MAKING PARTICLE PHYSICS, COSMOLOGY AND ASTROPHYSICS WORK TOGETHER

THE UNIVERSE
CONSTITUENTS, FORCES, SPACE-TIME

Swiss Institute of
Particle Physics
an Association according to Swiss law

CHIPP IN A NUTSHELL:

CHIPP is an Association according to Swiss law and – since 2012 – a member society of the Swiss Academy of Natural Sciences SCNAT.

The purpose of the CHIPP Association is to strengthen particle, astroparticle and nuclear physics in Switzerland by being active in particular in the following fields:

a. To help towards a successful participation of Swiss groups in projects;
b. To advise the Universities/ETHs on vacant professorships and academic strategies, and
c. To ensure a proper Swiss representation in relevant national and international bodies.
d. To promote public awareness on particle, astroparticle and nuclear physics.

The CHIPP Association is organized as a two-level system:

- the strategic level comprises the Plenary meeting – the supreme body of the Association – and the Board, where all Professors active in particle, astroparticle and nuclear physics assemble. Subcommittees are dealing with specific issues.
- the operational level, where the day-to-day business of the Association is handled by the Executive Board composed of the Chairman and up to three Vice-Chairs.

Members of the CHIPP Association are the particle, astroparticle and nuclear physicists holding a Master in physics and working for a Swiss institution, as well as the Swiss PhD nationals working at CERN.

For further and more detailed information see www.chipp.ch.

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PREFACE

Every-day life is arguably becoming more and more complicated. Science is becoming more and more complex and complicated. In many ways specialization of sub-disciplines develops at a speed which makes it difficult or impossible to track – for non-experts and sometimes even for experts from a neighboring field. We are working in specialized research fields using tools which have been developed and sharpened to the point. Actually, these tools must usually be developed by our field of research because there is nothing yet which could do the job. Later they are often used for other purposes as well. We are proud of these so-called spin-offs and examples are many.

We look at the very small, the smallest particles using particle accelerators and colliders and large detectors as our microscopes. We look at the very big, the biggest and oldest structures and phenomena in our universe using large telescopes or satellites. We try to find, build and test the theory which describes all the microscopic particles and phenomena which we discover. We try to understand the evolution of our universe and the conditions which influenced it. While these are indeed highly specialized fields, namely particle physics, astrophysics and cosmology, one realizes that a common theme exists in the desire for a deep understanding and insight into the most fundamental questions of our universe and why it is the way it is. The questions are easy to formulate, they are also very popular and attract a lot of interest by the public and attract many of the young generation to consider studying natural sciences.

Not only is there a common theme but also can we make a bold presumption and expect that the same physics governs the very small and the very large. If we find out the details at the two ends, at the so-called ‘two infinities’, we might be able to merge them into the same picture.

The present text reports on a trial to start an endeavor for more work on a merged picture. It is the pre-proposal for the NCCR Universe – Constituents, Forces, Space-Time. Major parts of the Swiss particle physics, astro-particle physics and cosmology communities set out to envisage common projects and to inter-connect our specialized research fields on a bigger scale, in the framework of a National Competence Center for Research – NCCR.

Usually people don’t publish their unsuccessful attempts. Our proposed NCCR didn’t find the support of the relevant decision making bodies to materialize and be funded. Nevertheless, we like to report on this attempt as we are convinced that a deep understanding of the laws of nature and of our universe will require continued enthusiastic research at the infinities, at the frontiers of our basic knowledge, and a strong effort to bring together seemingly disconnected fields.

Ruth Durrer, Klaus Kirch, Martin Pohl

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1 SUMMARY

Particle physics, cosmology and astrophysics have long been topics of focus in Geneva. With the establishment of CERN a handful of visionary scientists created a European particle physics laboratory, hosting thriving research in the field. A complementary corner stone of particle physics is strong national research laboratories, like PSI with its unique proton accelerator and meson factory. Both have led scientists throughout Switzerland to have an important impact in these fields and gain the respect of their peers worldwide. Today, we propose to federate Swiss research in the fields of particle physics, cosmology and astrophysics to advance the extraordinary capability and visibility of our country by allowing science to develop in new directions and inspire new generations of visionaries. The creation of NCCR Universe will allow Switzerland to strengthen its activities in fundamental physics, and implement transversal structures between the main directions of existing and future efforts. It will provide a “home” for the large pool of national and international scientists who have established their research in proximity of Geneva in the past decades. It will refocus on activities at our national laboratory.

NCCR Universe proposes an innovative approach by organizing the research by themes and thus crossing traditional boundaries. Using the existing “resources” (neutrino, high energy and astroparticle physics), three scientific topics have been identified as the major Challenges: elementary constituents and forces, dark matter and dark energy, sources and acceleration of particles. Never yet addressed as such in Switzerland, these research themes seek answers to issues on the basic laws of Nature, the role of gravity, and inconsistencies of the Standard Model with our current understanding of particle physics. Studied by physicists from different disciplines – experimental particle physics, astrophysics, observational cosmology and theoretical physics – these Challenges allow us to combine insights from controlled accelerator experiments as well as astrophysical and cosmological observations. The approach also allows us to exploit the phenomenal synergies between the traditional research directions in terms of experimental techniques, analysis methodology and cross-fertilization between theory and experiment. Switzerland’s large public investment in CERN’s infrastructure has led to anchor leaders in the field in our region. Yet, the return in terms of fundamental research done in Swiss institutions has not been able to match this effort due to a lack of a long term investment in manpower. The NCCR will streamline and solidify our field within Switzerland and position it worldwide. The Swiss Institute of Particle Physics, CHIPP, embraces this initiative. It is committed to support the NCCR Universe and perpetuate its work after its completion. However, partners in this NCCR also come from beyond traditional CHIPP boundaries.

As highlighted in its long-term strategic plan, the University of Geneva puts research in physical sciences at the highest priority. In particular, it is putting considerable resources into a new facility focused on fundamental research in physics, mathematics and astrophysics. A first step towards a higher degree of integration between the disciplines concerning this NCCR has already been made in Geneva with the foundation of the Center for Astroparticle Physics, CAP Genève. For PSI, particle physics and accelerators are key components of its strategic planning. PSI is at the forefront of accelerator development with its new SwissFEL, the SLS, the medical cyclotron and the world's most powerful proton accelerator, the PSI ring cyclotron. It is developing this important technology further. The Development Plan for 2012–2016 has “Particle Physics and the Structure of Matter” as one of its five thematic areas and places a strong emphasis on its user laboratory function.

The co-leadership of University of Geneva and PSI emphasizes the strategic collaboration between the universities and the ETH system as well as the operational and cultural balance throughout the country. With its proven record as leading house for other NCCRs, the University of Geneva and its Faculty of Sciences are committed to support the establishment of a new NCCR. PSI is the world leading federal institution in accelerator development and high intensity beams. Together they are in a natural position to host and manage this project of national interest with international outreach.

2 SCIENTIFIC QUESTION AND ITS REFERENCE TO SOCIETY

Physics provides the building blocks for all sciences. Fundamental research seeks to identify and understand the unknown, to push the boundaries of knowledge, fueling innovation and leading society into the future.

Particle Physics, cosmology and astrophysics are with no doubt the fields of physics that address the most questions of society's concerns since the beginning of times: What is the origin of matter, of energy? What is the origin of the Universe, of our planet? What are we made of? How are particles created at first? What are the dimensions of space-time and what is the role of gravity?

Although research in these fields has been active and productive for decades, the physics community still faces today fundamental challenging questions. There seems to be a huge discrepancy between what is seen and what is expected. Theories are developed and experiments validate, hopefully, over time. One stubborn candidate though is the Standard Model. This theory of particle physics explains a large variety of phenomena down to the smallest distances accessible to present day particle physics experiments. It has been a solid basis for almost everything, describing the particle-forces interactions that constitute matter. The Standard Model is able to explain all experimental data produced to date from man-made accelerators. Yet this model bases itself on many unexplained parameters, making it theoretically unsatisfactory. One of the key ingredients of the theory, the generation of mass through the Higgs mechanism, is on the verge of being proven or disproven. With today's extremely sophisticated experimental tools, we are able to push research further than ever before.

Despite the impressive agreement between theory and numerous precision experiments, it has become clear over the last decades that there remains a number of observed phenomena that the Standard Model in its original form cannot explain. Observations and analysis reveal that only about 4 % of the energy density of the Universe is ordinary matter, the matter we know how to describe with quarks and leptons, the rest consisting of about 70 % "dark energy" and 26 % "dark matter". Dark energy is, however, only a word that describes the cause of the observed apparent acceleration of cosmic expansion, while dark matter describes massive particles that are, to date, observed only through their gravitational pull. We also know that the complex structures observed in the present Universe, galaxies, clusters of galaxies and voids, emerged from an almost uniform early Universe. They grew from small initial fluctuations that are also imprinted on the cosmic microwave background. We assume that an inflationary phase of very rapid expansion has generated these initial fluctuations out of the vacuum.

Providing a unified view of the Universe requires a deeper understanding or a new vision. Cosmological observations combined with the application of the laws of particle physics to the expanding Universe lead to a number of observations that point beyond the present Standard Model. The work undertaken within this NCCR will point the way towards future progress in answering some of these most fundamental questions that can be asked about Nature, formulated in the Swiss Road Map [1, 2]. However, these questions can be investigated only by a combination of precise, controlled experiments like those now in operation at CERN at the LHC – the Large Hadron Collider – on one hand, and cosmological and astrophysical observations on the other. Among the most strikingly successful examples of such combination is the recent progress in neutrino physics coming from the combination of solar neutrinos, atmospheric neutrinos and neutrinos from accelerators and reactors. Moreover, the analysis of the observed large-scale structure of the Universe as well as the properties of individual galaxies and galaxy clusters allows to robustly excluding the possibility that dark matter is made of the (massive) neutrinos of the Standard Model. This makes dark matter one of the major "beyond the Standard Model" problems.

Particle, astroparticle physics and cosmology are of strategic importance for Swiss research. As one of the CERN host states, Switzerland has traditionally well supported basic research in particle physics and the efforts of federal and cantonal authorities have been widely acknowledged. Basic research is recognized as one of the major drivers for innovation beyond the gradual improvement of existing technologies. A competitive edge for Swiss researchers in particle physics can be derived from their privileged geographical position close to CERN, the major center of competence in this field worldwide. Independently, cosmology research as a novel approach to questions from particle physics and fundamental interactions has developed in different places in Switzerland – in Geneva, at EPFL and ETHZ, at University of Zürich. However, exploiting this edge requires an optimization of Swiss research structures aiming at an intelligent combination of these competences and also a sustainable coverage of the very long life cycle of particle and astroparticle physics experiments. Fostering this process is the role of the Swiss Institute of Particle Physics CHIPP, a bottom-up association with an outstanding track record covering all particle, astroparticle and nuclear physics in Switzerland.

NCCR Universe takes the scope of CHIPP a step further and broader. It focuses on the tremendous synergies between traditional particle physics, astrophysics and cosmology. These synergies concern the research questions but also the experimental techniques used in these fields. Here, especially astrophysical observations profit already from techniques developed for particle physics experiments. By intensifying the collaboration between particle physics, astrophysics and cosmology, educating graduate and undergraduate students in these increasingly intertwining fields, and developing infrastructure (especially in computing but also in detector development for future experiments), this NCCR will help us address the problems mentioned above and seek answers to the major challenges of our understanding of Nature.

With the worldwide political and public debates about the dangers of nuclear energy, the risks of nanoscience, or more generally on the value of spending on scientific research as society faces difficult times, there is an increasing need for physicists to open up and share the value of their work. Bridging the gap with society by providing a relevant dialogue permits an increased level of awareness and more educated decisions. Sharing the passion and discoveries of research awakens new vocations and promotes the freedom of the mind necessary to imagine what has not yet been formulated.

CERN offers a rare example of outreach, where scientists share between themselves their challenges and discoveries at the same time as they explain it to the rest of the world. The open-door concept of exposing science to outside communities, even possibly amateurs, proves its usefulness by providing additional brainpower to the issue, or simply by the benefit of having had to formulate it differently. NCCR Universe will not only naturally contribute to these efforts, it will enhance them by providing an academic perspective on the matter. With its other national partners and the co-leading house PSI, it can focus on the more fundamental questions and show how scientific thinking can enable new perspectives. The NCCR's extended network will also permit to reach out more precisely to the Swiss community, throughout its linguistic and cultural differences.

Through an innovative approach of interactive communications using virtual platforms, a well-coordinated program will target all actors of society, whether the scientific community, the industry or youth. Adapting our outreach with new tools will greatly increase the dialogue, stimulate technology transfer and revitalize scientific education.

