The sketched work program translates into a number of milestones that are well suited for monitoring the progress of the Topic. These are shown in the following table.

Table 2: Overview of milestones for the Topic MU-CML.

Number	Year	Milestone
CML-1	2021	Operation of the upgraded ALICE detector at the upgraded LHC at full Pb–Pb interaction rate
CML-2	2021	Result of the EDM precursor experiment at COSY
CML-3	2021	Final results of the solar neutrino analyses from Borexino
CML-4	2021	Use of the OSIRIS radiopurity detector during JUNO scintillator filling and start of the JUNO experimental neutrino program
CML-5	2022	FAIR PANDA DIRC particle ID algorithms fully tested with GlueX data
CML-6	2022	Technical design report on prototype ring for EDM experiments
CML-7	2022	Completion of ALP search in mass range up to 10^{-8} eV
CML-8	2023	First measurement of electromagnetic transition form factor of hyperons with the HADES/PANDA setup at SIS18
CML-9	2023	High-speed online Λ reconstruction with mCBM@SIS18 demonstrated
CML-10	2024	FAIR PANDA PWA algorithms fully tested and applied to CLAS, GlueX, and BESIII data
CML-11	2024	Completion of the HADES experimental program at SIS18: HADES ready to move to CBM cave at SIS100@FAIR
CML-12	2024	Axion search via oscillating EDMs at COSY completed
CML-13	2025	CBM silicon tracker installed, ready for SIS100@FAIR
CML-14	2025	FAIR Phase 0 NUSTAR experiments at FRS completed. Ready for experiments at Super-FRS at FAIR
CML-15	2025	FAIR Phase 0 NUSTAR experiments at SHIP(TRAP) and TASCA completed
CML-16	2027	Upgrade of the Yb parity violation experiment finished; measurement of neutron skins and nuclear anapole moments realized

Synergies and Collaboration

Here, we focus on synergies and collaborations across the Topics of the Program MU and within the Research Field *Matter*. Of course, we also maintain many collaborations with other national and international partners contributing to the Topic MU-CML.

MU-CML has close scientific and instrumental overlap with the two other Topics of the Program MU – particle physics (MU-FPF) and astroparticle physics (MU-MRU) – and also with the two other Programs in the Research Field *Matter*, MML and MT. This has resulted in strong collaborations between the Topics, generating many scientific-technological synergies. For example, a more precise knowledge of the nucleon structure as pursued in MU-CML will provide better estimates of the cross sections for high-energy proton–proton collisions to produce Higgs bosons (MU-FPF). Similarly, hadronic interaction data measured in MU-CML are an important input for modeling air showers produced by ultrahigh-energy cosmic radiation hitting the upper atmosphere (MU-MRU). Likewise, the activities within MU-CML nicely complement the efforts on axions described in MU-FPF.

Collisions of heavy ions at SIS18 allow us to study the properties of strong-interaction matter under extreme conditions of density and temperature similar to those that govern the dynamics in astrophysical events such as supernovae and neutron star mergers. Such studies thus also contribute to current astrophysics subjects, including the interpretation of gravitational-wave signals observed in these events and the quest for the origin of highly energetic cosmic rays. Constraints on indirect searches for new physics as obtained in EDM experiments or measurements of the weak mixing angle can be extended to very high mass scales for new particles and thereby help to confine the parameter space for new physics that is accessible at the LHC (MU-FPF). Instrumentally, the work pursued in MU-CML strongly benefits from and, at the same time, contributes to the development of forefront accelerator technology (e.g. electron beam cooling up to very high energies, modern superconducting CW linear-accelerator structures) and detector technology (radiation-hard silicon detectors) as well as state-of-the-art (free-streaming) data acquisition and analysis techniques involving high-performance computing and big-data management. For this, MU-CML closely collaborates with the Program MT.

Infrastructures

The researchers of the Topic MU-CML have access to large-scale infrastructures at the participating Helmholtz Centers (to accelerators such as UNILAC, SIS18, ESR, CRYRING, COSY and to experimental sites) and elsewhere (e.g. ALICE at LHC/CERN, STAR at RHIC, BM@N at JINR, BESIII at IHEP, and GlueX at JLab). Large-scale computing, provided by the GSI Green IT Cube and the Jülich Supercomputing Center, is essential for the success of the Topic. For more information, see the table of infrastructures in Chapter 3.2. and the description of the LK II facilities in Volume III.

Opportunities and Risks

The research opportunities covered by the Topic MU-CML have the potential for major breakthroughs in our understanding of the strong force, the existence and structure of exotic hadrons, the phase diagram of QCD matter as a function of temperature and net baryon density, and the type and role of the deconfinement and/or chiral phase transition for the formation and properties of hadrons. They will also considerably advance our knowledge of nuclei far off stability and their role in explosive nucleosynthesis for the creation of elements beyond Pt and Au in core collapse supernovae and in neutron star mergers. Moreover, they include promising developments for fundamental physics studies such as the search for axions, preparations for a future high-precision storage ring EDM experiment on deuterons and protons, and the participation in solar neutrino experiments (Borexino, JUNO). The basis for the planned work is provided by forefront research infrastructures operated and exploited at GSI, FZJ, and other laboratories worldwide, and – from 2025/26 on – the start of the physics program at the new FAIR facility. In view of the complexity of the FAIR project, there exists a risk that the start of FAIR might be delayed, impacting both the science output and the attractiveness for users. The FAIR Phase 0 program allows for mitigation of this risk by early commissioning and usage of FAIR detector instrumentation and by offering regular physics runs to the GSI/FAIR users, thereby bridging the transition time until the start of FAIR. Referring to the envisaged high-precision storage ring EDM experiment, the funding of the intermediate and in particular the ultimate step is not secured so far.

2.2.3. Topic Matter and Radiation from the Universe

Executive Summary

The Topic *Matter and Radiation from the Universe* (MU-MRU) operates facilities at the most remote locations in the world and performs high-precision experiments in the laboratory to study the largest structures in the universe and the properties of fundamental particles. We significantly contribute to the world's leading research infrastructures in astroparticle physics. DESY and KIT are jointly driving neutrino astronomy with the IceCube observatory at the South Pole, DESY hosts the Science Data Management Center of CTA, the future, worldwide unique observatory for high-energy gamma-ray astronomy, and KIT is a leader of the Pierre Auger Observatory in Argentina, the world's largest instrument to study ultrahigh-energy cosmic rays. KIT also hosts the KATRIN experiment for the measurement of the neutrino mass, which at the same time paves the way for DARWIN, the ultimate experiment searching for heavy dark matter particles and exploring fundamental properties of neutrinos. All experimental activities are complemented in a coherent and coordinated way by theoretical studies performed at DESY, IPP, and KIT.

Strategy

Astroparticle physics is a rapidly developing field of research that has achieved major breakthroughs in recent years. By building new or improving existing infrastructures, we will create an experimental landscape that will allow us to fully exploit the potential of research using cosmic messengers. As the least understood fundamental particles, neutrinos play a central role in our Topic. Activities in neutrino physics pave the way for decisive experiments in the search for dark matter. By combining the information gained through new windows to the cosmos opened up by gamma rays, high-energy neutrinos, cosmic rays, and gravitational waves, and by precisely determining the properties of neutrinos and performing dark matter searches with unprecedented sensitivity, we will develop a new, joint picture of the high-energy universe. In this way, we will make decisive contributions to answering fundamental questions about the structure and development of our universe.

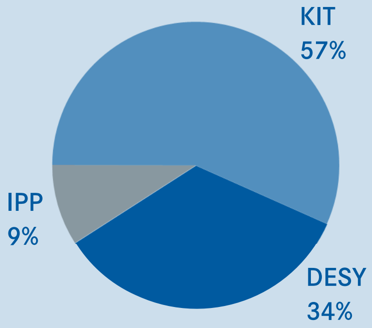
Facts and Figures

Participating centers:
DESY, IPP, KIT

Spokespersons:
Christian Stegmann, DESY
Kathrin Valerius, KIT

Core-funded scientists: 120 FTE (2021)

Core-financed costs: 40,9 Mio.EUR (2021)



Contributions of the centers to Topic MU-MRU:
Total core-funded personnel in 2021

Strategic Goal of the Topic

Astroparticle physics is a young and very rapidly growing field of research. With great success, methods and technologies developed for particle physics are applied to investigate astrophysical and cosmological phenomena and, conversely, the unique environments provided by astrophysical objects and the universe as a whole are used to learn more about particle physics.

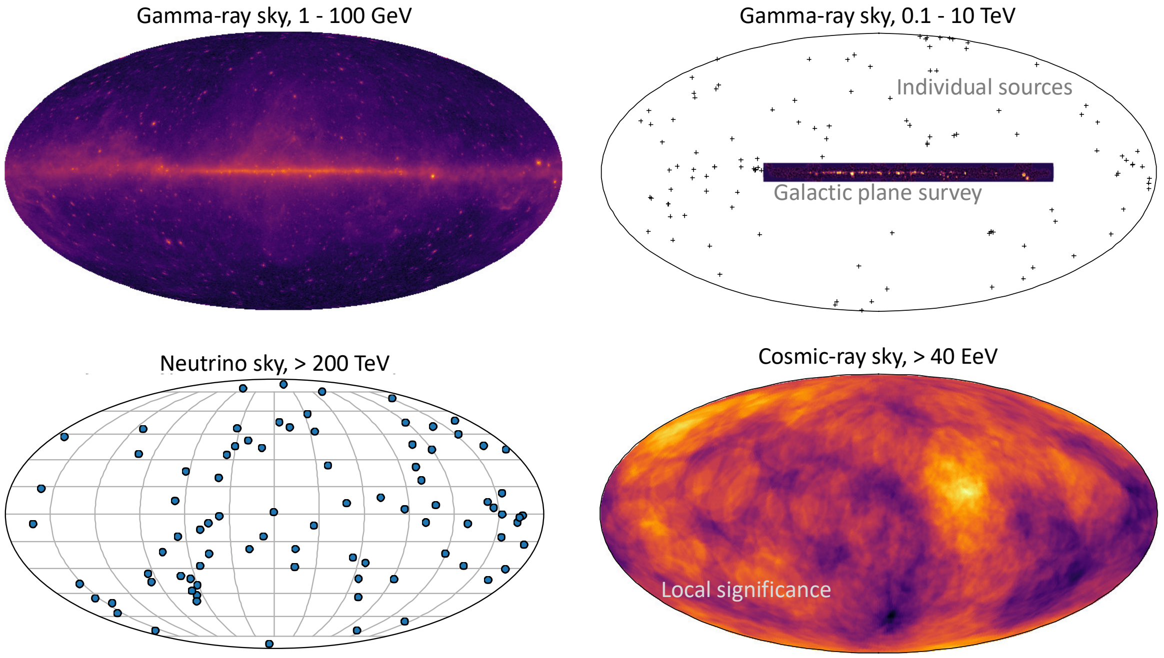


Figure 11: From upper left to lower right: Sky maps in high-energy and very-high-energy gamma rays, neutrinos, and ultrahigh-energy cosmic rays. The four all-sky maps show mainly two aspects: First, that we receive information from all high-energy cosmic messengers, and second, that we are only just beginning to see what the image of our universe transmitted through high-energy cosmic messengers looks like.

For centuries, the universe was observed in classical astronomy through photons produced in thermal processes. The extension of the observational window to high energies and to different messengers (charged particles, gamma rays, and recently also neutrinos and gravitational waves) has led to scientific breakthroughs – many of them through key contributions from our Topic together with our partners all over the world – and revolutionized our view of the universe. We have discovered a large number of different gamma-ray sources, first evidence for sources of high-energy neutrinos, and first clues in the search for sources of the highest-energy cosmic rays. We found a variety of non-thermal processes generating high-energy particles to be abundant throughout the visible universe. However, despite these amazing results, we are far from having a consistent and coherent picture of the high-energy universe. On the contrary, it is obvious that our picture is incomplete, and that we are only at the beginning of understanding what impact non-thermal processes and high-energy particles have on the evolution of our universe. Neutrinos play a special role, because they can escape from the core of the regions that harbor the most violent processes in the cosmos. As weakly interacting particles with a non-vanishing mass, neutrinos influence the structure formation of the universe. Yet, many of their fundamental properties are still not understood. The same holds for the nature of dark matter, which dominates the matter content of the universe.

It is our strategic goal in the Topic MU-MRU to address these urgent and fundamental questions in astroparticle physics in a coherent and effective way. These questions include:

- the search for the sources of high-energy and ultrahigh-energy particles in the cosmos,
- the quest to understand the production and propagation of particles and radiation in an extremely wide energy range, reaching from just above thermal energies up to energies well beyond the reach of man-made accelerators, and their influence on the evolution of the universe,
- the study of physics and fundamental symmetries under extreme astrophysical conditions,
- and the determination of the properties and nature of neutrinos and dark matter.

As progress in astroparticle physics is largely driven by observations and experimental data, we will continue to be the key players in designing, constructing, and operating the world's leading and most sensitive experimental facilities in this field. These are:

- The Pierre Auger Observatory in Argentina, the largest cosmic-ray detector ever built (KIT),
- The IceCube neutrino observatory at the South Pole, which detected the first very-high-energy neutrinos of astrophysical origin and which will be expanded into IceCube-Gen2 (DESY and KIT),
- The KATRIN experiment to measure the neutrino mass and search for sterile neutrinos, which just started taking data and produced already the world-best limit on the neutrino mass (KIT), and
- The Cherenkov Telescope Array (CTA), a worldwide unique future gamma-ray observatory whose construction will start soon (DESY). Until CTA takes over, we will continue to be involved in the operation of the current generation of gamma-ray instruments (DESY).

With our key roles in world-leading experiments on cosmic rays, gamma rays, and neutrinos, we occupy outstanding positions in the rapidly developing fields of multimessenger astronomy, neutrino physics, and the search for dark matter. We will further consolidate and expand these positions and fully exploit the technological synergies of the various experimental techniques. Based on our expertise from KATRIN and our participation in XENONnT, we will make substantial contributions to DARWIN, a planned multipurpose dark matter and neutrino detector with unprecedented sensitivity. We will transfer our experience in the radio detection of cosmic rays to the radio detection of cosmic neutrinos and to studies on future cosmic-ray experiments beyond the PoF IV period. We will combine our knowledge in the analysis of data from all relevant experiments in multiwavelength and multimessenger studies of astrophysical objects and thus use the different large-scale facilities in an optimal way. A special focus will be on the observation and analysis of transient phenomena. A key element in our strategy is the establishment of an international, open-access Astroparticle Physics Data and Analysis Center. It will facilitate access to multi-messenger data in near real time and provide the community with uniform storage formats and powerful analysis tools.

Independent theoretical and computational studies at DESY, IPP, and KIT complement the experimental efforts. They are indispensable for an optimal scientific harvest of the data that the experiments provide. Theory and phenomenology also inform the strategy of experiments and sharpen the questions that observations are supposed to answer. Theory and analysis are elementary in relating the insights gained in this Topic to those in other areas of research, in which the range of physical parameters is very different. It is therefore most fitting that our theoretical and computational investigations branch out into plasma physics (including laboratory studies of electron-positron plasmas and accelerators) in addition to the works conducted in neutrino and particle physics. Deepening our theoretical understanding together with pursuing cutting-edge experiments is needed to optimally combine the multitude of very diverse data sets available in astroparticle physics, to efficiently interpret the measurements, and to formulate targets for new measurements or observation campaigns.

We are currently experiencing a dramatic development in multimessenger astronomy with gravitational waves. Triggered by groundbreaking breakthroughs in the past few years, an intensive discussion is currently taking place in Germany about a participation in the Einstein Telescope, a third-generation gravitational-wave detector, in addition to the participation of the Max Planck Institute for Gravitational Physics in Hannover. Within DESY and KIT, there are currently lively discussions in order to facilitate the participation, which did not play a role in the agreement of the Strategic Guidelines with the funding agencies at the beginning of the preparation of the PoF IV period. In particular, the mission of the Helmholtz Association to facilitate large-scale research infrastructures has given DESY and KIT a special role in this discussion. We are convinced that a participation of DESY and KIT would pave the way for a significant participation of Germany. Such a participation would fit seamlessly into the multimessenger strategy of our Topic.

Competences

Our large-scale infrastructures are often set up at remote locations and in very challenging environments, namely the South Pole (IceCube), the Argentinian Pampa (Auger), the Canary Islands and Chilean Andes (CTA), and the Namibian desert (H.E.S.S.). Other experiments, which rely on very specific technological resources (such as the tritium cycle for KATRIN), can only be realized directly at a Helmholtz Center. Each facility takes many years of planning, construction, and commissioning before long-term scientific operation can start. Most research infrastructures are subject to several upgrades that broaden and deepen their science mission, resulting in a full life cycle of typically two to three decades (and beyond, considering data preservation). These long timescales require long-term technical support and scientific commitment that only we can provide for the entire scientific community, in line with the core mission of the Helmholtz Association.

Our unique competence in the management of large-scale research infrastructures allows us to support their entire life cycle. This is illustrated by the choice of KIT as the location for the KATRIN experiment or DESY in Zeuthen as the location for the Science Data Management Center of the CTA observatory. Examples of our leadership abilities are the successful on-budget completion of the Pierre Auger Observatory together with operating the project management office and acting as financial executive institution for both Auger and KATRIN. In addition, the spokespersons of Auger, H.E.S.S., and KATRIN as well as the science and analysis coordinators in many projects are scientists of the Topic MU-MRU.

Our technology competence spans a large range of advanced cutting-edge techniques, and many of us lead key tasks in the build-up and operation of large facilities at remote places and sometimes in a hostile environment. A prime example is the bundling of our long-term expertise in designing and operating large arrays of ultrasensitive photomultipliers to detect faint light signals down to the single-photon level in the readout of scintillators (Auger) and of Cherenkov radiation in ice (IceCube) and in air (CTA). We have also pioneered novel radio detection technologies to measure high-energy air shower parameters.

In neutrino and dark matter physics, we are technology drivers. We have pushed frontiers in many areas, such as ultrahigh-vacuum (UHV) technology (operating the KATRIN spectrometer as the world's largest UHV recipient [30]), tritium technologies (operating the largest closed tritium cycle), and high-voltage stabilization at the ppm scale [31]. We provide unique technologies for dark matter experiments, such as ultrapure cryogenic distillation, advanced high-voltage technologies, and the field layout of TPC cages.

Exploiting the full scientific potential of multimessenger astronomy requires combining diverse astronomical data in novel ways in near real time. We are already leading this effort within the individual collaborations that we are involved in, using for instance H.E.S.S. to follow-up gravitational-wave events or presenting the first identification of a cosmic neutrino source, the blazar TXS 0506+056 [32]. We combine the various efforts and data sets from the individual observatories and provide a central platform for multimessenger studies based on our dedicated alert stream software package [33]. In addition, with the KASCADE Cosmic-ray Data Centre (KCDC), we have acquired a unique competence in the sustainable provision of scientific data.