At a time when one speaks of A Knowledge-Based Society, NCCR Universe aims at creating knowledge and pushing its limits beyond today's comfort, all while making research available and sharing science with the stakeholders capable of leveraging on those efforts and produce collateral benefits.

3 RESEARCH PROGRAM 2014–2017

The representation of projects for NCCR Universe in Figure 1 exhibits the three scientific themes of Section 1. Underlying are very general questions: What is the Universe made of ? How can we best test our theories about this? The themes, crossing traditional boundaries, are best formulated in terms of Challenges:

- The Challenge of Elementary Constituents and Interactions comprises research concerning properties of known elementary constituents of matter (including bottom and top quarks, neutrinos, neutrons and muons) as well as searches for new, unknown phenomena responsible for particle masses, and the asymmetry between matter and antimatter. It includes uncovering open issues of the Standard Model, as the generation of mass through the Higgs mechanism and breaking of electroweak symmetry.
- The Challenge of Dark Energy and Dark Matter comprises all research concerning the dominant components of the Universe: Dark Energy and Dark Matter. It covers theoretical and experimental efforts towards understanding the apparent acceleration of the expansion of our Universe, commonly termed “Dark Energy”. It also strives to improve our knowledge of Dark Matter properties through theoretical analysis, as well as direct and indirect searches for its particle content.
- The Challenge of Particle Sources and Acceleration covers man-made accelerators and acceleration mechanisms of cosmic particles. It includes research and development towards the next generation of intense beams and colliders. It also aims at understanding cosmic particle accelerators (producing cosmic rays, photons, neutrinos and gravitational waves, spanning more than 12 orders of magnitude in energy and 30 orders of magnitude in intensity) with the goal to answer fundamental physics questions.

All three challenges will be addressed by physicists from different disciplines: experimental particle physics, astrophysics, observational cosmology and theoretical physics in a coherent collaborative approach.

While each project of this proposal has been assigned to one of these themes, the real strength of the approach is in their strong links; a Venn diagram presents them, see Figure 1. In choosing the three themes, the NCCR contributors make a strategic choice following the recommendations of the CHIPP Road Map [1, 2], while covering some of the main directions followed worldwide in search for the ingredients of the successor to today’s Standard Model for particle physics (SM).

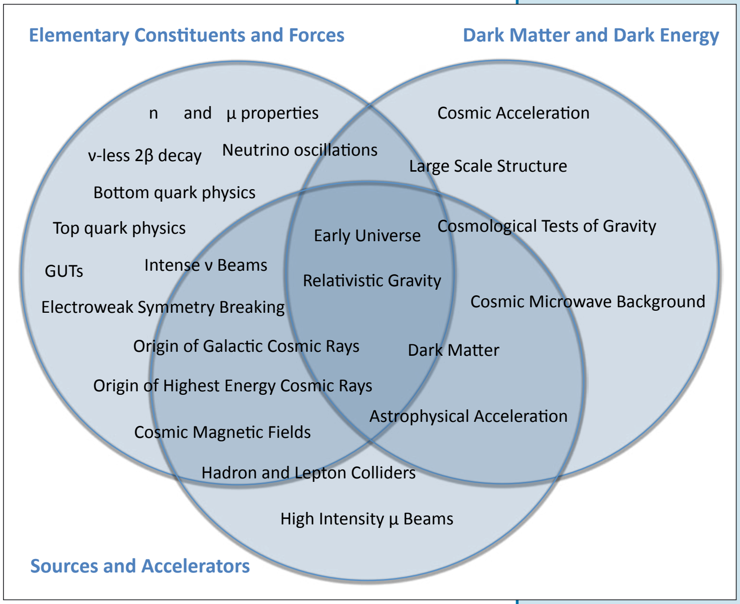

Figure 1: Conceptual chart of the NCCR Universe showing its main research themes and projects.

It is obvious that experimental and theoretical subjects of this fundamental nature require a sustainable long duration support. The LHC project and its experiments, to name a prominent example, started with first conceptual studies in the early 1990's. Full energy will be reached in 2014 and the current experimental program is expected to continue until at least 2020. CERN intends to extend the machine luminosity around 2020 by an additional factor. This will require a thorough update of the LHC detectors. The construction and operation life cycle of the LHC and its experiments thus spans over more than three decades. Similarly, data analysis and interpretation will dominate particle physics in a period of several decades. Comparable life cycles have been observed for non-accelerator experiments, such as particle detectors in space and large ground based and underground facilities. With their long duration, NCCR are an appropriate instrument to cover the typical life cycles of experimental and theoretical programs.

The NCCR Universe is not proposed to fund investment into experimental infrastructure, detector construction or upgrade. Existing funding lines like SNF grants, FORCE, FINES and their successor FLARE, EU Framework Programs like AIDA, ESA's PRODEX program and others are better suited for this purpose. Instead, the NCCR will install structures that coordinate and support cooperation between different theoretical and experimental approaches to confront the Challenges. In particular it will:

- Lead a joint program addressing the most fundamental challenges of the present day physical picture of the Universe by combining and coordinating the efforts of Swiss theoretical and experimental groups working in cosmology, particle physics and astrophysics.
- Coordinate and support the Swiss scientific return of investment from LHC experiments, neutrino and astroparticle physics experiments by creating PhD student and post-doctoral fellowships, closely networked and embedded in a Swiss-wide doctoral and post-doctoral research and education program.
- Intensify the contribution of Swiss research groups to particle physics experiments at PSI, enabling new experiments that require more intense beams and novel detection techniques.
- Increase the Swiss impact in the planning process for future accelerators, focusing on CERN projects for and beyond the present LHC.
- Establish a multi-messenger data repository for astroparticle physics to boost Swiss co-operation and help identify the nature of astrophysical particle sources and accelerators.

The activities of the NCCR within the three themes are briefly summarized in the following and detailed in Section 4. The descriptions of the individual projects in Section 4 are explicitly interlinked, one of them so strongly that it has been promoted to a "double project" (see 4.2.7). Inside projects and using these links, particle physics, cosmology and astrophysics are made to work together.

3.1 THE CHALLENGE OF ELEMENTARY CONSTITUENTS AND FORCES

Ordinary matter, composed of the known fermions – quarks and leptons – as well as gauge bosons, represents less than 5 % of the energy density in the Universe, yet it forms all known objects. A lot is known about its detailed properties, while important challenges remain. Fermionic matter comes in three generations comprising four particles each: up- and down-type quarks, charged leptons and neutrinos. There is no known compelling reason why there should be three and only three "light" fermion generations. Each charged particle has its antiparticle – neutrinos being neutral may or may not be their own antiparticles. The three generations are classified by increasing mass of the charged particles; we do not know if neutrinos follow the same hierarchy or not. Each particle carries a quantum number called flavor, which is conserved in strong and electromagnetic interactions, and presumably gravity. Electroweak interactions induce quark flavor transitions, mostly within each generation, but to a lesser extent also across generations, by what is called mixing, described in the current SM by a mixing matrix. This matrix also accommodates breaking of the symmetry between the properties of particles and their antiparticles – CP violation – by including a complex phase. A CP asymmetry is indeed observed in the quark sector and at the actual level of precision well described by such a phase. Whether a corresponding mixing also occurs for the charged leptons is an important open issue and most sensitively studied in rare muon decay searches. The properties of the known leptons and quarks are addressed by the projects: *Search for new physics using bottom hadrons and top quarks, Exotic hadrons, Neutrino oscillations, Neutrino-less double beta decay and Lepton flavor violation.*

CP violation is a crucial ingredient for the explanation of the observed asymmetry between matter and antimatter in the Universe. The amount of the CP violation within the SM is not sufficient to account for the asymmetry observed in the Universe which therefore calls for physics beyond the SM. The asymmetry might be due to new physics around the electroweak energy scale. This scenario is dubbed electroweak baryogenesis. It is testable through the observation of new states at the LHC or via observation of non-standard CP violation in the B meson systems. New CP violation at the electroweak scale usually also leads to sizeable electric dipole moments (EDM), e.g., of the neutron. If, however, CP violation is introduced at a higher energy scale, baryon asymmetry may be directly related to the fact that neutrinos are massive. This scenario is dubbed leptogenesis. CP violation in the neutrino sector can be measured via neutrino oscillation experiments and Majorana mass terms in neutrino-less double beta decay. The question of CP violation and baryon asymmetry is addressed by the projects: *Electric dipole moment of the neutron, Searches for new physics using bottom hadrons, Neutrino oscillations and Neutrino-less double beta decay.*

The interpretation of the tests of the SM-particle properties requires a direct search for the new particles involved in any extension of the SM. This can only be performed at the high-energy frontier, i.e. the LHC and a potential future linear e^+e^- collider. One of the primary challenges at the LHC is the search for the Higgs boson in order to establish (or exclude) the perturbative Higgs mechanism for electroweak symmetry breaking which gives rise to the mass and mixing matrices of the SM. This realm of questions is addressed by the projects: *Electroweak symmetry breaking, and Grand unification.*

3.2 THE CHALLENGE OF DARK MATTER AND DARK ENERGY

Dark matter is investigated through cosmological and astrophysical observations and its nature is explored with both, colliders and non-accelerator experiments. Dark energy has been observed through cosmological observations only.

Dark matter has been first postulated by the Swiss astrophysicist Fritz Zwicky, who realized that the luminous mass in galaxy clusters is not sufficient to gravitationally bind the objects and explain the velocities of their components. Dark matter must be non-baryonic in order not to spoil the success of Big Bang Nucleosynthesis, which explains the abundance of Helium and Deuterium in the Universe. The SM neutrinos are too light to explain the observed large scale structure of the Universe as well as the dynamics of individual galaxies and clusters; an extension of the SM is required. Dark matter is formed by new heavy particles and can be detected directly by their interaction, or indirectly by their annihilation, decay or influence on cosmic observables. These topics are addressed in the bouble project *Dark Matter, direct & indirect detection*.

Dark energy has been proposed by several cosmologists in the 90ies. In 1998, observations on Type-1a supernovae (SN1a) have yielded a distance-redshift relation, which is not compatible with a decelerating Universe. The 2011 Nobel Prize in physics has been awarded to these observations. Gravity of ordinary matter is attractive and therefore leads to a decelerated expansion of the Universe. To obtain acceleration, a strong negative pressure is needed, so that gravity becomes repulsive. The simplest proposal for dark energy is vacuum energy or, equivalently, a cosmological constant. Other possibilities are a dynamical scalar field, quintessence, or an infrared modification of General Relativity. Another idea is that back-reaction from cosmic structure may spoil the distance-redshift relation of a homogeneous and isotropic Universe such as to mimic Dark Energy. In project *Cosmic acceleration* we want to investigate dark energy from all is facets: Can Dark Energy be simple vacuum energy and why is it so small? How can we best distinguish quintessence from a cosmological constant? Might General Relativity be violated at very large scales, in the infrared?

We can use cosmological observations to test the properties of dark energy or modifications of gravity via measurements of weak gravitational lensing, by observations of the cosmic matter distribution, and by measuring velocity flows generated by gravity. The advantage of these probes is that lensing and velocities respond to the total gravitational mass and not only to the visible mass. The most challenging new experiment is Euclid, an ESA satellite project with strong involvement from Geneva and EPFL. At this stage, we can still influence the experimental strategy to optimize the information about dark energy and dark matter properties as well as modified gravity. This latter topic is addressed in project *Cosmological tests of gravity*.

Cosmic Large Scale Structure (LSS) has formed by gravitational instability from primordial fluctuations. Observations of LSS and comparison with theoretical predictions and cosmological simulations therefore provide a wealth of information how gravity has acted in the Universe and allow to check our understanding of the evolution of the Universe, including its early stage, when unknown physics was important. We can compare observations of the galaxy distribution with cosmological N-body simulations. This tool is, however, hampered by the fact that we only observe galaxies directly and most of their matter is actually dark matter. The question of biasing, i.e. the relation between the galaxy distribution and the underlying dark matter distribution, has to be included in such studies. All aspects of LSS are the subjects of the three projects on *Cosmic large scale structure*.

The anisotropies and the polarization of the cosmic microwave background (CMB) are another superb cosmological tool. On the one hand, they can be calculated with high accuracy nearly fully within cosmological perturbation theory. On the other hand, high precision data is available and much more is coming, especially from the Planck satellite currently in orbit. Their analysis and interpretation will be a major tool to learn more not only about cosmological parameters, but also about the initial perturbations coming from inflation: Is there a gravitational wave component? Can non-Gaussianities be detected? The analysis of Planck data will continue largely into the funding period, even beyond the first four-year period. Follow-up experiments, especially to measure B polarisation of the CMB, are under construction or planned. These topics are addressed in project *Cosmic Microwave Background*.