We have profound competence in theoretical and computational investigations of the high-energy universe, in which systems many light-years in size accelerate particles through physical processes on length scales of light-milliseconds. This disparity of scales represents a major challenge to astroparticle physics, the mastery of which requires joining various methods that each have validity on only a limited range of scales. On small scales, plasma physics effects – from plasma turbulence to magnetic reconnection to wakefield acceleration – are of key importance, leading to a better understanding of the creation and propagation of cosmic rays in astrophysical plasmas.

Our scientific competences are expressed in key contributions to current breakthroughs, such as the discovery of high-energy cosmic neutrinos [32], the detection of new gamma-ray source types [34], or the precise measurement of the energy spectrum and the observation of a large-scale anisotropy in the arrival directions of cosmic rays [35]. We have developed advanced algorithms to reconstruct the directions of messenger particles, to detect sources, to separate gamma rays or neutrinos from background events, or to differentiate light and heavy primary cosmic rays.

Computing is an essential ingredient for our work both in the form of hardware resources and in the form of subject-specific support in the research tasks, where the close connection to the computing infrastructures of the Tier-1 center GridKa at KIT and the Tier-2 center at DESY are used. The applications of modern computing technologies range from control and data acquisition systems, calibration and reconstruction algorithms and computation-intensive simulations to advanced analysis techniques.

A key competence of our Topic is the development, long-term maintenance, and exploitation of world-leading simulation tools [36, 37]. A prime example is CORSIKA, which has been used by the worldwide community in the accurate modeling of extensive air showers for more than three decades. Groups at IPP, DESY, and KIT develop and operate state-of-the-art simulation codes that track charged particles in self-produced and external electromagnetic fields The applications are diverse, ranging from particle tracking in KATRIN to the modeling of plasma turbulence under astrophysical conditions and to particle acceleration in a variety of environments.

An important asset of our Topic is the close interaction of experimentalists with theorists. Some of our theory staff members are full members of experiment collaborations and assume relevant leadership roles, such as chairing science working groups. Between theory and experiment, each side is aware of the difficulties and accomplishments on the other side, which has proven to form fertile ground for scientific advance (e.g. [38, 39]).

We offer outstanding working environments for the best talents in our field, from doctoral students to senior scientists. KIT runs the Helmholtz International Research School for Astroparticle Physics and Enabling Technologies (HIRSAP) together with the Universidad Nacional de San Martin in Buenos Aires, Argentina, and DESY the Helmholtz–Weizmann International Research School on Multimessenger Astronomy together with the Weizmann Institute in Israel. Three junior research groups funded by the Helmholtz Association and one Emmy Noether junior research group are currently working in our Topic. Three scientists of MU-MRU are principal investigators of ERC Consolidator or Starting Grants. Two professors are supported through the Helmholtz First Appointment Program for excellent female scientists, and two senior scientists are funded through the Helmholtz Distinguished Professorship Program.

Objectives and Approach

Our work program is structured along three lines of research: the study of the high-energy universe with all available messengers in order to understand the role of the high-energy processes in the universe, in particular the creation, acceleration, propagation, and interactions of high-energy particles and their feedback on cosmic evolution; the measurement of fundamental properties of neutrinos; and the search for dark matter. All activities are closely linked in many ways. We will explore the high-energy universe by measuring gamma rays with existing instruments and in the future with CTA, high-energy neutrinos with the IceCube observatory, and cosmic rays with the Pierre Auger Observatory. At the same time, the instruments offer the possibility to search for dark matter and, in the case of IceCube, to measure fundamental properties of neutrinos. These observatories thus complement the dedicated measurement of the neutrino mass and the search for sterile neutrinos with KATRIN and the future direct search for dark matter and measurement of neutrino properties with DARWIN.

Our work program covers two main aspects of multimessenger astronomy as an important cornerstone of our high-energy astroparticle physics program: (i) Strong contributions in a broad portfolio of experimental activities covering all cosmic messengers, supported by specially selected astronomical instruments that provide relevant electromagnetic information for transient astronomical events. (ii) Strong involvement in multiwavelength and multimessenger observation campaigns as well as the development and use of tools specifically for the combined analysis of all available observations. These activities are complemented by theoretical work and joint interpretation of combined data.

In gamma-ray astronomy, the prime focus is CTA. In the first half of the PoF IV period, we will focus on producing and delivering CTA in-kind contributions: We are leading the CTA medium-size telescope project and providing leading contributions to software and cameras. At the same time, we will continue to work with data from the ground-based telescopes H.E.S.S., MAGIC and VERITAS, as well as from the Fermi satellite, covering the entire sky and the full GeV to TeV energy band. In the second half of the PoF IV period, CTA science operations are expected to commence [milestone MRU-6][12], and the gamma-ray personnel resources will then entirely shift to doing science

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[12] *See Table 3 for an overview of the Topic's milestones.*

with CTA. To prepare for future CTA upgrades, we will commence R&D studies of optimized silicon photon sensors and telescope designs, starting at the beginning of the PoF IV period.

One of the main activities in measuring cosmic rays in the PoF IV period will be the science exploitation of the AugerPrime extension of the Pierre Auger Observatory with planned observations until 2030. We play a leading role in the calibration and reconstruction as well as the physics analysis of the new data, building on extensive theoretical investigations. The primary goal will be composition-assisted anisotropy studies and the measurement of the fraction of protons at ultrahigh energies with a sensitivity down to 10% [MRU-7]. The high statistical accuracy of the nuclear-composition data at ultrahigh energies provided by AugerPrime will shed new light on the origin of the highest-energy messengers in the universe. Lower-energy cosmic rays will be measured with IceCube, where we will focus on studying the transition from galactic to extragalactic sources. We will also work on developing a design of a next-generation Global Cosmic Ray Observatory (GCOS).

During the PoF IV period, the existing IceCube detector will retain its worldwide unique sensitivity for cosmic neutrinos at high energies. It will become even more sensitive with the upgrade project IceCube-Gen2 Phase 1, the addition of a densely instrumented core consisting of seven strings and an improvement of the surface detector until 2023 [MRU-1]. We contribute significantly to the upgrade of the detector, for which we lead the sensor development and deliver the majority of devices. In addition, we are prepared to play a leading role in the calibration and analysis of the upgraded detector, with the goal to reduce the detector energy threshold down to 5 GeV in order to improve the sensitivity to the mass differences and mixing angles of neutrinos. We will work on understanding the optical properties of the ice, which represent the dominant systematic uncertainty, resulting in a better directional and energy reconstruction of the entire archive of neutrino events relevant for neutrino astronomy [MRU-8]. The extended surface array will further improve the identification of cosmic neutrinos. To expand the window to the universe to the highest energies, the radio detection technique is the most promising approach. We will pursue the respective R&D within IceCube-Gen2, for which a pathfinder detector will be deployed in Greenland. We will complete the design study of the full IceCube-Gen2 observatory [MRU-1] and work towards the start of construction during the PoF IV funding period. In addition, we search for neutrinos at extremely high energies with the Pierre Auger Observatory, and we explore the feasibility of alternative detection concepts, such as a large radio detection array called GRAND (Giant Radio Array for Neutrino Detection).

The Einstein Telescope project aims at the realization of a third-generation gravitational-wave observatory as a scientifically crucial research infrastructure in Europe. To enter the field, we investigate the exploitation of particle physics methodology for gravitational-wave observations and the preparation of technological contributions. A possible greater involvement is currently being discussed both at DESY and at KIT.

In addition to our involvement in the existing network of optical instruments for follow-up observations of astrophysical transients, we joined the ULTRASAT project, a satellite for ultraviolet (UV) observations planned to be launched around 2024. We will deliver the UV camera and lead the multimessenger science of astrophysical transients in this mission. As demonstrated by the recent discovery of bright UV emission from a neutron star merger, a wide-field UV survey satellite has major discovery potential.

All cosmic messenger activities within the Topic and worldwide will benefit from the development of the next-generation air shower simulation framework CORSIKA 8 performed within the Topic [MRU-4]. We also envision setting up a multimessenger portal to foster optimized analysis of the data. It will combine public access and real-time data streaming, a platform for new analysis methods, and access to federated computing infrastructure, and it will be useful for astroparticle physics as a whole. A detailed concept will be presented and implemented in PoF IV [MRU-9].

The properties of neutrinos not only constitute the core science focus of KATRIN (neutrino mass and search for sterile neutrinos), but will also form a strong part of the science programs of the IceCube upgrade (neutrino mass pattern and mixing) and of the future DARWIN observatory (neutrinoless double beta decay, precision measurement of solar neutrinos). We will address the quest for dark matter both with indirect searches (IceCube and CTA) and with direct methods (XENONnT and DARWIN).

KATRIN successfully started its neutrino mass search with the first science run in spring 2019 and published a first, already a factor of two improved limit on the neutrino mass in fall 2019 (see Figure 12) [42]. KATRIN will collect about 200 days of neutrino mass data per calendar year, the remainder of the time being allocated to explorative studies of novel readout technologies, to calibration runs, and to technical maintenance. After five calendar years, a unique data set will be available to assess the fundamental mass scale at a sensitivity level of 0.2 eV/c^2 [MRU-3] and to search for exotic neutrino and weak-interaction properties at unprecedented levels of precision.