The early universe was a unique laboratory for particles and fields at high temperatures. The models of baryogenesis, inflation, tests of theoretical ideas (such as e.g. Grand Unified theories) will be the subject of the theoretical investigations in this project, using the input from particle physics experiments and observational cosmology, especially the CMB and LSS, and leading to predictions of possible properties of new particles to be searched. This will be elaborated in project *Early universe*.

3.3 THE CHALLENGE OF PARTICLE SOURCES AND ACCELERATION

The future of precision particle physics hinges critically on progress in accelerator technology: major developments in particle physics since the 1950s have resulted almost entirely from the parallel development of powerful and increasingly sophisticated accelerator facilities. The exploitation periods of collider and accelerator complexes at CERN and elsewhere indeed define eras, such as the past LEP era and the current LHC era, producing a coherent chain of results dominating particle physics over many years. Progress in particle accelerator and collider technology has to be supported by accelerator research and development encouraging new ideas. This concerns the high-energy frontier with the immediate necessity to support LHC machine upgrades and the longterm goal of defining the next lepton collider. It also concerns the intensity frontier, where more intense proton beams will produce neutrino and muon beams of unprecedented intensity and quality. Accelerator development times are long and on-going R&D is impossible to disentangle from the perspective of physics requirements for the future. Although Switzerland hosts CERN and the world class facility for low energy beams PSI, accelerator research and development has so far not received the support it deserves. The NCCR Universe proposes to change this by incorporating important R&D projects in this area, covering *Hadron and lepton colliders, High intensity muon beams at PSI* and *Intense neutrino beams:*

To extend the discovery potential of the LHC, two major upgrades are under study, a High Luminosity LHC and a High Energy LHC. At the same time Linear Collider study groups are pursuing R&D on possible high-energy lepton collider options. Superconducting RF technology of the International Linear Collider (ILC) and the two-beam scheme of the Compact LInear Collider (CLIC) are under investigation.

At PSI, the world's most powerful proton cyclotron generates highest intensities of low momentum pions, muons and ultra-cold neutrons. Many high precision and intensity frontier experiments can only be performed at this facility. R&D on higher muon intensities and brighter slow muon beams will be pursued. Unique relevant expertise exists, such as for the design and operation of high-power targets, RF-resonators for cyclotrons, or technical interlock systems that ensure the safe operation of the high intensity beam.

The next generation of neutrino beams constitute a considerable challenge, concerning intensity but also beam parameter control. The LAGUNA-LBNO program foresees the study of neutrino beams from CERN. On a longer time scale a neutrino factory where muons are stored in a storage ring is ideal for precise measurements of neutrino oscillations. This may be the first step towards muon colliders, as alternative, distinct high-energy lepton collider. Ionization cooling is an essential technique to master for these machines.

Despite all foreseeable progress in the field of man-made accelerators, they will never rival cosmic accelerators as far as the attainable energies are concerned. In fact, ultra-high energy cosmic rays reach macroscopic energies. This is due to the extreme sizes and fields that cosmic accelerators can have, which are unique environments to study the behavior of matter under extreme conditions. Just 100 years after the discovery of cosmic rays, their sources, acceleration and transport mechanisms are still unclear. In particular, powerful accelerators must exist inside our galaxy but have so far remained unidentified. The origin of ultra-high energy cosmic rays is completely unknown, but must also be sought at relatively modest distances.

There is little technological synergy between man-made accelerators and the techniques for studying cosmic ones. However, the goal to reach energies and intensities as close as possible to conditions in the early universe provides a strong link. Consequently, the third challenge addressed by the NCCR will comprise important research projects covering cosmic accelerators.

The power of particle accelerators operating in the Galaxy, $\sim 10^{28}$ MW, is so high that cosmic rays significantly affect the structure of the interstellar medium and magnetic fields. Cosmic accelerators outperform manmade ones also in the attainable energy scales. The observed cosmic ray spectrum extends at least to 10^{20} eV, i.e. seven orders of magnitude higher than the LHC. These questions are addressed by the projects *Origin of Galactic cosmic rays and highest energy cosmic rays,* as well as *Cosmic magnetic fields.*

Cosmic particle accelerators most probably come from regions with strong gravitational fields (supermassive black holes) and also emit neutrinos and gravitational waves. To understand them, a multi-messenger approach, as discussed in the project *Cosmic sources in a multi-messenger strategy,* as well as studies of neutrino emission, see *Neutrinos from supernovae,* and gravitational waves, see project *Nature of relativistic gravity,* is needed.

3.4 DRAFT PERSPECTIVE FOR THE SECOND FOUR YEAR PERIOD

The second period of the NCCR Universe will be characterized by the simultaneous exploitation of major facilities in particle and astroparticle physics, as well as progress in the definition of future directions.

The LHC upgrade, towards higher luminosities or higher energies, will have been defined and its implementation will have started. In parallel, the corresponding upgrades of LHC detectors will be constructed. In this important preparatory period for the “second life” of the LHC, Swiss groups from NCCR Universe will play an important role in providing the ground for consolidating new phenomena and study their properties. If the new physics uncovered at the LHC, in precision experiments at PSI or elsewhere will require the construction of specialized experiments, NCCR participants will no doubt be involved in their design and construction.

In parallel to the implementation of the next phase of LHC and its detectors, the plans for large future facilities will be concretized. This concerns linear electron-positron colliders, next generation B factory as well as first generation neutrino factories. In these activities, projects of the first four-year NCCR period provide crucial input.

The second period of the NCCR Universe will also see the simultaneous exploitation of next generation instruments for the X-ray, gamma-ray and cosmic ray observations. The X-ray observatories Astro-H and POLAR will deliver data with unprecedented sensitivity and precision, for the study of violent phenomena. The LOFT X-ray timing mission will be in the final phase of construction. The next-generation Cherenkov Telescope Array will start operation. The experiments in the ISS, AMS-02 and JEM-EUSO will be in their final phase of operation, covering an unprecedented energy range in cosmic ray studies. The neutrino telescope IceCube and its surface array IceTop will collect large multi-year data sets. The Swiss Data Center for Astroparticle Physics will collect all these rich sets of data and make them, available for multi-messenger astronomy, astrophysics and particle physics studies.

Large amount of data produced by the currently operating and next generation cosmic ray, gamma-ray and neutrino detectors will require a new approach to the data management, which will allow quick and efficient data sharing between cosmic ray, neutrino and multiwavelength astronomy communities. We foresee a set up of a dedicated Swiss Data Center for Astroparticle Physics which will have a central role in providing access to all relevant data for different research groups in Switzerland and worldwide. This should allow a full-scale implementation of the multi-messenger approach in high-energy astroparticle physics.

The ESA satellite Euclid is foreseen to be launched in 2019 delivering highest quality data on weak lensing and other tools for the study of dark matter and dark energy, in addition to smaller large scale probes like DES and BOSS. We also might already have some indication on the nature of dark matter, especially if it is a WIMP, from LHC or from direct and indirect detection experiments and pursue the determination of its properties. We may have measured primordial gravitational waves from inflation by CMB polarization experiments like QUIET-II or POLARBEAR. This will be very important to constrain inflationary models. Even a null result until 2018 will be very relevant as it would exclude the simplest single field models of inflation. Furthermore, if Planck has measured non-Gaussianities, the era of exploration very high energy (the scale of inflation may be as high at 10^{16} GeV) physics interactions will start.

In all of these projects, NCCR participants will have first-hand access to data and contribute decisively in making them generally available and interpreting them.

4 RESEARCH PLANS OF INDIVIDUAL PROJECTS

4.1 THE CHALLENGE OF ELEMENTARY CONSTITUENTS AND FORCES

Coordinating authors: G. Iacobucci (UniGe), M. Spira (PSI)

Research question and state of the art
Properties of light quarks and muons are studied using the unique opportunities of the **Swiss national laboratory PSI**, with an excellent international reputation, delivering the world's most intense beams of low-energy pions, muons and ultra-cold neutrons. The flagship particle physics experiments taking place at PSI are searches for the lepton flavor violating decay $\mu \rightarrow e\gamma$ (MEG) and for the CP-violating electric dipole moment of the neutron (nEDM), with important Swiss contributions. Both are unique opportunities to discover physics beyond the SM and complementary to collider experiments. Extensions of these searches are being planned, investigating options for an improved search for the decay $\mu \rightarrow eee$.

Heavy quarks and leptons – b and t quarks and tau leptons – play an important role in the study of ordinary matter. The properties of b and t quarks are studied at **LHC**, where they are abundantly produced. At LHC, proton-proton collisions – today at 7 TeV center-of-mass energy, at twice that energy in the future – are used to produce known and unknown particles and states of matter. The LHC went into operation in 2009 with its four large detectors ALICE, ATLAS, CMS and LHCb. Swiss groups are active since many years in ATLAS (Universities of Bern, Geneva), CMS (ETHZ, PSI, University of Zürich) and LHCb (EPFL, University of Zürich), with important contributions to the design, construction, commissioning and exploitation of the experiments, and with important management and coordination responsibilities. ATLAS and CMS are general-purpose detectors, designed to exploit the full potential of the LHC, while LHCb will take advantage of the high statistics available at the LHC to investigate the subtle differences between hadronic matter and antimatter, using particles composed of b quarks. Top quarks, as studied with ATLAS and CMS, constitute a laboratory in themselves, in that they decay before having a chance to form hadrons, as all other quarks do. Their interaction and decay products thus directly reflect properties of bare quarks. As the heaviest known elementary particles, they show up in the decay chains of many postulated extensions to the SM. Swiss groups are contributing in an important way to the research of top quark properties with ATLAS and CMS, as well as b quark properties with LHCb. The incompatibility between gauge symmetry and massive particles is still one of the mysteries behind the apparent success of the SM. The SM Higgs mechanism should have been eliminated or confirmed before the start of the NCCR.

Research on **neutrinos** and their properties focuses on four main scientific questions: What is the mass of neutrinos? What are the precise values of the leptonic mixing matrix elements? Is there a measurable amount of matter-antimatter symmetry violation in the leptonic sector and can its action be described by a phase in the mixing matrix, as seems to be the case in the quark sector? Is the neutrino its own antiparticle (Majorana type particle) or not (Dirac type particle)?

Swiss researchers participate in the international long baseline neutrino oscillation program in a coordinated fashion. Initially the Bern group was member of OPERA and the ETHZ group of ICARUS, both experiments located at the underground Laboratori Nazionali del Gran Sasso (LNGS) on the CNGS beam from CERN. Meanwhile, the University of Geneva group spearheaded studies of future neutrino facilities, including the HARP experiment at CERN, which led to participation in the K2K and T2K experiments in Japan. The K2K experiment observed first the disappearance of a man-made muon neutrino beam. The Swiss groups have now achieved convergence into two main streams with OPERA and T2K. This focus of Swiss neutrino resources has made most efficient use of investments, and increased the impact and visibility of Switzerland in those experiments.

The GERDA and EXO experiments aim at the detection of the neutrino-less double beta decay in ^{76}Ge and ^{136}Xe, respectively, and hence probe the nature of massive neutrinos (Majorana versus Dirac particle), as well as possible lepton number violation. Both experiments feature a visible participation of the Swiss groups of Zürich and Bern.

Intended contribution to the NCCR

The NCCR Universe will contribute in a major way to the LHC program in Switzerland. It will increase the return on investment for Swiss groups having contributed to the LHC detectors ATLAS, CMS and LHCb by increasing data analysis personnel in Swiss groups and coordinate their effort better. It will increase the visibility of Swiss groups inside and beyond their respective collaborations by helping them to reach critical mass, by means of cooperation with other experimental groups and with theorists in Switzerland. It will coordinate the upgrade contributions of Swiss groups to the LHC detectors. And it will enhance the visibility of Swiss scientists at CERN experiments. (Presently we contribute 9 % to the costs and only 2 % to the authors of publications!). This NCCR will also coordinate the upgrade contributions of Swiss groups to the LHC detectors. And it will enhance the educational program and public awareness of high-energy particle physics by organizing schools, workshops and public events on the subject. The main scientific contributions are described in projects 4.1.3, 4.1.2 and 4.1.5.

The high-energy frontier is complementarily pushed with high precision experiments at low energies at PSI, see projects 4.1.1 and 4.1.9. The NCCR will enable a new generation of experiments on flavor changing neutral current decays of the muon by coordinating development of even more intense beam lines and detector development to cope with the high data rates and supreme experimental resolutions required by these experiments.

As far as neutrino properties are concerned, the Swiss groups will continue the participation in the OPERA and T2K, studying the neutrino mixings and especially also CP violation in the ν sector, and actively prepare the next steps. The results of T2K on ν_e appearance will contribute in guiding the next steps worldwide. The logical next aim will be the search for CP violation in neutrino oscillations and the measurement of the δ_{CP} phase. The measurement method varies with the magnitude of the transition which depends on the last unmeasured angle of the neutrino mixing matrix, θ_{13}; high statistics is always required, implying high intensity beams and very large detectors. The NCCR Universe will help Swiss scientists develop a program with a broad international participation towards the realization of the next generation neutrino experiment, including the large underground observatory, a suitable high intensity beam and the necessary instrumentation and near detectors.