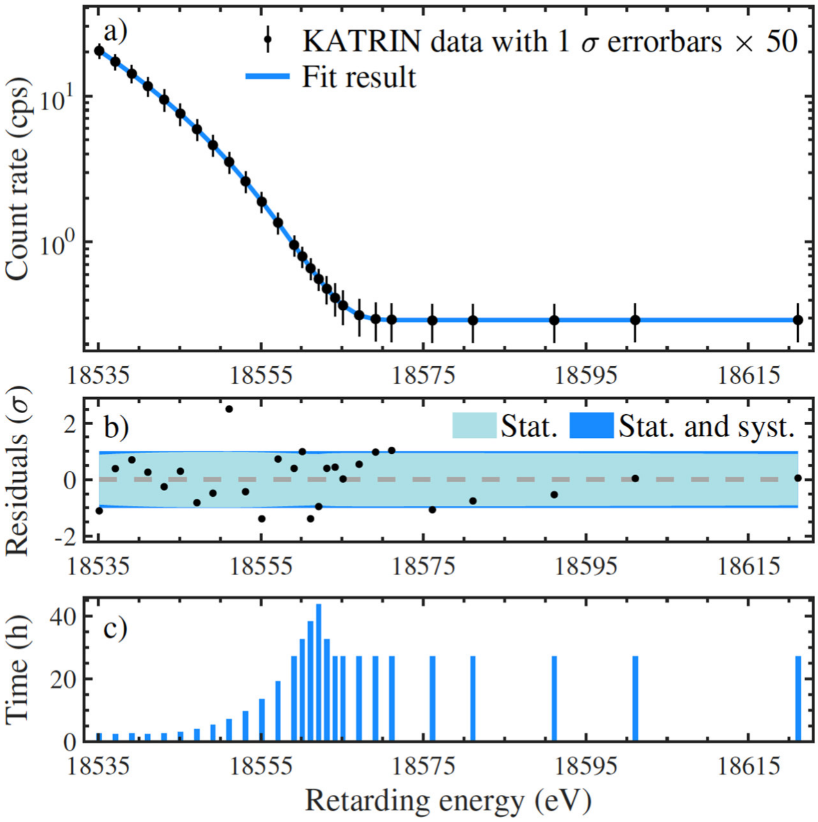

Figure 12 a) Spectrum of electrons over a 90 eV wide energy range and best-fit model (line). b) Residuals relative to the 1-sigma uncertainty band of the best-fit model. c) Accumulated measurement time distribution.

Following this milestone, we will upgrade the 70 m long KATRIN beamline by two distinct measures to expand the physics reach of the experiment. First, we will explore novel techniques and set up instrumentation to transition from the present integral measurement of the beta spectrum to a differential one [MRU-3]. This will allow tritium spectroscopy at enhanced sensitivity and almost free of background and push the neutrino mass reach below 0.2 eV/c^2. A very promising proof of principle, using the time-of-flight technique, has already been established. Second, we will deploy a large-area, high-resolution array of silicon drift detector pixels, dubbed TRISTAN [40]. The measurement will cover the entire phase space of tritium beta decay and enable a search for sterile neutrinos at keV masses down to the ppm mixing scale, surpassing the sensitivity of current laboratory experiments by more than four orders of magnitude [MRU-10].

These improvements will be complemented by R&D efforts to develop a quasi-atomic tritium source [MRU-5] e.g. based on graphene, which, in the long term, would permit tritium beta spectroscopy beyond the “molecular excitation wall”, which limits the sensitivity of molecular tritium sources to around 0.1 eV/c^2.

Based on the unique pool of expertise gathered in the successful construction and commissioning of KATRIN, we will make leading contributions to the realization of DARWIN, the ultimate experiment to directly detect dark matter. Our R&D efforts will contribute in a highly visible way to the conceptual and technical design [MRU-2], and we aim to set up the technical office at KIT. We will be strongly involved in the operation of two large-scale demonstrators and their measurement programs. To that end, we will focus on the optimized charge readout of both large-scale TPCs (as well as of the final TPC) thanks to our expertise in high-voltage stability and field design. Regarding purification of the xenon target, we will apply for KIT strategic funds to set up and operate a cryogenic distillation plant for xenon at KIT as a large-scale demonstrator, which will later be shipped to operate at the experimental underground location. Elimination of radioisotopes in the xenon target by cryogenic distillation will be the single largest challenge in reaching unprecedented low levels of background and thus ensuring the full science reach of the observatory. We are already centrally involved in establishing a procurement strategy for up to 50 t of xenon, which will determine the start of commissioning, envisioned towards the end of the PoF IV funding period. In parallel, we will use gamma rays and neutrinos to search for dark matter annihilation signals from cosmic objects that are rich in dark matter, such as the inner galaxy (neutrinos and gamma rays) or the Sun, or from light dark matter particles up-scattered by cosmic rays (neutrinos).

All experimental activities are linked to and supported by theory and simulation efforts that span the entire range of physics aspects relevant to the Topic. We model and study the acceleration and propagation of high-energy cosmic messengers to understand gamma-ray, neutrino, and cosmic-ray signals. We put the interpretation of experimental results into a larger context and assess the implications for precision tests of the Standard Model of particle physics and cosmology and for the search for BSM phenomena such as exotic neutrino properties or sterile neutrinos. We investigate the phenomenological consequences of various dark matter candidates, including WIMP-like candidates, axions, or sterile neutrinos – both in the context of model building and regarding their experimental and cosmological signatures. Future challenges will arise from the large number of results expected from future instruments and from null results in establishing a genuine BSM signal, calling for novel pathways and ideas to guide experimental efforts.

Expected Results

The sketched work program translates into a number of milestones that are well suited for monitoring the progress of the Topic. These are shown in the following table.

Table 3: Overview of milestones for the Topic MU-MRU.

Number	Year	Milestone
MRU-1	2023	IceCube upgrade operation started, IceCube-Gen2 design studies completed
MRU-2	2023	DARWIN technical design completed
MRU-3	2024	KATRIN reaches neutrino mass sensitivity of 0.2 eV/c^2 and sets up differential measurement of the beta spectrum
MRU-4	2024	First release of air shower simulation framework CORSIKA 8
MRU-5	2025	Proof of principle for quasi-atomic tritium source; concept for large-scale cryogenic distillation for DARWIN
MRU-6	2025	Construction of CTA finished, first science results obtained
MRU-7	2027	Auger publication of the proton fraction of ultra-high energy cosmic rays and of corresponding source searches
MRU-8	2027	First science results from IceCube upgrade on neutrino mixing parameters, recalibration of ice properties
MRU-9	2027	Release of sustainable user-led portal for astroparticle physics data and analyses
MRU-10	2027	KATRIN reaches ppm sensitivity for keV sterile neutrinos and probes exotic weak interactions

Synergies and Collaboration

The large experiments or infrastructures necessary to achieve our scientific goals can only be realized in international collaborations. Together with partners from all over the world, we develop the experiments from the initial idea to construction and handle the operation and analysis up to the final scientific harvest. Our theory groups play a crucial role in integrating and highlighting the Helmholtz activities in the global effort towards the exploration of the universe. There is no other way to achieve our scientific goals.

Partners from universities and non-university research organizations optimally combine their strengths in the aforementioned experiments. In recent years, a very beneficial division of work has been developed between the various partners in astroparticle physics in Germany. DESY and KIT play a key role here, as our commitment enables university groups to participate in large experiments. Typically, ten German university groups and Max Planck Institutes are involved in each of the large experiments, together with DESY and KIT. Our joint professorships with the universities in Potsdam, Erlangen-Nürnberg, Karlsruhe, the Technische Universität München, the Humboldt-Universität zu Berlin, and the University of Delaware (USA) additionally strengthen these ties.

Astroparticle physics in Germany is coordinated in the Committee for Astroparticle Physics (KAT) with elected members from all astroparticle physics communities in Germany; three members are from DESY and KIT. In addition, DESY and KIT have permanent seats in the KAT, and the present vice-chair of KAT comes from KIT. On the European level, DESY and KIT are also represented in the Astroparticle Physics European Consortium (APPEC). The current vice-chair of the APPEC General Assembly comes from DESY. We thus contribute visibly to the development of astroparticle physics at the national and international level.

Within the current PoF III funding period, DESY and KIT have tightly interlinked their efforts. In addition, in the coming PoF IV period, the activities of IPP will be closely integrated. As an example, the joint participation of DESY and KIT in the IceCube experiment is a clear success of the close cooperation in recent years. Together, DESY and KIT were able to assume an even stronger position, especially in the upgrade of the experiment. This created an excellent starting position for the further development of the experiment in the course of PoF IV.

There is a strong link between this Topic and the Topic MU-FPF (implications for BSM physics, dark matter and axion searches, hadron interaction physics, cosmology, and computing) as well as to the worldwide activities in astroparticle physics in both experiment and theory. There is a strong link between this Topic and the Topic MU-FPF (implications for BSM physics, dark matter and axion searches, hadron interaction physics, cosmology, and computing) as well as to the worldwide activities in astroparticle physics in both experiment and theory. Moreover, we have a longstanding tradition of close cooperation with the Program MT, for instance in the development of radio antennas and electronics for cosmic-ray detection, in the H.E.S.S. camera upgrade and development of the CHEC camera concept for CTA, and regarding the realization and planning of data infrastructures for KATRIN and DARWIN, respectively. We will continue to exploit these and further important synergies in PoF IV.

Infrastructures

We have selected our research infrastructures according to our scientific goals.