We plan also to consolidate our participation in the GERDA and EXO experiments which will eventually reach a sensitivity of 130 meV for the effective Majorana neutrino mass. They will explore the nearly degenerate mass pattern of neutrinos within the next years using different isotopes and technologies. The two projects will probe the mass range predicted by neutrino oscillation experiments for the case of an inverted neutrino mass hierarchy. The NCCR will enhance Swiss participation in these projects by making additional manpower available. Options to address the next level of sensitivity, requiring one ton of a double-beta emitter and a background level below one count per year and ton, will be studied with a visible contribution from the NCCR.

Our neutrino projects are described in 4.1.6 and 4.1.7

The projects are complemented by an investigation of exotic hadrons 4.1.4 and a project on grand unified theories, GUTS 4.1.8.

4.1.1 PROJECT: ELECTRIC DIPOLE MOMENT OF THE NEUTRON

Coordinators: K. Kirch (PSI and ETHZ), A. Weis (Fribourg)

Research question and state of the art

Some of the most stringent constraints on models of CP violation (CPV) come from the non-observation of electric dipole moments (EDM) of fundamental systems like the neutron, atoms and molecules [3, 4]. An EDM of a spin 1/2 particle would violate both parity and time reversal symmetry and by the CPT theorem also CP. The EDM of the neutron has been searched for since the 1950s with ever improving precision and results still consistent with zero. Already the present upper limit of 2.9×10^{-26} $e$cm at 90 % C.L. [5] poses severe theoretical problems: (i) The so-called 'strong CP-problem' is the fact that no QCD-induced CPV has been found so far, limiting by experiment the so-called θ_s parameter (naturally of order 1) to be smaller than about 10^{-10}. (ii) The so-called 'SUSY CP-problem' describes the fact that simple supersymmetric models with particle masses in the TeV range also already now require a small CPV phase or cancelations between various contributions. More generically, in new physics models the EDM of the neutron can be related to a CPV phase and the typical mass scale of particles involved. With a phase of order 1 the present EDM limit is already sensitive to order 10 TeV masses and future improvements will push this to 100 TeV and beyond.

A yet unknown source of CPV is thought to be required in order to explain the observed baryon asymmetry of the universe. Extensions to the Standard Model of particle physics often lead to observable particle EDM. Clearly, the observation of a finite neutron EDM would be a sensation. Highly interesting is also that its non-observation at two orders of magnitude improved sensitivity can rule out electro-weak baryogenesis in connection with many models, e.g. with the so called Minimal Supersymmetric Standard Model [6].

Improvements in sensitivity for neutron EDM experiments are thus considered to be of high priority and are pursued by several collaborations worldwide. One international collaboration resides at PSI aiming at an improvement of almost two orders of magnitude [7, 8]. It is presently working on a factor 5 improvement and planning for a major next step thereafter in the years 2014 – 2017. PSI has over the past years constructed a new world class facility to produce the highest intensity of ultracold neutrons (UCN) needed for the EDM experiment [9]. This source has been commissioned in

2010/11 and delivered the first UCN to the present neutron EDM effort. The UCN source at PSI constitutes a user facility with two experimental areas and beam time assigned after review by an international physics advisory committee (PAC). The neutron EDM experiment is approved at PSI and continuously monitored by a special PAC subcommittee.

With an experimental apparatus on the floor and the PSI UCN source running, the international neutron EDM collaboration at PSI has an excellent chance to push the precision frontier. The Swiss groups from PSI, University of Fribourg and the ETH Zürich involved in the neutron EDM effort play a crucial role within the international consortium, they have contributed and prepare major contributions for the next analysis and upgrade steps.

Intended contribution of the project

The project here concerns the next phase of the search for the neutron EDM starting 2014. A new ‘n2EDM’ apparatus will be used to improve the sensitivity by another order of magnitude into the region of several $10^{-28}\,e$cm. Specific contributions from the Swiss partners to n2EDM are the UCN guiding system, the active surrounding field compensation system, the passive multi-layer mu-metal magnetic shield, mercury co-magnetometry [10] and multi-sensor optical Cs magnetometry [11]. Especially the issues connected to a magnetically suitable environment are of utmost importance and of greatest interest. The Swiss partners in n2EDM have already secured considerable funding for investments into the experimental hardware like the passive multi-layer shield. The project here is about implementing a magnetometry and shielding knowledge center and assembling a group of sensor and analysis experts with critical mass to guide the technical design effort and to fully exploit the physics data. In particular, the following activities will be pursued within the project: (i) Complete characterization and optimization of a multi-sensor active feed-back stabilization system for the magnetic field surrounding the passive mu-metal shield. (ii) Optimization of the passive multi-layer shield with emphasis on the innermost shielding layer, which is most crucial for the low noise performance of all subsystems inside the shield and for the homogeneity of the magnetic field over the relevant measurement volume. (iii) Implementation and full exploitation of a laser system in n2EDM for pumping and probing of ^{199}Hg used as co-magnetometer. Specific studies on related false effects due to light shift effects, gravitational offsets and geometric phase effects. (iv) Optimization for highest sensitivity and full exploitation of arrays of laser optically pumped Cs magnetometers. Implementation of high precision, absolute magnetic field measurements. Development and characterization of vector magnetometry and studies of fully optical operation of the sensors. (v) Full system analysis of magnetic shielding and magnetic field measurements. Correlation studies of all subsystems and development of counter measures to systematic false effects for the neutron electric dipole moment experiment. (vi) Independent physics analysis group to contribute at all levels to the n2EDM analysis. This affects service work like the preparation of raw magnetometry data for the collaboration to a stand-alone blind neutron analysis. (vii) A systematic theoretical analysis of the reach of the neutron EDM experiment with respect to physics beyond the Standard Model will be aimed at. Cooperation of experimental and theoretical physicists will allow to investigate possible side-tracks and spin-offs in the physics analysis. The collaboration has already in the past performed first measurements limiting neutron – mirror-neutron oscillations [12, 13], limiting Lorentz violation effects [14, 15] and searching for anomalous spin gravity couplings [14]. The experiment will also be sensitive to new short range interactions and check on models of extra-dimensions [16]. With improved precision, these and potentially other well motivated exotic physics searches can be pursued, complementary to other efforts at low and high energies.

Links to other projects of this NCCR

The participating Swiss partners of the neutron EDM collaboration will integrate their project-oriented manpower into the NCCR. The senior scientists (2 from Fribourg, 5 from PSI, 1 from ETHZ) will be associate members of the NCCR. Besides the manpower from the NCCR, about 3 Postdocs and 3 PhD students will be contributing. Progress and results of the EDM project will be reported in NCCR meetings, at the annual Swiss Physical Society meeting, and at international conferences. In cooperation with other high precision and intensity oriented projects of the NCCR, the EDM project will organize workshops on precision physics and work on establishing aspects of complementarity between high energy and precision also in the particle physics outreach and education. The project will establish cross links within the NCCR and connections to the outside, especially trying to set up a dialogue with particle theory to map the reach of the neutron EDM experiment in particular and low energy precision experiments in general. With the example of the neutron EDM we will investigate options for other high precision experiments with UCN making use of the unique Swiss UCN facility at PSI. The project will also work on increasing the awareness concerning novel, strictly non-magnetic materials and their machining, magnetic field measurement capabilities and magnetic shielding. We will analyze the potential to transfer aspects of the related know-how to other partners in the NCCR and to industry.

4.1.2 PROJECT: SEARCHES FOR NEW PHYSICS USING BOTTOM HADRONS

Coordinators: O. Schneider (EPFL), U. Straumann (UniZH)

Research question and state of the art

One of the outstanding scientific challenges of particle physics is the understanding of the origin of the matter-antimatter asymmetry in the Universe. So far, all measurements of CP violation are compatible with a single source of asymmetry arising from the irreducible complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix between the three known generations of quarks. However, this Standard Model (SM) explanation is quantitatively insufficient to account for the baryonic asymmetry of the Universe, calling for new sources of CP violation. These may well exist in the lepton sector or an extended gauge sector. However, with the copious production of charm and bottom hadrons available at the LHC or planned at super-flavour factories, the quark sector will remain, for at least the next decade, the best place to look for non-standard CP violation effects.

More generally, flavour observables are sensitive to physics beyond the SM, with or without new sources of CP violation. Indeed yet unknown particles may affect the decay properties of charm and bottom hadrons through quantum corrections. This is expected to be more easily visible in flavour-changing neutral current (FCNC) transitions, which are suppressed in the SM. Indirect searches for new physics consists of measuring such transitions and comparing them with the SM predictions, in contract to direct searches aiming at the observation of new particles produced at energy-frontier colliders. Both approaches are complementary: while the indirect approach is sensitive to higher energy scales and may thus sense a new effect earlier, a direct observation can establish the discovery and main properties of a new particle. A tantalizing possibility would be the discovery of new particles constituting the dark matter of the Universe.

During the last decade, heavy flavour physics has been dominated by e^+e^- colliders operating just above the open beauty threshold. Together, the BaBar experiment at PEP-II (SLAC, USA) and the Belle experiment at KEKB (KEK, Japan) recorded more than 1.24 billion $\Upsilon(4S) \rightarrow B\bar{B}$ events in the period 2000–2008. While the final data analysis is still ongoing, important breakthroughs are no longer expected. All measurements appear to be consistent with the SM: some interesting hints for New Physics have appeared along the road, but their significances diminished with time. Global fits [17] of flavour and CP-violation results show overall consistency within the SM, although some tension exists (at the level of 2.6σ) between the measurements of the $B^+ \rightarrow \tau^+ \nu_\tau$ branching fraction and those of mixing-induced CP-violation in B^0 decays governed by $b \rightarrow c\bar{c}s$ transitions [18]. Some measurements still have large statistical errors. A striking example is that of the angle γ, the least well measured angle of the CKM unitarity triangle. The current uncertainty obtained from the combination of all direct γ measurements is approximately 14 degrees [18]. A substantial reduction is very desirable as it would allow to test more deeply the consistency of the Kobayashi-Maskawa picture of CP violation.

While a number of B^0_S physics results have been obtained by Belle using data collected at the $\Upsilon(5S)$ resonance, the most interesting B^0_S measurements were pioneered at high-energy hadron colliders, where larger statistics and better decay time resolution are available. The operation of the $p\bar{p}$ Tevatron collider (USA) at $\sqrt{s}$ = 2 TeV came to an end in September 2011, after the CDF and DØ experiments each collected a data sample of ~10 fb^{-1}; some B physics analyses still use only half of it, so improved results are expected in the near future. On the other hand, the LHC experiments, in particular LHCb which has collected 1.2 fb^{-1} of data at $\sqrt{s} = 7$ TeV in 2011, are now overtaking the Tevatron experiments. More generally the full heavy flavour physics programme at LHC is now being deployed, with LHCb taking the lead for the next several years.

The next-generation experiments dedicated to flavour physics are being planned at two new B factories with design luminosities in the range $(0.8-1) \times 10^{36} \text{cm}^{-2}\text{s}^{-1}$ [19]: SuperKEKB [20], an upgraded version of KEKB scheduled to be commissioned starting in 2015, and SuperB [21] to be built from scratch in Italy.

Intended contribution of the project

We propose to searches for New Physics, and possibly characterize its nature, through new and high-statistics measurements of b-hadron decays. This will be done by analyzing the data collected by the LHC experiments. The most significant contributions are expected from LHCb, and will be obtained under the responsibility of the Swiss research groups involved in LHCb, at the University of Zurich and at the Swiss Institute of Technology of Lausanne (EPFL). The ATLAS and CMS experiments can contribute to a restricted number of topics, as shown by the PSI group in CMS. All Swiss groups interested in B physics are heavily involved in their experiments since many years and have acquired significant experience in data analysis, having for example directly contributed to the first physics results with $B^0_S \rightarrow \mu^+\mu^-$ [22, 23, 24] and $B^0_S \rightarrow J/\psi\phi$ [25] decays.

The LHCb experiment recently placed itself at the forefront of beauty physics, where virgin territory can be explored for many years with a large number of decay channels. During the first phase of LHCb, defined as the data-taking period with the present detector configuration until the start of the upgrade shutdown currently foreseen in 2018, an expected total integrated luminosity in the range 6 – 10 fb^{-1} will be collected. This unprecedented statistics will be sufficient to either find or exclude large deviations from the SM predictions. As part of this NCCR we plan to continue or launch efforts on a number of fronts which may include

- the search for the very rare decay $B_S^0 \rightarrow \mu^+\mu^-$, with a sufficient sensitivity to observe any signal with a branching fraction larger than the SM prediction of $(3.2 \pm 0.2) \times 10^{-9}$ [26],
- the measurement of the CP-violating phase ϕ_s in B_S^0 decays involving a $b \rightarrow c\bar{c}s$ transition, with a statistical precision comparable to the central value of the SM expectation of -0.0363 ± 0.0017 [17],
- measurements of branching fractions and CP asymmetries in not well known or yet unobserved charmless *b*-hadron decays involving FCNC transitions,
- a measurement of the CKM angle γ, e.g. with $B_S^0 \rightarrow D_S^{\mp} K^{\pm}$, with a combined precision of a few degrees.

In parallel, the LHCb experiment will be upgraded [27] such as to be able to collect, starting in 2019, an integrated luminosity of ~ 5 fb^{-1}/year with a more flexible and efficient software-based trigger. The upgrade involves a full detector readout at 40 MHz, new front-end electronics, as well as the replacement of some subdetectors needed to cope with the increased occupancy. The Swiss groups will design and build new tracking stations. The upgraded detector will bring the experiment to the next level of precision, uniquely equipped to fully exploit the flavour physics potential of the LHC. In case of direct discoveries by ATLAS and CMS of new signals beyond the SM, the role of the upgraded LHCb experiment will be to understand which is the correct theoretical model describing the new phenomena and measure its parameters. In the opposite scenario, LHCb may still be able to provide evidence for New Physics beyond the limit for direct production.

Links to other projects of this NCCR

The most exciting contribution to this NCCR would be the indirect discovery of new phenomena in the mixing or decay of bottom hadrons, correlated with a direct observation of new particles at the LHC, and explained by a theoretical extension of the SM incorporating dark matter candidates. In the worst scenario where no new effects are seen, this project will provide severe constraints on new models, including those with cosmological consequences. In all cases, obtaining these results, reaching firm scientific conclusions from them, and communicating them to the public will need significant efforts from both the experimental and theoretical sides.

This NCCR will provide an ideal framework for such efforts to be developed and coordinated at three different levels: between the experimental groups at LHC working on *B* physics, between these groups and the theorists using the *B* physics results as contraints in the models, and finally more widely together with cosmologists.

4.1.3 PROJECT: SEARCHES FOR NEW PHYSICS USING THE TOP QUARK

Coordinators: G. Iacobucci (UniGe), R. Wallny (ETHZ), M. Weber (UniBe).

Research question and state of the art

One of the expected signatures of new physics at the LHC is the abundant presence of heavy Standard Model (SM) particles in the final state. The top quark, in particular, is very often part of the decay chain of such new particles in numerous extensions of the SM and therefore its accurate reconstruction is an essential tool in searches for new physics.

The top quark was discovered in 1995 at the Tevatron [28, 29], after many years of searching. At the LHC, SM $t\bar{t}$ pairs are produced through the strong interaction with about 85 % of events coming from the fusion of two gluons from the colliding protons. Due to its high mass of 173.2 ± 0.9 GeV/c^2 [30], it has an extremely short life-time. Therefore its electroweak decay occurs on timescales shorter than that of the strong interaction, with the consequence that the top quark decays before it hadronizes. The only observed decay of the top quark is the weak decay to a b-quark and a W-boson. The identification of the two b-quarks in the final state plays a vital role in top physics since much of the other SM backgrounds do not contain heavy-flavour particles. In addition, the two W-bosons decays, either leptonic or hadronic, characterize $t\bar{t}$ event topologies further. Searches for new physics using top quarks have been performed at the Tevatron and the first LHC results are being published.

Most of the current BSM theories predict new particles just above the electroweak scale, of the order of one to a few TeV, and thus within the reach of the LHC. Due to its anomalously high mass, the top quark plays a special role in searching for new physics in a number of BSM models [31], in particular those with alternative methods of electroweak symmetry breaking (EWSB). Examples of such models include dynamical EWSB that could be caused by a new strongly interacting sector [32, 33, 34], and seesaw mechanisms of quark condensation [35]. Some flavours of technicolor [36, 37, 38] predict a special role for the top quark. Models that incorporate gravity will generally produce enhanced couplings of the mediators of gravity to top quarks, in particular extra dimension models where the gravitons can propagate through to the extra dimensions [39, 40, 41, 42]; if the extra dimensions are small, this could explain the mystery of the large mass hierarchy observed between particles.

Many of these models predict new resonances or gauge bosons that are strongly coupled to the top quark or produce particles that decay to top quarks. Examples of the first category are Z’ bosons [43, 44] as well as the previously mentioned gravitons in extra dimension models. The second category includes the supersymmetric (SUSY) partner of the top quark ($\tilde{t}$ or stop) [45, 46], a vector-like T, sometimes referred to as $\tilde{t}$’, predicted in a number of Little Higgs theories [47, 48], top partners $T_{5/3}$ with electric charge 5/3 predicted in models where the Higgs is a pseudo-Goldstone boson [49], or fourth generation t' quarks [50, 51].

Intended contribution of the project

SUSY and the 3rd generation: Searches for SUSY are vigorously pursued at the current LHC run at 7 TeV. In the simplest SUSY scenario, low mass squarks and gluinos are pair-produced and decay in spectacular cascade decay chains including the production of several jets, leptons and missing transverse energy from the lightest supersymmetric particle (LSP). It is however conceivable that SUSY manifests itself at a higher energy scale than targeted with these “early” LHC SUSY searches.

The third generation would be especially important for such a scenario as the lightest squark initiating such a decay chain is expected to be one mass eigenstate of the left and right handed stop quarks. This is due to the large SM top quark mass and the resulting large mass splitting in the stop quark sector, particularly in high tan β scenarios of the Minimal Supersymmetric Standard Model (MSSM). In the main part of the mass range allowed for stop quarks, stop quarks would decay primarily to a top quark and a neutralino, $\tilde{t} \to t\tilde{\chi}_2^0$, giving rise to a top quark and large missing transverse energy and possibly further leptons from the $\tilde{\chi}_2^0$-decay to the lightest supersymmetric particle. In the direct production process stop quarks will look very much like top quarks in terms of the final state but have different kinematics due to e.g. their different spins.

These 3rd generation SUSY searches will therefore be important for the 14 TeV run of the LHC, which will take place during the timescale of this NCCR. Due to the similarity of the signal and the background, these searches will have to employ sophisticated multivariate analysis techniques, such as boosted decision trees, neural nets and matrix element methods. Establishing such analyses techniques and commissioning them on data is therefore a major contribution to this NCCR project. Pinning down the SM background, in particular $t\bar{t}+X$ production where X could produce significant missing transverse energy (such as $Z \to \nu\nu$) will be particularly important for these searches as well. Another milestone for this NCCR project would therefore be the measurement of SM $t\bar{t}+Z$ production. The $t\bar{t}+X$ topology is furthermore important for establishing the existence of the SM Higgs boson in the top quark associated production mode, $t\bar{t}+H$ (see section 4.1.5). Researchers participating in this NCCR are already deeply involved in current inclusive SUSY searches and are well poised to tackle the search for SUSY at higher mass scales using top quarks in the final state.

Boosted top quarks: Boosted-top production[3] is considered to be among the most powerful probes for discovery of new physics at the LHC. Numerous extensions to the Standard Model predict massive particles whose couplings to top quarks are enhanced, which implies that decays to top-quark pairs are favored [39, 40, 41, 42, 52, 53, 54, 55, 56, 57]. One example is the production of *Z’* bosons. Due to constraints from experiments at the LHC and at earlier colliders, the postulated BSM particles must be considerably more massive than top quarks. Therefore, top quarks produced in the decay of such resonances would be emitted with very high momenta, i.e. the top quarks will be highly boosted. The researchers of this NCCR plan to be involved in searching for resonant production of top quark pairs from a new particle and for heavy new particles that have signatures similar to $t\bar{t}$ or that decay to top quarks and other particles.

Boosted-top identification constitute a challenge with respect to the reconstruction of the events. For boosted systems it might not be possible to resolve all of the particles, since they would appear in the detectors as a collimated jet-like structure (*“fat jets”*). In order to not lose acceptance, algorithms are being developed to enable the reconstruction of the decay products of the top quark into a single large radius jet. Although the limits obtained so far using boosted systems [58, 59] are slightly lower than for the traditional $t\bar{t}$ resonance search, the gain will become very significant at higher invariant masses. The researchers of this NCCR are deeply involved in this program, in both the ATLAS and CMS collaborations. The NCCR will allow acquisition of a leading role in this field within the international community.

Links to other projects in this NCCR

The search for new particles and physics phenomena is a motivation to other projects in the challenge of constituents and forces of this NCCR. By combining the information from different projects we can gain a more complete picture of possibly discovered new physics. As an example, an indirect signal of new physics from a non-vanishing neutron EDM would have to be confirmed by the direct search from this

[3] Boost here refers to the Lorentz boost due to the top quark being produced not at rest in the lab frame.

project. The relation to the EWSB and Higgs project is very close, as has been pointed out above, due to the massive coupling of the top quark to the Higgs and also for the exploration of EWSB theories proposing new particles as searched for in this project. The discovery of SUSY would be an important step also towards GUT models.

This project also links to the Dark Energy and Dark Matter challenge of this NCCR. Indeed, a lightest supersymmetric particle in R-parity conserving SUSY, which is being searched for at the LHC, is a candidate for dark matter in the universe.

4.1.4 PROJECT: EXOTIC HADRONS, HADRON-IN-MEDIUM PROPERTIES, AND (EXOTIC) HADRONIC MATTER

Coordinator: B. Krusche (UniBs)

Research question and state of the art
Although according to present knowledge our universe is composed of ≈ 4 % baryonic matter, ≈ 26 % Dark Matter and ≈ 70 % Dark Energy, so far only baryonic matter has been directly observed. An understanding of the development and structure of the Universe is impossible without a detailed knowledge of the properties of hadrons – strongly interacting particles – also under extreme conditions as they can be found in very hot or very dense environments like for example in the early universe or in neutron stars.

The project concentrates on the search for "exotic" types of hadrons which are not made of quark-antiquark pairs (mesons) or three quarks (baryons), on the modification of hadron properties in nuclear matter, and on the properties of exotic types of matter such as mesic nuclei. It is currently based on electron accelerators (MAMI in Mainz, 1.5 GeV and ELSA in Bonn, 3.5 GeV) with state-of-the-art detector systems. Together with Jlab in the United states these are the world-wide leading facilities in this field. In the near future, the upcoming PANDA detector at the HESR antiproton-ring of the new FAIR facility in Darmstadt, Germany, will open exciting new opportunities for this project.

Quantum Chromodynamics (QCD) allows in principle the existence of many types of hadrons, which must only fulfill the condition of being colorless objects. However, so far only mesons and baryons have been observed in experiments. Other types like di-baryons (six-quark systems), penta-quarks ($qqqq\bar{q}$), glueballs, hybrids of mesons and glueballs, and objects called 'strangelets', which involve a similar numbers of up, down, and strange quarks [60], have been discussed, but for none of them conclusive experimental evidence has yet been reported.

A few years ago, several experiments (see e.g. [61, 62, 63, 64, 65]), claimed the observation of a very narrow state assigned to a manifestly exotic ($uudd\bar{s}$) member of the predicted anti-decuplet of pentaquark states [66] termed Θ^+. However, follow-up experiments, partly done by the same groups (see e.g. results from the CLAS collaboration [67]) could not confirm this finding. A very recent somewhat different analysis [68] of the same CLAS data again claims a signal. Therefore, the situation is still not completely settled, although there is certainly no generally accepted evidence for the Θ^+. During the excitation created by the early pentaquark- search results, also predictions for the properties of another member of the anti-decuplet, the non-strange P_{11}-like state were made (see e.g. [69, 70]), in particular, that if existing it should show up in the reaction $\gamma n \rightarrow nn$.

Surprisingly, all experiments that looked at this reaction in the relevant energy range (GRAAL/Grenoble [71], CBESLA/Bonn [72, 73], LNS/Sendai [74], Crystal Ball@MAMI [75]) observed a prominent, unusually narrow structure ($\Gamma < 50$ MeV) around $\sqrt{s} \approx 1.68$ GeV. Due to the lack of photoproduction data off the neutron, it had been previously overlooked. The nature of this structure is not yet understood. Apart from a relation to exotic hadrons, other explanations like intricate interference and/or cusp effects are under discussion. One should, however, note that for photoproduction reactions in this energy range the structure is quite a unique feature. Currently, programs are active at the MAMI and ELSA accelerators to investigate it with polarized photon beams and polarized targets in order to collect information about the relevant partial waves.