The experiments and infrastructures to study the high-energy universe cover the entire energy range from GeV energies to beyond 10^{21} eV. Energies above some tens of GeV are measured with the ground-based gamma astronomy experiments H.E.S.S., MAGIC, and VERITAS. We are involved in various functions in the development, construction, and future operation of CTA, the world's first open observatory for ground-based gamma astronomy. DESY plays a key role as one of the largest partners in CTA and as host of the CTA Science Data Management Center and scientific director at its campus in Zeuthen. Higher energies are made accessible by neutrino astronomy. DESY has been one of the driving forces behind IceCube, the world's leading neutrino telescope, for many years. In 2019, KIT has become a full member of the IceCube collaboration. Together, we are pushing ahead with the upgrade of the IceCube detector and assume important management functions in the upgrade project. DESY and KIT plan to make substantial contributions to IceCube-Gen2, the further expansion of IceCube beyond the current upgrade. We expect that a joint application for a Helmholtz strategic investment (> 15 million EUR investments) will be submitted in the course of PoF IV to secure the participation of DESY and KIT in IceCube-Gen2. The energy coverage up to the highest-energy cosmic rays is completed by the Pierre Auger Observatory. KIT is the leading institute in the Auger Observatory and, with its project office located at KIT, fulfills a key function in the experiment. Smaller projects and project participations round off the experimental portfolio: With the development of the radio detection of high-energy neutrinos, we seek to extend the energy range of neutrino astronomy and to achieve a connection to the highest-energy cosmic rays. The participation in the ULTRASAT project, an Israeli satellite mission planned to be launched around 2024, gives us outstanding access to follow-up observations in the UV range, especially for gravitational-wave events.

To measure neutrino properties and search for dark matter, we develop advanced technologies to detect particles at low energies in the keV range. We play a leading role in the international flagship missions KATRIN and DARWIN, for which these efforts provide enabling technologies.

To measure the absolute mass scale of neutrinos, we conduct the KATRIN experiment at KIT, which will reach a neutrino mass sensitivity of 0.2 eV/c^2 midway through the PoF IV funding period. The high-luminosity tritium source of KATRIN requires all resources of the Tritium Laboratory Karlsruhe, an unmatched research infrastructure with world-leading expertise and experience in tritium technology. In the coming years, we will employ our technological and scientific competence to further improve the sensitivity of the experiment for the neutrino mass and the search for novel neutrino states (sterile neutrinos at the keV scale). The very same technologies and expertise will then be applied to the technical design and construction of the DARWIN observatory, the ultimate experiment to directly detect dark matter. In PoF IV, we will set up large cryogenic distillation columns, which are essential for the purification of the 50-ton liquid xenon target. To this end, we will apply for strategic funds of KIT (on the scale of several million EUR). Our contributions will help to ensure that DARWIN can be realized in a timely manner.

Opportunities and Risks

The thriving, lively development of our field fosters a wealth of opportunities to be pursued during the coming decade. We are about to change our view on our universe. We have just begun to find out that high-energy processes play an even more important role in the matter–energy cycle than previously assumed. New windows have been or are about to be opened, offering new and surprising insights into the evolution of our universe. With the observation of transient events, a phase transition to time-dependent astronomy has been initiated. In unlocking fundamentally new sources of information, astroparticle physics is entering a new era in which discoveries are not just expected as a serendipity. In addition, our instruments enable surprising new approaches to difficult measurements in other research areas. A current example is the measurement of star diameters with gamma-ray telescopes by means of the diffraction patterns from the stars generated during the fly-by of meteorites [41]. Our large-scale research facilities offer a rich science program that will enable us to reach competitive sensitivities for physics phenomena beyond the Standard Model of particle physics, for instance in the search for novel particles or exotic types of particle interactions.

The benefits promised by the scientific advancements outlined above are associated with comparatively low risk. Our research often relies on strong international consortia and locations/sites abroad, which certainly entails challenges in coordinating schedules of large projects, maintaining management processes, and balancing dependencies on important stakeholders (such as the US National Science Foundation (NSF) in the case of IceCube). Based on our long-standing experience in leading large-scale research missions, we are well positioned to mitigate such risk through several key measures. On the project level, cutting-edge technology developments are subject to a detailed and meticulous quality control. The long-term planning of new projects (DARWIN, IceCube-Gen2, CTA, etc.) will be ensured by top-down risk mitigation plans, such as the one successfully implemented for the operation of KATRIN in cooperation with DOE in the USA. For the procurement of large quantities of xenon required for DARWIN, we are adopting a strategy based on recommendations by the German Federal Institute for Geosciences and Natural Resources (BGR). We are confident that these measures will enable us to pursue our sustained mid- to long-term program in basic research, while at the same time remaining responsive to novel opportunities and to emerging structural developments in our scientific community.

3. PROGRAM ORGANIZATION

This section provides information about the most important partners, the scientific and technical infrastructures, and the management aspects of the Program MU.

3.1. Strategic Partners and Cooperation

An important element in the organization of our research is our intense cooperation with universities and other research facilities. Outstanding examples in the context of the Program MU are KIT as the Research University in the Helmholtz Association, the recently granted cluster of excellence Quantum Universe, the long-standing Partnership for Innovation, Education and Research (PIER) between DESY and the Universität Hamburg, and the Helmholtz Institute Mainz (HIM) as a joint endeavor of GSI and the Johannes Gutenberg-Universität Mainz.

The international cooperation within the Program MU is outstanding. It operates across countries and continents, across cultures and languages, and irrespective of political differences. The research is conducted where it can be done best, depending on human resources, infrastructure availability, and site characteristics.

3.1.1. Non-university partners

In the following table, we list selected non-university partner institutions of the Program MU with a brief indication of the specifics of the interaction.

Table 4: Most important non-university collaboration partners of the Program MU (in alphabetical order by country).

Partner, Country	Cooperation subjects	Topic
CAS (IMP/Lanzhou, IHEP/Beijing), China	Hadron physics, nuclear reactions, dense matter; operates BESIII experiment; substantial contributions to FAIR experiments	MU-CML
CEA, France	Nuclear structure/reactions, superheavy elements, accelerators, neutrino physics; contributions to FAIR and KATRIN	MU-CML, MU-MRU
APC, Paris, France	Cosmology, gravitation, high-energy astrophysics, neutrinos, dark matter; strong theory group working on all those subjects	MU-MRU
IN2P3, France	Widespread cooperation of most IN2P3 institutes with the Research Field *Matter*; LoI between CNRS and Helmholtz Association signed in February 2019	MU-FPF, MU-CML, MU-MRU
FAIR, Darmstadt, Germany	Facility for Antiproton and Ion Research	MU-CML
Weizmann Institute, Tel Aviv, Israel	Contributions to LUXE, ATLAS and DARWIN experiments, detector R&D (in particular for forward calorimeters for linear colliders), theory; Helmholtz International Research School	MU-FPF, MU-MRU
INFN, Italy	Hadron physics, nuclear physics, accelerator physics, astroparticle physics; operates Gran Sasso underground laboratory	MU-FPF, MU-CML, MU-MRU

IPMU, Tokyo, Japan	Important partner in our theory collaboration network	
KEK, Tsukuba, Japan	Particle physics experiments, development of accelerators (SCRF technology, in particular for the ILC) and detectors. KEK is home to the Belle II experiment; collaboration with ATLAS	MU-FPF
RIKEN, Tokyo, Japan	Atomic and nuclear physics, superheavy elements	MU-CML
JINR, Dubna, Russia	Accelerator physics, magnet and detector technology, CBM detector components at BM@N, superheavy elements; numerous common interests between DESY and JINR in particle physics	MU-FPF, MU-CML
BINP, Nowosibirsk, Russia	Accelerators, hadron physics; substantial contributions to FAIR	MU-CML
CERN, Geneva, Switzerland	All aspects of experimental and theoretical particle and nuclear physics including future strategy. MU-FPF: involvement in ATLAS and CMS. MU-CML: accelerator physics; involvement in ALICE, ISOLDE, and AD complex; magnet and detector testing; laser spectroscopy; CPEDM. MU-MRU: IceCube, Auger, and KATRIN are “CERN recognized experiments”	MU-FPF, MU-CML, MU-MRU
NIKHEF, Amsterdam, The Netherlands	Numerous collaborations in the context of ATLAS experiment, in particular construction of HL-LHC tracker end-caps and detector R&D; theory; strong cooperation within the Pierre Auger Observatory	MU-FPF, MU-MRU
LBNL, Berkeley, USA	Close collaboration in data analysis for KATRIN	MU-MRU
Fermilab, Chicago, USA	Accelerators (SCRF developments); CMS experiment; computing (dCache); several common detector R&D projects	MU-FPF
JLab, Newport News, USA	Hadron physics; operates CEBAF and GlueX experiment	MU-CML
Oak Ridge, Oak Ridge, USA	Superheavy elements, nuclear structure	MU-CML
SLAC, Stanford, USA	Theory; ATLAS; detector R&D	MU-FPF

3.1.2. University partners

Here, we list only the most important partnerships with universities in Germany and abroad; universities in other countries offer a particularly rich portfolio of beneficial interactions in research, academic training, and cultural exchanges. Numerous other collaborations – often also in the form of joint professorships – exist that we cannot all list here. For our German university partners, the BMBF provides the ErUM framework program, which is dedicated to collaborative research at universities using large-scale facilities constructed and/or operated with substantial federal resources, i.e. by the Helmholtz Association or the Max Planck Society.

Table 5: Most important German and international university partners of the Program MU (in alphabetical order by city).

University (city)	Cooperation subjects	Topic
Aachen	CMS; Cosmic rays, neutrino astronomy (IceCube, Pierre Auger Observatory, Borexino); EDM; joint professorships; Jülich Aachen Research Alliance JARA	MU-FPF, MU-MRU, MU-CML
Berlin, Humboldt	ATLAS experiment, theory, gamma-ray astronomy, neutrino astronomy, neutrino properties (CTA, IceCube, KATRIN), joint professorship(s)	MU-FPF, MU-MRU
Bonn	ATLAS, Belle II, KATRIN, detector R&D; joint professorship on detector R&D	MU-FPF, MU-MRU
UNSAM, Buenos Aires, Argentina	Partner of KIT within the Helmholtz International Research School for Astroparticle Physics and Enabling Technologies; multiple other joint research and academic projects	MU-MRU
Darmstadt	Hadronic and quark matter, accelerator physics, nuclear structure, astrophysics in experiments and theory; joint professorships, Helmholtz Alliance Hessen for FAIR, Graduate School HGS-HIRe, Collaborative Research Center SFB 1245	MU-CML
Dresden	Particle physics in ATLAS; detector R&D	MU-FPF
Erlangen	Gamma-ray astronomy, neutrino astronomy (IceCube, CTA); detector development for FAIR	MU-CML, MU-MRU
Frankfurt	Hadronic and quark matter, theory, accelerator physics, nuclear astrophysics; joint professorships, Helmholtz Alliance Hessen for FAIR, Graduate School HGS-HIRe	MU-CML
Freiburg im Breisgau	Particle physics in ATLAS; detector R&D; dark matter; joint professorship	MU-FPF, MU-MRU
Gießen	ATLAS, Belle II; Hadron physics in theory and experiment, nuclear astrophysics; joint professorships, Helmholtz Alliance Hessen for FAIR, Graduate School HGS-HIRe	MU-FPF, MU-CML
Göttingen	Particle physics in ATLAS; detector R&D; scientific computing; Belle II	MU-FPF
Hamburg	Physics at the LHC, future colliders, detector development, accelerator research, theory; Partnership for Innovation, Education and Research (PIER), cluster of excellence Quantum Universe	MU-FPF
Heidelberg	Particle physics experiment and theory (esp. LHC physics, ATLAS, ALICE), dark matter searches, scientific computing, hadronic and quark matter theory and experiment; joint professorship, Graduate School HGS-HIRe	MU-FPF, MU-CML, MU-MRU
Karlsruhe	KIT is “The Research University in the Helmholtz Association” and hence a Helmholtz Center participating in the Program MU; Collaborative Research Center SFB 257	MU-FPF, MU-CML, MU-MRU
University of Wisconsin, Madison, USA	Prime collaboration partner within IceCube	MU-MRU
Mainz	LHC physics in experiment and theory; HIM, joint professorships, cluster of excellence PRISMA+, Collaborative Research Center SFB 1044	MU-FPF, MU-CML

München TU	Belle II; Neutrino astronomy, neutrino properties (IceCube, KATRIN, plasma studies), nuclear structure, hadronic and quark matter; cluster of excellence UNIVERSE	MU-FPF, MU-CML, MU-MRU
Münster	Theoretical particle Physics; dark matter search, neutrino astronomy, neutrino properties (IceCube, DARWIN, KATRIN), hadronic and quark matter, hadron physics	MU-FPF, MU-CML, MU-MRU
Wuppertal	LHC physics (joint professorship), detector R&D; cosmic rays, neutrino astronomy, neutrino properties (IceCube, Pierre Auger Observatory, KATRIN), quark and hadronic matter	MU-FPF, MU-CML, MU-MRU
Oxford, UK	LHC physics, future colliders (accelerators, detectors)	MU-FPF
Washington, Seattle, USA	Prime collaboration partner within KATRIN	MU-MRU
British Columbia and Toronto, as well as TRIUMF	ATLAS experiment, detector R&D, scientific computing	MU-FPF
Zürich, Switzerland	Dark matter search (XENONnT and DARWIN)	MU-MRU

Networks play an important role in the organization of our research. Helmholtz Alliances were funded from 2007 to 2016: “Physics at the Terascale”, “Extreme Matter Institute,” and “Helmholtz Alliance for Astroparticle Physics”. About 600 scientists in the Helmholtz Centers and 1,800 in the partner institutions participated in these networks. The scope of activities was wide, ranging from the establishment of joint professorships to training and education. As a sustained effect, a core program of workshops and an internship program are still being conducted. The networks fostered clusters of excellence and European initiatives.

3.2. Infrastructures

Cutting-edge research infrastructures are essential for the success of the Program MU. In the following tables, we present the current situation and the mid-term future. The planned instruments are differentiated according to whether the contribution of the centers is smaller or larger than 15 million EUR. The former may be handled within a center’s budget, whereas the larger projects require the approval of the Helmholtz General Assembly.

Existing and approved infrastructures (e.g. currently under construction) are listed in Table 6. They are undergoing continuous upgrades and/or dedicated extension programs.

Table 6: Existing and approved large-scale research infrastructures (> 2,5 Mio.EUR).

Name	Contributing centers	Start of operation	Description
ALICE	GSI	2006	A Large Ion Collider Experiment at CERN
ALPS	DESY	2007	Any Light Particle Search at DESY
ATLAS	DESY	2006	A Toroidal LHC ApparatuS and upgrade of the ATLAS detector at LHC at CERN
Belle II	DESY	2018	Belle II detector at the SuperKEKB e^+e^- collider in Japan
CBM	GSI	2025	Compressed Baryonic Matter, part of future FAIR facilities
CMS	DESY	2006	Compact Muon Solenoid and upgrade of the CMS detector at LHC at CERN

COSY	FZJ	1993	COoler SYnchrotron accelerator and storage ring at FZJ
CTA	DESY	2021	Cherenkov Telescope Array in Chile and Spain
DAF[13]	DESY	2020	Detector Assembly Facility at DESY
FAIR accelerators	GSI	2025	Facility for Antiproton and Ion Research (SIS 100, HESR, Super-FRS)
FRS	GSI	1990	Fragment separator for production of radioactive beams at SIS 18 at GSI, part of GSI-MU LK II facilities
Green IT Cube	GSI	2016	High-performance computing center at GSI, part of GSI-MU LK II facilities
GridKa	KIT	2002	Grid Computing Centre Karlsruhe, Tier-1 center at KIT, LK II facility of the Program MU
HADES	GSI	2002	High-Acceptance DiElectron Spectrometer at GSI, part of GSI-MU LK II facilities
HDF[13]	6 centers	2019	Helmholtz Data Federation among DESY, KIT, GSI, FZJ, AWI, and DKFZ
IceCube	DESY, KIT	2009	IceCube Neutrino Observatory and IceCube upgrade at the South Pole
KATRIN	KIT	2018	KArlsruhe TRItium Neutrino experiment at KIT
LHC	DESY	2015	Large Hadron Collider at CERN
NUSTAR	GSI	2019	NUclear STructure, Astrophysics and Reactions experiments, part of future FAIR facilities
PANDA	GSI	2025	Detector for antiproton collisions at a fixed target, part of future FAIR facilities
Pierre Auger Observatory	KIT	2004	Detector array for ultrahigh-energy cosmic rays in the province of Mendoza, Argentina, and AugerPrime upgrade
SIS 18	GSI	1990	Heavy-ion synchrotron at GSI, part of GSI-MU LK II facilities
SHIP(TRAP)	GSI	1976	Ion trap facility for superheavy elements at GSI, part of GSI-MU LK II facilities
TASCA	GSI	2006	TransActinide Separator and Chemistry Apparatus at GSI, part of GSI-MU LK II Facilities
Tier-2[13]	DESY	2005	Tier-2 center at DESY; evolves into IDAF (LK II) in the Program MT
TLK	KIT	1993	Tritium Laboratory Karlsruhe at KIT
ULTRASAT	DESY	2022	Ultraviolet Transient Astronomy Satellite; together with Israel Space Agency and Weizmann Institute of Science
UNILAC	GSI	1975	Linear accelerator at GSI, part of GSI-MU LK II facilities

Planned infrastructures related to the Program MU are listed in Tables 7 and 8 according to the anticipated financial volume.

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[13] *This research infrastructure has relevant contributions also in other programs of the Research Field Matter and will also be listed there.*

The readiness level varies as follows:

- In discussion (disc.)
- Preparation: creating the TDR/feasibility study (prep.)
- Proposal submitted (prop.)
- Funding commitment: > 50% of the estimated project costs (fund.)

Table 7: Planned large-scale research infrastructures (2,5–15 Mio.EUR). The investment sum in TEUR refers to the Helmholtz part (with the total project sum in brackets).

Name	Contributing centers	Helmholtz investment (total project) in TEUR	Planned start of operation	Project status	Description
BabyIAXO	DESY	3.000	2023	prep.	Prototype experiment for IAXO at DESY
LUXE	DESY	4.000 (13.000)	2027	prep.	Test of quantum physics at the European XFEL using high-intensity laser at DESY
DARWIN	KIT	4.000 (210.000)	2026	disc.	DARk matter WImp search with liquid xenon, candidate site Laboratori Nazionali del Gran Sasso (LNGS)
MADMAX	DESY	5.000 (20.000)	2025	prep.	MAgnetized Disc and Mirror Axion eXperiment at DESY
GridKa for LHC Run 3	KIT	6.000	2022	prep.	GridKa upgrade at KIT for LHC Run 3
IAXO	DESY	10.000 (60.000)	2027	prep.	International Axion Observatory, searching for solar axions at DESY

The implementation of a federated Astroparticle Physics Data and Analysis Center is considered to be important for the full exploitation of multimessenger astroparticle physics. A precursor is currently being set up, funded by the BMBF Innovation Fund for 2019 and 2020. The project is not listed in Table 7, because it comprises mostly personnel and novel software rather than hardware.

Table 8: Planned large-scale research infrastructures (> 15 Mio.EUR). The investment sum in TEUR refers to the Helmholtz part (with the total project sum in brackets).