The generation of the mass of hadrons is a central problem in the theory of strong interactions, closely related to the spontaneous breaking of chiral symmetry. However, for hadrons embedded in nuclear matter theory predicts at least a partial restoration of chiral symmetry. Such questions are partly investigated with ultra-relativistic heavy ion beams, but also in the range of normal nuclear matter densities signatures should show up and are then more easily interpreted than in the complicated environments of heavy ion reactions. This type of experiments form a significant part of the photon-induced research program at ELSA and MAMI and in future also for the antiproton induced reactions at PANDA.

Intended contribution of the project

The further investigation of the hadron spectrum, in particular the $c\bar{c}$ system, glueballs and hybrids will largely profit from the upcoming Proton-Antiproton facility with the PANDA detector at FAIR in Darmstadt, which is the leading international project in this field.

For the in-medium properties of hadrons we mention few examples. There is a long, controversial discussion in the literature, whether it is possible to form (quasi)bound states of mesons and nuclei via the strong interaction. This would be a new type of hadronic matter and could serve for detailed studies of the meson-nucleus interactions for short lieved mesons. The so far best studied examples are for the n-meson. Experiments at the MAMI accelerator have shown an extremely strong enhancement of the cross section at the (coherent) n-production threshold from ^{3}He nuclei [76, 77], indicating a resonant-like behavior. These findings are in line with hadron induced reactions, which have also observed strong threshold effects [78, 79]. Further experiments are planned for the ^{4}He nucleus, using coherent photoproduction of $\pi^0 n$ pairs (because coherent production of single n mesons is forbidden on spin- and isospin-zero nuclei). Another example is the in-medium behavior of the σ-meson which is the chiral partner of the pion and if chiral symmetry were respected, should be degenerate in mass with it. In vacuum, the σ is much heavier, but already for normal nuclear matter models predict a significant reduction of its mass [80]. Since the main decay channel of the σ-meson is to pion pairs, such a signal can be searched for in the invariant mass spectra of pion pairs produced in nuclei [81, 82]. The interpretation of the results requires a careful investigation of final state interaction effects of the pions [83].

Links to other projects of this NCCR

The properties of nuclear matter and its equation of state (EoS), also under extreme conditions, are important for many astrophysical phenomena. We shortly discuss two examples, the proton fraction in supernovae formation and neutron stars and the strangeness contribution to the EoS, which are relevant for the supernova evolutions studied by the Basel theory group [84].

Neutron stars are created with high temperatures and then cool by neutrino emission, mainly by the modified URCA reaction $n+n \rightarrow n+p+e^{-}+\bar{\nu}_e$. Faster cooling processes are provided by the direct URCA mechanism $n \rightarrow p+e^{-}+\bar{\nu}_e$ followed by electron capture $e^{-}+p \rightarrow n+\nu_e$. The probability of this reaction chain is very sensitive to the symmetry energy of nuclear matter under extreme conditions. The relevant properties of the nuclear force [85] can be constrained by the measurement of the 'neutron skin' of heavy nuclei such as ^{208}Pb. A large experimental program for this is under way at Jlab, using parity violating electron scattering. An alternative approach to study nuclear mass distributions via the coherent photoproduction of π^0-mesons has been developed by our group at the MAMI accelerator [86] and will be further explored.

The future PANDA experiment at FAIR will much contribute to the investigation of nuclei with strange baryons (hyperons). The program includes studies of hypernuclei and in particular also of strange-double hypernuclei. The strangeness degree of freedom is expected to soften the EoS with respect to a purely nucleonic EoS and thus would limit the maximum mass/radius of neutron stars. The observation of a neutron star with two times the solar mass [87] therefore puts limits on the behavior of the EoS and seems to disfavor hyperon contributions unless effects like the three-body repulsion known for conventional nuclear systems or effects from the strong interaction coupling constant and/or color superconductivity provide an additional stiffening.

The concept of stable strange matter ('strangelets') has been much discussed and would have significant impact on astrophysical questions. The recently launched Alpha Magnetic Spectrometer (AMS) has the capability of direct searches for such particles. However, so far not much is known for the elementary interaction of particles with strangeness, which is at the root of this concept. Here, the investigation of double-strange hypernuclei with PANDA will for the first time allow to study directly the $\Lambda\Lambda$-interaction in nuclear matter.

4.1.5 PROJECT: ELECTROWEAK SYMMETRY BREAKING

Coordinators: G. Dissertori (ETHZ), M. Grazzini (UniZh)

Research question and state of the art

The Standard Model (SM) of particle physics is a $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory that describes the strong and electroweak interactions of the known subatomic particles at an impressive level of accuracy. The validity of the SM has been established during the last 30 years. The experimental facilities that played a major role in validating the model are SPS at CERN, where the W and Z bosons were first observed, HERA at DESY, where the proton structure was studied in detail, LEP and SLC, where accurate tests of the SM where performed, the Fermilab Tevatron, where the top quark was discovered, and finally the LHC, where the SM is tested at unprecedented energy scales.

Despite its success, the SM has some well known problems. In particular the mechanism that gives masses to the particles remains to be understood. Gauge boson mass terms are forbidden because they violate gauge invariance. Moreover, contrary to what happens in vector theories like QED and QCD, also fermion mass terms are not allowed: the $SU(2) \times U(1)$ electroweak sector is in fact a *chiral* theory: left and right handed fermions couple differently to the gauge group. The solution to this problem is provided by the concept of Spontaneous Symmetry Breaking (SSB). Through SSB the Lagrangian remains gauge invariant, but the gauge symmetry is not respected in the spectrum of the physical states.

There are several possibilities to realize SSB: the standard one, which is implemented in the minimal version of the SM is to introduce a complex scalar $SU(2)$ doublet endowed with a symmetry breaking potential. Three out of the four degrees of freedom go to give mass to the W and Z bosons, leaving the photon massless, and the fourth remains present in the spectrum, the so-called Higgs boson [88, 89, 90]. More involved models imply the existence of more than one Higgs doublet, such that more than one Higgs boson exists in the spectrum. It is clear that, since such Higgs boson(s) play a central role in giving masses to the elementary particles, their experimental search is one of the most important tasks of modern high energy particle physics.

It is important to note that SSB does not necessary imply the existence of Higgs boson(s). Besides direct tests of the SSB sector through Higgs searches, there are other processes that are directly sensitive to the breaking of the electroweak symmetry. If the Higgs boson does not exist, vector boson pair production violates the unitarity constraint at high energies, and thus some new physics effect must play a role to restore unitarity of the corresponding high energy scattering amplitudes.

Even if the Higgs boson is not observed, if it exists it must manifest itself in loop corrections. In particular, it will affect the self energies of the W and Z bosons, and thus precision electroweak data provide indirect information on the Higgs mass, as has happened in the past for the top quark. As a consequence, a precise knowledge of the electroweak parameters (such as gauge boson masses M_W, M_Z, top-quark mass M_t, Weinberg angle θ_w) can be used to constrain the Higgs mass. The top mass appears quadratically in the one-loop radiative contributions. For this reason the top mass was predicted with good precision before its discovery. Unfortunately the Higgs mass enters only logarithmically at one-loop order, and it is difficult to obtain stringent constraints.

The present electroweak data suggest that the Higgs boson should be light ($M_H \lesssim 200$ GeV).

Up to now the Higgs boson has not yet been observed. LEP experiments have put a lower limit to the Higgs mass at $M_H > 114.4$ GeV [91]. Tevatron experiments recently excluded the SM Higgs in the mass region $156 < M_H < 177$ GeV and $M_H < 108$ GeV [92]. Higgs searches are now being carried out by the ATLAS and CMS experiments at the LHC. Very recently, these efforts have entered a crucial phase and reached first important milestones. Thanks to the high-luminosity LHC running in 2011, the ATLAS and CMS collaborations were able to present important progress from their analyses of many Higgs production and decay channels [93, 94]. Currently, the main conclusion is that the SM Higgs boson, if it exists, is most likely to have a mass constrained to the range 116 to 130 GeV by the ATLAS experiment, and 115 to 127 GeV by CMS. An intriguing excess of events in this mass region has been found by both experiments. However, with the available statistics this excess is compatible with both hypotheses, namely the existence as well as non-existence of a SM Higgs boson. Additional data, to be collected in 2012 before the long LHC shutdown in 2013 and 2014, should allow to obtain firm conclusions on this all-important question.

Intended contribution of the project

Under the assumption that there is indeed (at least one) Higgs boson with mass in the 115 to 130 GeV region, a central focus point of the future LHC activities, in particular during the high-energy (13 to 14 TeV) and high-luminosity running after the long shutdown in 2013/2014, will be the in-depth study of the properties of this boson. These studies will comprise observations and cross section measurements in as many channels as possible, in an attempt to obtain first determinations of Higgs coupling constants to fermions and vector bosons (or at least ratios of a set of branching ratios). The cross section and branching ratio measurements are important steps towards establishing if the observed new state corresponds to what is expected for a SM Higgs boson or not. An important element of the efforts will be to observe the Higgs boson also in the $t\bar{t}H$ channel. This is interesting since the top-Higgs Yukawa coupling might play a central role in the understanding of electroweak symmetry breaking. However, it constitutes a real challenge because of the large and complicated backgrounds to be controlled in this channel. It is clear that this activity will considerably profit from the synergy with another project of this NCCR (Top Quark Physics, cf. Sec. 4.1.3).

On the other hand, if it turns out that the LHC completely rules out the mass range still allowed for a SM Higgs boson, the focus will shift to the preparations of the experimentally even more challenging study of vector boson scattering, which requires both highest possible centre-of-mass energy and luminosity (hundreds of inverse femtobarns). Because of the required tagging of forward jets, the very forward regions of the LHC detectors will get more and more attention, and the envisaged upgrade activities, in particular for the Phase 2 upgrades, will change part of their focus to this area.

Links to other projects of this NCCR

Researchers involved in this NCCR are expected to make substantial contributions, both in terms of preparing and executing the data analysis, towards a precise mapping of the properties of an assumed light Higgs boson. Considerable synergy can be exploited with another projects of this NCCR, on Top Quark Physics, as well as in general among the experimental and theoretical particle physics groups in Switzerland. For both areas we are in the fortunate position to have many world-leading experts among us, thus a yet closer collaboration fostered by this NCCR will allow them to have an even stronger impact. Indeed, the theoretical physicists contributing to this NCCR will play a crucial role in providing state-of-the art, high precision predictions of signal and background processes, implemented in modern and efficient computational tools, then used by the experimental groups to optimize their analysis strategies.

In the scenario of an exclusion of a SM Higgs boson by the end of 2012, the researchers of this NCCR are expected to contribute to two research lines: (a) further extensions and improvements of the existing search analyses, towards probing of smaller than expected Higgs production cross sections and/or non-standard decay mechanisms; (b) start a concerted effort towards the preparation and execution of the necessary long-term plans for measuring vector-boson scattering, including the possible upgrades and improvements of the very forward LHC detector regions.

4.1.6 PROJECT: NEUTRINO OSCILLATIONS

Coordinators: A. Blondel (UniGe), A. Ereditato (UniBe), M. Shaposhnikov (EPFL)

Research question and state of the art

The physics of neutrino oscillations [95][96] can be separated in two classes: i) the study of transitions between the three known active left-handed neutrinos; ii) the search for departure from this minimal scenario that could point to the existence of sterile right-handed neutrinos [97] and to other unexpected phenomena.

The neutrino oscillation between the three known active neutrinos depends on three mixing angles θ_{12}, θ_{13} and θ_{23}, a phase δ, and two differences in squared masses $\Delta m^2_{21} = m^2_2 - m^2_1$ and $\Delta m^2_{32} = m^2_3 - m^2_2$, where m_1, m_2, m_3 are the masses of the mass eigenstate neutrinos. The present status of can be found in [98, 99]. While the sign of Δm^2_{21} is determined to be positive from matter effects in the sun, the sign of Δm^2_{32} is unknown: it is not clear yet whether 'normal' or 'inverted' hierarchy of neutrino masses is realized in Nature. The phase δ is presently unknown; if it were different from 0 CP violation would occur in neutrino oscillations.

The best estimate of the value of the third mixing angle θ_{13} was until recently consistent with zero. In 2011 a substantial step was achieved: T2K [100], first, then MINOS [101], both in the $\nu_\mu \rightarrow \nu_e$ appearance channel, and the nuclear reactor Double Chooz experiment [102] reported indications consistent with a large value of $\sin^2 (2\theta_{13}) \simeq 0.080 \pm 0.025$. The value of this angle governs the ability to measure the sign of Δm^2_{32} and to observe a possible signature of CP violation from the complex phase δ.