Name	Contributing centers	Helmholtz investment (total project) in TEUR	Planned start of operation	Project status	Description
IceCube-Gen2	DESY, KIT	20.000 (300.000)	2027	disc.	Next-generation IceCube detector at South Pole; anticipated funding period: 2023–2027
GridKa for HL-LHC	KIT	(see text) (24.000)	2026	disc.	GridKa extension at KIT for HL-LHC Run 4; anticipated funding period: 2024–2027

The last entry in Table 8 deserves a comment. The high-luminosity operation of the LHC is planned to commence in 2026; hence, the preparations will take place during the LHC Long Shutdown 3 (LS3), which is scheduled from the beginning of 2024 to the middle of 2026. The installations will comprise intense work on the accelerator itself, on the detectors, and last but not least on the data-handling scheme from the data source to the end users. An indispensable element in this chain is the GridKa data and computing center at KIT, which has to be prepared during LS3 to manage the anticipated data flood. The financial effort is estimated to be 24 million EUR over the period 2024 to 2027 in order to acquire the most capable hardware components and make use of the most advanced methods of data reduction, e.g. based on AI. This is a challenge for the particle physics community that cannot be solved by KIT alone.

We also add a few remarks concerning projects not listed in Table 8, but which are mentioned in the proposal.

The DARWIN experiment for the search for dark matter particles and for neutrino physics has been mentioned as an important asset of the Topic MU-MRU. The anticipated route to the full 50 ton liquid-xenon detector includes the provision of a cryo-distillation apparatus by KIT towards the end of the PoF IV period, based on experience with the XENONnT project. This is under discussion within the DARWIN collaboration. Hence, DARWIN is listed in Table 7.

The Global Cosmic Ray Observatory (GCOS) has been mentioned as a possible next-generation project following the Pierre Auger Observatory. Subject to the results of Auger, GCOS design studies will take place during PoF IV. Should the project move forward, e.g. driven by firm indications of cosmic ray sources, major funding efforts are required starting with PoF V.

The Einstein Telescope is being pushed forward as a potential European project, driven by the spectacular detections of gravitational waves by the current VIRGO/LIGO interferometers. KIT and DESY have significant and probably indispensable competences to contribute. While preparatory considerations are ongoing, the time frame for this enterprise (estimated volume on the order of 1.500 million EUR) is beyond PoF IV.

Very large projects with an anticipated German contribution larger than 50 million EUR are subject to the national roadmap process defined by the BMBF. This roadmap is updated once per legislation period. Currently, MU-related entries in the roadmap are CTA and FAIR. It is expected that e.g. the Einstein Telescope project for the detection of gravitational waves will have to apply for admission on the national roadmap.

3.3. Management

The activities within the Program MU are conducted in the four Helmholtz Centers DESY, GSI (including TransFAIR (FZJ/GSI)), IPP, and KIT at the seven locations Hamburg, Zeuthen, Darmstadt, Mainz, Jülich, Garching, and Karlsruhe. A number of platforms for information, discussion, and decision-finding facilitates this distributed organization.

Like the Programs MT and MML, MU is part of the overall organization of the Research Field *Matter* with the Management Board and the Research Field Platform as decribed in Volume I, Chapter 7.1.

Information flow and discussions within the Program take place in the MU Program Board, which is comprised of the two Program spokespersons, the six Topic representatives, the two LK II representatives, and at least one member of each participating center, if such coverage is not yet given. The MU Program Board meets several times per year in person. One of the major tasks is to organize the annual Program Workshop ("MU Days"), which brings together as many proponents of MU as possible. Program Workshops are attended by scientists and administrators from all the participating centers, and cooperation partners from universities and other institutions are explicitly invited. For this procedure, we make use of the networks that have been established within the Helmholtz Alliances. The venue of the MU Days rotates among the participating centers.

Topic Boards are organized by the respective Topic spokespersons to discuss matters within the Topic. They call for topical workshops and exchanges.

The mechanisms for planning and controlling within the Program MU are defined by the Helmholtz Association. The Program Progress Report ("*Programmfortschrittsbericht*") summarizes the scientific, technical, and structural status and is submitted annually to the Helmholtz Senate Commission for discussion and approval. A different point of view is taken by the Center Progress Report ("*Zentrumsfortschrittsbericht*"), which is also submitted annually to the center's Supervisory Boards.

3.3.1. Talent Management

The Helmholtz Association has a broad array of measures developed to attract and to retain a diverse talent pool, and the Program MU takes advantage of many of these. In addition, specific further supporting programs exist at the centers themselves, and the Program MU complements them.

At the senior level, in the past five years 17 professors were recruited through the W2/W3 recruitment initiative. Thirteen of them are female, and nine came from outside Germany, in part from very prestigious institutions such as Oxford University or University of California, Berkeley. Since these positions are joint between a Helmholtz center and a university, they also facilitate a close interaction of the Helmholtz centers with university students. Joint professorships now exist with a total of 18 universities. Another important measure are the “Young Investigator Groups” (YIGs) which offer tenure-track positions to talented researchers with a few years of experience beyond PhD. Also here, the MU program has been extremely successful in identifying candidates who were then selected by the Helmholtz-wide selection committee. Within the past five years seven YIGs were awarded, and ten group leaders were tenured in this period, nine of them female. For the Helmholtz initiatives described above, the primary role of the centers is to scout and recruit excellent persons who have the potential to be selected by the Helmholtz-wide selection committees. It is planned to continue to identify excellent researchers using the world-wide network of researchers we are part of.

Another critical aspect of our research is the attraction and afterwards the education and mentoring of excellent students and postdocs. At all Helmholtz centers active in the Program MU, the students are part of graduate schools (EMMI, HGS-HIRe, HICforFair, HIRSAP, KSETA, PIER, QURS) with closely collaborating universities. The graduate schools offer the students a broad and interdisciplinary education program that goes beyond their specific research area, as well as further mentoring and course work. For postdoctoral researchers, prestigious fellowship programs exist (e.g. DESY fellowship) that succeed in attracting excellent postdocs from a worldwide talent pool. During the annual MU Days, poster sessions for early-career researchers are held, and parallel sessions also offer opportunities to present work to a broader audience. We also target talents at earlier stages, e.g. through summer student programs (DESY, GSI) for undergraduates, through internships for high-school students, and through “master classes” during which high-school students analyze collisions events recorded at the LHC or IceCube or the Auger Observatory.

Within the Program, we strive to foster diversity and an inclusive environment. The recruitment programs discussed above were designed in part to target researchers who are female and/or from abroad to diversify the workforce, and they have indeed attracted a number of excellent female researchers to MU. These now also serve as role models for the next generation. In addition, while no quota has been imposed for postdoctoral researchers, preference was given to female applicants in case of equal qualification, and now more than 30% of the postdoctoral researchers are female. There are also targeted programs that offer mentoring (e.g. DynaMENT at DESY and the Young Investigator Network YIN at KIT) to help young scientists master the challenges they might face. Furthermore, initiatives to help with real-life challenges (e.g. childcare, flexible working hours, working from home, dual career) are a priority at all centers and are steadily being extended.

It is critical to periodically review the large variety of measures in place for all aspects of talent management to understand their effectiveness. This has been done at the centers but not centrally in the Program MU so far. For PoF IV, one member of the MU Program Board will assess the talent management of the Program MU. Our efforts will thus be continuously monitored and reported in the meetings of the MU Program Board. We believe this to be important to ensure that there are no omissions and to coordinate our activities in this area.

Last but not least, it is pivotal to reach out to the general public to spark their interest in science and raise their awareness for our research. Fortunately, our area of research inspires many lay people, and we are able to draw large crowds at public events such as public lectures. For instance, each year, DESY researchers talk about science in around 50 pubs across the city of Hamburg ("Wissen vom Fass", or "Science on tap" in English). In 2018, 25% of the scientists were researchers directly associated with the Program MU at DESY. Another example is the participation of MU scientists in the biannual science festival EFFEKTE in Karlsruhe. And this is only one of the many activities in this area. We do ramp up our efforts to reach out to the general public, in particular to children, to attract them to STEM research in general by communicating our exciting research effectively and transparently (e.g. Girls' Day and "Berufsbilder von Wissenschaftlerinnen am KIT").

3.3.2. Transfer of Knowledge and Technology

The transfer of knowledge and technology from science to industry, society, and the general public is a central element of the Helmholtz mission. Embedded in the Research Field *Matter*, we strive to encourage and support these transfer activities and provide an ideal environment for a rapid exchange of knowledge and technology to mutual benefit. We will organize the collaboration and close interaction between the Topics and the different groups across the participating Helmholtz Centers to accelerate the transfer of knowledge and technology while ensuring professional intellectual-property management. The strategy of the Program MU is based on raising awareness about existing funding and support measures, fostering collaborations, and facilitating optimal use of the various support measures provided by the Helmholtz Association in general and by the participating centers in particular. Examples of general support and funding programs provided by the Helmholtz Association are the Helmholtz Validation Fund for bridging the gap between scientific findings and their commercial applications as well as between public research and private investment, and the Helmholtz Enterprise program for spin-offs from the Helmholtz Association. In addition, the participating Helmholtz Centers offer a multitude of dedicated offices and measures to support knowledge and technology transfer to foster innovation. Examples are Industrial Liaison Officers at DESY, the service unit for Innovations and Relations Management at KIT, and the Technology Transfer staff unit at GSI. Many of the activities related to knowledge and technology transfer will naturally be implemented in very close collaboration with the Program MT, but also with MML. For example, the construction of a large research infrastructure such as FAIR requires an intensive exchange with industry and offers many opportunities for direct technology transfer. ROSE, a device for four-dimensional emittance measurements, has been developed in such a cooperation with industrial partners. Other examples include the development of dedicated optical sensors (silicon photomultipliers and photomultiplier tubes), radio antennas, and various components of CTA (e.g. mirrors, light-weight support structures).