Among the unexpected observations, the recent measurement of time-of-flight of neutrinos in the OPERA experiment [103], which seems to be shorter than expected. If this were confirmed, the fact that neutrinos travel faster than the speed of light would be of earth-shattering importance. The measurement will be verified by OPERA itself, but it could also by tested by the MINOS and T2K long baseline experiments. More data will be available in 2012 also from other experiments at the Gran Sasso laboratory.

Intended contribution of the project

The main objectives of the neutrino oscillations program are:

1. To confirm the large value of θ_{13} by acquiring more statistics on T2K. At present an exposure of 150 kW.10^7 seconds has been accumulated and the experiment is restarting with an ultimate aim of 5x 750 kW.10^7 seconds thus a multiplication by a factor 25 of the integrated exposure, and should allow a determination of θ_{13} with a precision of better than ±0.01.
2. To complete precise measurements of mixing parameters, with a precision similar to those of the quark mixing matrix; a first measurement of the atmospheric neutrino parameters was recently produced by T2K [104] by study of the $\nu_\mu \rightarrow \nu_\mu$ disappearance.
3. The search for sterile neutrinos in the accessible parameter range and for unexpected phenomena will continue. This will require close collaboration between theorists and experimenters and excellent understanding of the systematics on fluxes and cross-sections.

Improvement of the T2K measurements will constitute the core of the common experimental activity of the Swiss groups for the next ~5 years. This will involve continuation of ongoing activities. The swiss groups lead the measurement of particle production in the T2K target at CERN in the NA61/SHINE experiment [105][106][107]. Studies of cross-sections and systematic errors will be performed in the T2K near detector. The Swiss groups have contributed the T2K ND280 near detector magnet delivery, magnetic measurements and commissioning, the TPC modules construction and tests, and have presently leading role in the cross-section measurements. In addition to this ongoing program, the Swiss researchers will study the possible extension of the program to allow the determination of the neutrino mass hierarchy and search for leptonic CP violation. This has been the object of considerable study [108], [109], [110]; [111]; [112], and will undoubtedly require new facilities with improved beams and detectors. There are several aspects to this; 1) phenomenological and simulation studies of various scenarios of oscillation facilities, including beams and baselines, near and far detectors and ancillary measurements; 2) studies of new long baseline neutrino beams (this is described in more detail in subsection 4.3.3); 3) a vibrant program of detector R&D to establish the feasibility and performance of the desired detector systems.

All three Swiss experimental groups of Bern, ETHZ and Geneva are involved in the LAGUNA-LBNO FP7 design study started in September 2011 for three years, with ETHZ as leading house of the project. The outcome will be the design of a long baseline neutrino experiment including a far detector site, a near detector complex and a neutrino beam design, building on studies in EUROnu and for CNGS. CERN is one of the main partners. The present priority of the LAGUNA-LBNO consortium is the design of a beam driven by the CERN SPS, aimed at a far detector site situated at 2300 km in the Pyhasalami mine in Finland. At that distance, and for values of $\sin^2(2\theta_{13}) \geq 0.05$, a determination of the mass hierarchy of neutrinos can be made with a fine grain detector of moderate mass (10 kton) with the available SPS intensities in 5 years [113]. This distance is also consistent with an extension to a more powerful beam from a new high power proton accelerator at CERN, or from a Neutrino Factory based on a muon storage ring. This program is complementary to the Japanese proposal T2HK[114] which is primarily sensitive to the CP violation.

The work program for the next few years will consist of:

- continuing the developments towards very large Liquid Argon detectors, with innovative methods of readout, intermediate steps including a 5m drift prototype, large prototype exposure to test beam for study of e/π^0 separation, and design of multi-kton detectors.
- study of the near detector station and of the solid scintillator detector options, including the large Magnetized Iron Detector (MIND) appropriate as Neutral Current detector or as muon spectrometer, and on a longer time scale for a neutrino factory detector.
- study of possibilities to use the same beam for sterile neutrino searches.

The NCCR will strongly support this detector R&D. By the end of the first four years of the NCCR, these studies should have led to the a large scale proposal to CERN.

Links to other projects of this NCCR

The discovery that neutrinos have mass is arguably one of the most significant steps in particle physics, and the first indication of physics beyond the Standard Model established in the 70s. The scheme for generation of neutrino masses is not unique and could lead to the solution of a number of pending problems in our understanding of the Universe. Sterile neutrinos with masses ranging from hundreds of MeV to the GUT scale could lead to an explanation of the matter-antimatter asymmetry of the universe by leptogenesis for which leptonic CP violation and fermion number violation are essential ingredients. Sterile neutrinos could also constitute a significant or all of the dark matter of the Universe [97], [115]. Neutrino oscillations experiments address directly the issues of the mass spectrum of neutrinos, of the mixing angles, of the Matter-antimatter asymmetry, and via sterile neutrino searches within the accessible range, the question of neutrino mass generation.

The experimental program is challenging, requiring new, large infrastructures and technologies. The Swiss groups have established a remarkable level of international leadership and initiative in this program, in the T2K and NA61 experiments, the OPERA experiment, the MICE and LAGUNA-LBNO projects. The Swiss groups have achieved a high level of integration and complementariness with each other. Neutrino oscillation physics will be one of the highlights of the scientific life and output of the NCCR.

4.1.7 PROJECT: NEUTRINO-LESS DOUBLE BETA DECAY

Coordinators: L. Baudis (UniZh),
R. Gornea (UniBe)

Research question and state of the art

During the last decades, neutrino oscillation experiments using solar, reactor, atmospheric and accelerator neutrinos have established that neutrinos being produced as a certain flavor eigenstate can be detected as a different flavor eigenstate after they propagate over macroscopic distances. The interpretation of these observations is that neutrinos have mass and that, like in the quark sector, the mass eigenstates are different from the weak eigenstates, i.e. neutrinos mix. The observation of the neutrinoless double beta ($0\nu\beta\beta$) decay would prove that the neutrino is Majorana fermion and that lepton number is violated. The measurement of its rate would provide information on the so-called effective Majorana neutrino mass, $(m)_{eff} = |\Sigma_i U_{ei}^2 m_i|$, where the sum is over the mass eigenstates, and U_{ei}, the corresponding entries in the lepton mixing matrix are complex numbers [116]. Current best experimental limits on $(m)_{eff}$ are of the order $(m)_{eff} \leq 0.2–0.9$ eV, with the most stringent upper limits from ^{76}Ge coming from the past Heidelberg-Moscow [117] and IGEX [118] experiments. The best limits for ^{130}Te and ^{100}Mo, of $(m)_{eff} \leq 0.3 – 0.7$ eV, and $(m)_{eff} \leq 0.45 – 0.9$ eV, respectively, come from the CUORICINO [119] and NEMO-3 experiments [120].

To scan most of the parameter space predicted by theory, multiple detectors with sufficient sensitivity are needed. Two existing experiments, GERDA and EXO, have significant Swiss contributions.

GERDA is an experiment to search for the $0\nu\beta\beta$-decay in enriched ^{76}Ge detectors at the Gran Sasso Laborator. It uses a novel shielding concept, with Ge crystals being operated directly in a 65 m^3 volume of liquid argon (LAr). The experiment proceeds in two phases: Phase I employs HPGe detectors from the Heidelberg-Moscow and IGEX experiments, with a total mass of 17.7 kg, as well as natural Ge detectors from the Genius Test Facility [121]. The goal is to improve upon current limits and scrutinize the hint of a signal [122] after one year of data taking with an exposure of 15 kg·y and a background of 10^{-2} counts/(keV kg y). In case no events will be observed above background, a half-life limit of $T_{1/2} > 3 \times 10^{25}$ y can be established, resulting in an upper limit for the effective neutrino mass of $(m)_{eff} \leq 0.23 – 0.39$ eV. Phase II will use additional enriched broad-energy germanium detectors, aiming for a total exposure of 100 kg·y.

With a background goal of 10^{-3} counts/(keV kg y), the half-life sensitivity is $T_{1/2} > 20\times10^{25}$ y and the corresponding range of effective neutrino masses is $\langle m\rangle_{eff} \leq 0.09 - 0.15$ eV, taking into account the uncertainty in the matrix element and neglecting new lepton number violating interactions. The construction and commissioning of GERDA were completed in November 2010 and 2011, respectively, the physics run with eight enriched Ge detectors has started.

For GERDA phase II, a higher total mass, and a background lower by another order of magnitude is needed. The lower background can be reached by instrumenting the LAr with PMTs and by an effective pulse shape analysis (PSA) in the Ge diodes [123, 124] adopted by the collaboration. The entire production chain was validated with depleted Ge, and four detectors were fully characterized regarding their charge collection, spectroscopic and PSD performance, as well as long-term stability [125]. The production of enriched BEGe detectors with existing GeO_2 material has started in 2011. The detectors will be tested during the second half of 2012 and commissioned in early 2013.

The Enriched Xenon Observatory (EXO) proposes to search for the $0\nu\beta\beta$ decay with a ton-scale TPC (Time Projection Chamber) using xenon highly enriched in the isotope Xe-136 which is a favorable source and particle detection medium. Substantial reduction of the cosmic ray flux is needed, making the installation of such a detector deep underground an imperative. The reduction of the residual radioactive background imposes a severe material screening program, the development of an optimized detector design and ultra-clean construction techniques. EXO proceeds through a multi-phase program which balances between an intense R&D effort in preparation of the EXO-full detector and the prototype EXO-200, employed as an R&D test bench and as a physics detector. EXO-200 (a double-barrel TPC with both charge and scintillation light readout, loaded with 200 kg of 80 % enriched liquid xenon) has been in operation since fall 2010 and has clearly demonstrated the extremely low radioactive background obtained through the massive material screening effort [126]. EXO-200 is also the first detector which has provided a clear signal for the allowed (two-neutrino) double beta decay [127] as predicted by the standard model and thus giving confidence for the numerical calculations of the nuclear matrix elements for Xe-136. Presently, the EXO-200 setup undergoes final preparation for a two-year run optimized for $0\nu\beta\beta$ decay search. An excellent performance is predicted even in the case that no $0\nu\beta\beta$ signal is detected.

EXO-200 should be able to provide a lower limit on the half-life better than 6.4×10^{25} years or equivalently a higher limit of the effective neutrino mass of 130 meV. For the EXO-full detector the collaboration proposes barium tagging for the complete reduction of the residual radioactive background. This novel technique is based on the extraction and identification of each Ba-136 ion produced by the decay of Xe-136 along with the two electrons which classically provide the signal in the detector.

EXO-200 will run until middle of 2014 and requires monitoring shifts and a continuous effort for data analysis; its operation may be extended past 2014. For EXO-full, major R&D elements will be finalized by 2014 so that its design and construction can start. The EXO-full location will be decided until 2014 among the main contenders, DUSEL and SNOLab.

Intended contribution of the project

The Zürich group is responsible for the calibration system of GERDA. The group has designed, built and installed a fully motorized source insertion system, along with low-neutron emission sources in collaboration with PSI, which is used for the operation of the three strings of enriched Ge detectors. The group is in charge of analyzing the weekly calibration runs and monitor the stability of the Ge diodes, regarding their energy calibration and resolution. For the next phase, the group is involved in the production and testing of enriched BEGe detectors. In addition, the group participates in the design and testing of the instrumentation of the liquid argon cryostat with light sensors. The liquid argon veto will be used to further reduce the backgrounds in the second phase of the experiment.

The EXO-200 cryostat has been designed and manufactured by Laboratory for High Energy Physics (LHEP) Bern, in collaboration with the Swiss Welding Institute in Yverdon-les-Bains. The Bern group has been extensively involved with the deployment, commissioning and operation of the EXO-200 detector. The critical competence of Swiss members in EXO-200 operation has been acknowledged with the installation of the only remote control center in Europe. There are two Swiss contributions to the R&D effort for EXO-full. For the gas option, the use of large-gap Micromegas for charge readout in high-pressure xenon mixtures is studied in collaboration with RD51 group at CERN, which manufactures the Micromegas planes. For the baseline option of EXO-full (a liquid xenon TPC), the development of an efficient barium ion extraction device has started. Once it is well tested in Bern, it will be merged with the laser-based barium ion tagging apparatus.

Links to other projects of this NCCR
The groups involved in the NCCR are expected to significantly contribute to the data analysis effort of these projects. Within the NCCR, the science data of GERDA and EXO will be analyzed coherently in view of the various double beta decay channels: the Standard Model allowed process with emission of two neutrinos, and, most importantly, beyond-SM processes such as the neutrinoless double beta and various other decay modes predicted by Beyond-Standard-Model physics. The goal is to explore the predicted parameter space using these two different experimental techniques, and thus different systematics, as well as two double beta emitters with different uncertainties in the theoretically predicted matrix elements for the various decay channels.