One member of the MU Program Board will be responsible for coordinating the Program-wide activities for supporting knowledge and technology transfer. The individual actions will be discussed and decided in the meetings of the MU Program Board, and status reports will be provided at the annual meetings (MU Days). The success of the measures will be reported in the annual progress reports and monitored by international advisory boards of the participating centers and the Steering Committee of the Research Field *Matter*.

Efficient knowledge transfer from science to society is one of the central aims of the Program MU. One of the most important ways to achieve this transfer is the thorough education of students by teaching university classes, supervising bachelor, master, and Ph.D. projects, and engaging in summer schools. Many of our students work later in the most innovative companies of Germany and Europe. These teaching activities are complemented by a whole suite of outreach activities targeted at a general audience to make the research results accessible to the public. Examples are public lectures, lectures and Master Classes held at schools, and "open-door" days for inviting the public to visit the Helmholtz research facilities. The series of master classes for schools, which started originally with particle physics master classes, will be extended further to cover all research areas of MU.

The Program MU has taken a pioneering role in supporting open access for publications, research data, and data analysis algorithms. Following the lead of astronomical and astrophysical observatories, data of the CERN experiments have been made publicly accessible (including the corresponding analysis algorithms). As a seed for a future large-scale, distributed Astroparticle Physics Data and Analysis Center, the data of the KASCADE and KASCADE-Grande air shower detectors have also been published (KCDC). Classes are being held to educate interested people on how to analyze these large amounts of public data. Another increasingly important aspect of knowledge transfer is the development and dissemination of expertise on methods of AI for data analysis. AI methods, in particular deep learning, are developed and used in all Topics of the Program MU. The KIT spin-off Blue Yonder, which focuses on data mining, is today a very successful, international company. A series of workshops has been organized together with German universities to bring the different groups together, and a very fruitful collaboration has been established. As there is a great demand in society for scientists and engineers who have a good understanding of AI algorithms, we will intensify these cross-topical activities and also deepen the collaboration with the Topic MT-DMA. In addition, the participation of members of the Program MU in international review and strategy panels and their engagement in advising government agencies is an important channel of knowledge transfer. Coordination of these activities within MU will ensure a coherent presentation of the relevant information in these committees.

4. RESOURCES

In this section, we present different aspects of the planned and current resources, in terms of costs and personnel, for the Program MU.

Please note the used notation which applies to the entire proposal: Costs are given in thousand euros (TEUR), and for all resource numbers the thousands separator is a dot, and the decimal separator is a comma.

Table 9: Costs and personnel resources of the Program MU and its Topics, planned for 2021. The costs include general and administrative costs, internal services etc.

Program costs (TEUR)	**94.009**
Fundamental Particles and Forces	34.186
Cosmic Matter in the Laboratory	18.893
Matter and Radiation from the Universe	40.930
Program personnel (FTE)	**654**
Fundamental Particles and Forces	**267**
Scientists	158
Doctoral students	78
Scientific support personnel	31
Cosmic Matter in the Laboratory	**168**
Scientists	82
Doctoral students	64
Scientific support personnel	22
Matter and Radiation from the Universe	**219**
Scientists	120
Doctoral students	28
Scientific support personnel	71

Planned costs and personnel resources of the program and the participating centers

The program costs by center typically include general and administrative costs, internal services etc., except for the contribution TransFAIR (FZJ/GSI). Here we have a special regulation: The TransFAIR program costs do not include noncash expenditures and costs for infrastructure. The TransFAIR cash expenditures are initially located at FZJ and are planned to be successively transferred to GSI during PoF IV.

Table 10: Program resources by center (in TEUR), planned for 2021. The costs include general and administrative costs, internal services etc.

Proposed program costs	**94.009**
DESY part costs	**47.449**
thereof personnel costs (including personnel of infrastructure)	32.166
TransFAIR (FZJ/GSI)* part costs	**3.849**
thereof personnel costs	2.072
GSI part costs	**15.044**
thereof personnel costs (including personnel of infrastructure)	7.980
IPP part costs	**3.800**
thereof personnel costs (including personnel of infrastructure)	2.583
KIT part costs	**23.868**
thereof personnel costs (including personnel of infrastructure)	13.311
DESY part investments	
continuing investments	5.007
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	0
TransFAIR (FZJ/GSI) part investments	
continuing investments	0
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	0
GSI part investments	
continuing investments	1.700
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	0
IPP part investments	
continuing investments	250
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	0
KIT part investments	
continuing investments	2.085
ongoing individual large investments > € 2,5 million financed through Helmholtz large investment budget	714

**Special regulation: The TransFAIR Program costs do not include noncash expenditures and costs for infrastructure.*

Table 11: Reconciliation of total Program costs to cash expenditures (in TEUR). Noncash expenditures include depreciation, reserves, variations in receivables and liabilities.

DESY program costs	47.449
- noncash expenditures	4.332
+ continuing investments	5.007
+ ongoing individual large investments > € 2,5 million	0
DESY cash expenditures	**48.124**
TransFAIR (FZJ/GSI)* program costs	3.849
- noncash expenditures	0
+ continuing investments	0
+ ongoing individual large investments > € 2,5 million	0
TransFAIR (FZJ/GSI)* cash expenditures	**3.849**

GSI program costs	15.044
- noncash expenditures	3.041
+ continuing investments	1.700
+ ongoing individual large investments > € 2,5 million	0
GSI cash expenditures	**13.703**
IPP program costs	3.800
- noncash expenditures	250
+ continuing investments	250
+ ongoing individual large investments > € 2,5 million	0
IPP cash expenditures	**3.800**
KIT program costs	23.868
- noncash expenditures	2.942
+ continuing investments	2.085
+ ongoing individual large investments > € 2,5 million	714
KIT cash expenditures	**23.724**

** Special regulation: The TransFAIR cash expenditures are initially located at FZJ and are planned to be successively transferred to GSI during PoF IV.*

Table 12: Program personnel capacity by center (FTE), planned for 2021.

DESY part personnel	334
Scientists	200
Doctoral students	98
Scientific support personnel	36
TransFAIR (FZJ/GSI)* part personnel	30
Scientists	14
Doctoral students	12
Scientific support personnel	4
GSI part personnel	138
Scientists	68
Doctoral students	52
Scientific support personnel	18
IPP part personal	20
Scientists	14
Doctoral students	5
Scientific support personnel	1
KIT part personnel	132
Scientists	64
Doctoral students	3
Scientific support personnel	65

** Special regulation: The TransFAIR program costs do not include noncash expenditures and costs for infrastructure. The TransFAIR cash expenditures are initially located at FZJ and are planned to be successively transferred to GSI during PoF IV.*

The number of doctoral students is varying a lot between the contributing centers which is caused by different administrative structures at the centers. At KIT, doctoral students are usually employed in the university sector and thus not accounted for here. A large fraction of doctoral students financed from GSI in this program are employed at a partner university through a Strategic Partnership Program between GSI and the university. Therefore, those personnel costs are not included in the costs given in Table 10, however, those doctoral students are included in the head count as they will work for the respective program.

Current resources

The current personnel resources are given here projected to the PoF IV structure and thus are not directly comparable to the program resources in PoF III. According to the PoF IV projection, for GSI the Helmholtz Institutes in Jena and Mainz and campus Darmstadt are included. In PoF III, campus Darmstadt was exempted from the evaluation and therefore is not reported in the PoF programs in regular PoF III reports. In 2019, IPP contributed to the Research Field *Energy*. The resources 2019 are not projected to the new PoF IV (beginning 2021) structure within *Matter*.

As already mentioned for the anticipated Program personnel in Table 12, the number of doctoral students is varying a lot between the contributing centers which is caused by different administrative structures at the centers. At KIT, doctoral students are usually employed in the university sector and thus not accounted for here. At the time of writing the proposal there are 46 doctoral students working on subjects related to this proposal at KIT. A large fraction of doctoral students financed from GSI in this program are employed at a partner university through a Strategic Partnership Program between GSI and the university. Therefore, those personnel costs are not included in the costs given here, however, those doctoral students are included in the head count as they will work for the respective program.

Table 13: Current personnel resources projected to the PoF IV structure, preliminary resources for 2019.

	Helmholtz Program		**Third-party funding**	
	TEUR	FTE	TEUR	FTE
DESY	25.860	372	3.038	51
Scientists	19.378	218	2.304	29
Doctoral students	4.113	118	720	22
Scientific support personnel	2.369	36	14	0
TransFAIR (FZJ/GSI)*	2.031	30	0	0
Scientists	1.267	14	0	0
Doctoral students	511	12	0	0
Scientific support personnel	254	4	0	0
GSI	6.587	131	218	5
Scientists	5.115	68	75	1
Doctoral students	693	45	132	4
Scientific support personnel	779	17	11	0
IPP	0	0	0	0
Scientists	0	0	0	0
Doctoral students	0	0	0	0
Scientific support personnel	0	0	0	0
KIT	9.171	122	543	8
Scientists	5.358	61	208	3
Doctoral students	197	4	258	4
Scientific support personnel	3.615	57	78	1

* *Special regulation: The TransFAIR program costs do not include noncash expenditures and costs for infrastructure. The TransFAIR cash expenditures are initially located at FZJ and are planned to be successively transferred to GSI during PoF IV.*

5. LIST OF PUBLICATIONS RELATED TO THE PROGRAM PROPOSAL

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