4.1.8 PROJECT: GRAND UNIFICATION

**Coordinators: S. Antusch (UniBs),
A. Rubbia (ETHZ)**

Research question and state of the art
What is the origin of the three forces between the known elementary particles described by the SM? Are they unified at high energies, i.e. can they be derived from a single “unified force”? These questions are addressed in so-called Grand Unified Theories (GUTs) [128]. Unification is one of the key ideas towards a more fundamental understanding of elementary particles. The idea of GUTs is supported, for instance, by the renormalisation group (RG) running of the gauge couplings in supersymmetric extensions of the SM, which meet at high energy $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, as well as by the automatic cancellation of gauge anomalies, and by the quantized values of the electric charges of the SM particles. GUT models have been constructed based on various symmetry groups G_{GUT}, which contain the symmetries of the SM as subgroups, $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y} \sim G_{\mathrm{GUT}}$, for example $\mathrm{G_{GUT} = SU(5)}$ [128] or SO(10) [129]. Beyond explaining the origin of the three forces of the SM, GUTs have other far-reaching consequences. For instance, in GUTs not only the forces are unified, but also

the different types of elementary particles of a given family, with strong implications for flavour model building. GUTs may furthermore be connected to the question why neutrino masses are so small compared to the masses of the charged particles of the SM. From the point of view of effective field theory, the scale Λ at which neutrino masses are generated by an extension of the SM is related to the electroweak scale $v_{\mathrm{EW}} \sim 175$ GeV of the SM by the relation $m_\nu \sim (175\ \mathrm{GeV})^2 / \Lambda$ [130]. With Λ about 10^{16} GeV, i.e. around the GUT scale M_{GUT}, one would indeed expect neutrino masses of about 10^{-3} to 10^{-2} eV, which is in the range indicated by the smaller of the two observed mass squared differences. Although progress has been made towards the construction of realistic GUTs, various aspects still remain challenging. For instance, regarding neutrinos, it is currently unknown which of the possible mechanisms to generate massive neutrinos is realized. Further long-standing issues of GUTs concern the so-called "doublet-triplet splitting", or more generally the problem of constructing a viable GUT-Higgs sector, and early universe cosmology in supersymmetric GUTs.

Another challenge of GUTs consists in the fact that they operate at such high energies that they can only be probed indirectly. The smoking gun signal of Grand Unification is the decay of the proton (or of the bound neutron). In this context, massive underground neutrino detectors can be considered as sort of observatories for rare physics phenomena such as nucleon decays [131]. Nucleon decay signal events are experimentally characterized by (a) their topology (b) their kinematics. By topology, we mean the necessary presence of a lepton (an electron, a muon or a neutrino) in the final state, in general, few particles in the end products (for example, two body decays are believed to be favored), and obviously no other energetic nucleon in the final state. The exact kinematics of the event depends on the type of target. For free protons (target with hydrogen), the total momentum of the event should be compatible with zero, while for nucleon decays occurring in nuclear targets, we expect a smearing from Fermi motion and also other nuclear effects (rescattering, absorption, etc.). The total energy of the event should be equal to the nucleon mass, which means in the GeV range. These kinematical features and their exclusive final state topologies allow, if well reconstructed in the detector, separating nucleon decay signals from the much more abundant and mundane atmospheric neutrino interactions, with a level of suppression that increases with improved spatial granularity and energy resolution. Two complementary technologies are presently discussed for potential future applications: Water Cerenkov ring imaging (WC) and liquid Argon Time Projection Chamber (LAr TPC). The Japanese proposal HyperKamiokande[114] considers a next-generation 540 kton fiducial mass detector, continuing the path defined by the predecessors Kamiokande and SuperKamiokande. Among Swiss groups, the focus has been on the complementary approach provided by a Giant liquid Argon TPC, called GLACIER [132, 133]. A liquid argon detector of 100 kton = 6×10^{34} nucleons yields a sensitivity for protons of $\tau p / Br > 10^{34}$ years × T(yr) × ϵ at the 90 % C.L. in the absence of background. This means that lifetimes in the range of 10^{35} years can be reached within 10 years of operation. Channels like $p \rightarrow \nu K$ have been shown to be indeed essentially background free, even at shallow depths [134]. We conclude by stressing the complementarity of the two approaches, HyperKamiokande characterized by the huge volume and GLACIER by its smaller mass but finer resolution, noting however that, given the foreseeable timescale for these next generation experiments, the new challenging technique of the LAr TPC might offer more discovery potentials.

Intended contribution of the project
The goal of the project is to contribute to the development of realistic GUTs which can resolve the above mentioned open issues in GUT model building as well as to the development of techniques to experimentally test the predictions of GUTs, in particular proton decay. The topics for research in this project will include:
Proton decay experiments: Massive underground detectors are designed by optimizing their performance for the search of nucleon decays. However, such detectors will have a much larger physics program, for example with the observation and study of astrophysical (solar, atmospheric, and supernova neutrinos) and artificial beam neutrinos. Such a comprehensive physics program, possibly with non-accelerator and accelerator-based components, makes massive underground detectors "general purpose" facilities, sort of observatories for rare physics phenomena. The European *LAGUNA* design study [135], coordinated by ETHZ, is dedicated to the feasibility of such an underground neutrino experiment of next generation. GLACIER will be further developed as one of the detector option considered. A letter of intent will be submitted to CERN.

Neutrinos and GUTs: Although left-right symmetric GUTs have successfully predicted that neutrinos have small masses, there are currently no indications which of the possible mechanisms to generate the masses (such as seesaw type I [136, 137, 138, 139], type II [140] or type III [141]) is the right one. To get new insight in this question, the interplay between the neutrino mass mechanism and the other aspects of GUT model building, such as flavour issues and cosmology, will be investigated. In neutrino model building, another key aspect is provided by the question how the difference between the large mixing in the lepton sector and the small mixing in the quark sector can be explained in a predictive way. New ways to predict the quark and lepton flavour structures in the context of GUTs will therefore be investigated as well.

Supersymmetric GUTs and the early universe: Connecting inflation with GUT scale physics is attractive since the required vacuum energy V_0 is typically around the GUT scale M_{GUT}. Recently, new classes of inflation models have been proposed where the inflaton resides in the matter sector of a supersymmetric GUT theory, allowing for particularly close connections between inflation and particle physics [142]. Cosmology in supersymmetric theories faces some challenges, such as the "cosmic moduli problem" [143] or the "gravitino problem" [144], but also some benefits, for example the lightest neutralino or the gravitino as promising candidates for the dark matter particle. One task of this project will be the development and phenomenological analysis of new supersymmetric GUT models of inflation, including the above mentioned issues.

Links to other projects of this NCCR
Direct evidence for GUT and baryon number violation represents one of the outstanding goals of particle physics.

As has beed described above, GUTs are deeply connected to various of the other projects of the NCCR proposal. One particular contribution of the project *Grand Unification* will be to "unify" the theoretical and experimental progress in the various fields towards a more fundamental theory framework. Since the research within the project is linked to various other projects, it will benefit strongly from the new interactions and collaborations that will be initiated by the NCCR.

4.1.9 PROJECT: LEPTON FLAVOR VIOLATION

Coordinators: S. Ritt (PSI), A. Bravar (UniGe)

Research question and state of the art
In the neutrino sector, lepton flavor violation (LFV) has been observed in the form of neutrino mixing. Observation of LFV in the charged lepton sector, however, is still lacking: processes like the decay $\mu^\pm \to e^\pm e^+ e^-$, or $\mu^+ \to e^+\gamma$, or the $\mu^\pm A \to e^\pm A$ conversions have not been observed yet. LFV addresses the fundamental issue of the role played by leptons in the mechanism generating the Universe's baryon asymmetry (leptogenesis).

In the SM charged LFV processes are forbidden at tree level and can be induced by lepton mixing through higher order loop diagrams. Loop diagrams involving neutrinos are strongly suppressed with branching ratios $B < 10^{-40} - 10^{-50}$ for muon decays. Sizable LFV effects are expected in many extensions of the SM such as grand unified models (GUTs), supersymmetric models, compositness, leptoquarks, left-right symmetric models, models with an extended Higgs sector, dynamically broken electroweak symmetry models, extra dimensions, etc. These models predict an experimentally accessible amount of LFV in a large region of the parameters space [145] [146]. The search for the decays $\mu^+ \to e^+\gamma$ or $\mu^+ \to e^+e^+e^-$ are sensitive to many such models. The observation of LFV in the charged lepton sector would be a sign for new physics at scales far beyond the reach of direct observation, up to several 1000 TeV.

Several experiments have been performed or are in operation searching for LFV in the decay of muon or tau leptons. The best current limit on the LFV are set by PSI muon experiments. In the 80s the SINDRUM experiment searched for the $\mu^+ \to e^+e^+e^-$ decay. No signal was observed and a limit $B(\mu^+ \to e^+e^+e^-) < 10^{-12}$ was set at a 90 % C.L. [147]. The SINDRUM II experiment searched for the $\mu^- A \to e^- A$ conversion using different targets. The strongest of these limits has been obtained using a gold target with $B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$ compared to capture decay rates [148].

In the 90s, the proton beam intensity and therefore the muon intensity available at PSI increased steadily, making it possible to improve existing limits on the $\mu \to e\gamma$ decay. In 2000 the MEG collaboration, aiming at a new $\mu \to e\gamma$ search to improve the existing limit by two orders of magnitude has been formded with a strong participation of PSI. MEG is taking physics data since 2008. No LFV decay signal was observed yet, setting a limit on $B(\mu^+ \to e^+\gamma)$ of $2.4 \cdot 10^{-12}$ at a 90 % C.L. [149]. The present MEG limit is more incisive (about 10 times) than the SINDRUM II limit of $7 \cdot 10^{-13}$ since in beyond the SM models the ratio $B(\mu^+ \to e^+e^+e^-)/B(\mu^+ \to e^+\gamma) \sim O(\alpha_{EM})$ and $B(\mu^+A \to e^+A)/B(\mu^+ \to e^+\gamma) \sim O(\alpha_{EM})$. One of the technical challenges of the MEG detector is the drift chamber system needed to detect the positron from the $\mu \to e\gamma$ decay. This ultra-low mass detector was designed and built by the PSI detector group together with the associated readout-electronics. For the readout of all detector signals a new ASIC chip named DRS4 has been developed at PSI. The DRS4 is now also used in the MAGIC and FACT gamma-ray Cherenkov Telescopes.

Intended contribution of the project
The MEG experiment started taking data in 2008 and published a first improvement of the B $(\mu \to e\gamma)$ of $2.4 \cdot 10^{-12}$ in 2011 [149]. The experiment will continue taking data in the current configuration until the end of 2012, aiming for a limit of a few times 10^{-13}. Since the experiment runs presently only at 1/3 of the maximum muon rate possible at PSI, higher statistics can be reached by increasing the

rate of stopped muons. This requires better pile-up rejection and higher resolutions in order to suppress the background from accidental overlaps of ordinary muon decays. Possible upgrade scenarios are currently under discussion and will demand a significant involvement of the PSI detector and electronic groups as well as of the associated PSI scientists.

A new experiment, Mu3e, to search for the LFV decay $\mu^+ \rightarrow e^+e^+e^-$ is being proposed at PSI. Mu3e aims at a sensitivity of one in 10^{16} muon decays (~10^4 better than previous searches). This sensitivity requires a muon stopping rate of $2 \cdot 10^9$ muons per second. This high rate experiment will be possible thanks to novel tracking detectors based on thin monolithic active silicon pixel sensors with high granularity (high voltage monolithic active pixel sensors – HV-MAPS) providing high spatial resolution, and silicon photomultiplier (Si-PM) photon detectors for the time of flight (ToF) system providing very precise timing information. By combining both technologies the sensitivity of $B(\mu^+ \rightarrow e^+e^+e^-) < 2 \cdot 10^{-16}$ at 90 % C.L. in absence of a signal can be reached.

After an initial R&D phase, which has already started, the experiment will be performed in two phases. In the first phase (2014 – 2017) an existing muon beamline at PSI will provide a sensitivity of about $B(\mu^+ \rightarrow e^+e^+e^-) \sim 10^{-15}$. The construction of a new beamline to increase the beam intensity to $2 \cdot 10^9$ stopped muons per second is currently under investigation (see section 4.3.2). With this new beamline (2018 – 2020) the experiment will reach the ultimate sensitivity of $B(\mu^+ \rightarrow e^+e^+e^-) \sim 10^{-16}$.

In Mu3e, surface muons of 28 MeV/c are stopped on a hollow double cone aluminum target. Electrons from muon decays will be detected by two cylindrical double layer silicon pixel detectors (HV-MAPS). The detectors sit in a strong solenoidal magnetic field. Curling tracks will be measured by a second double layer cylindrical silicon pixel detector upstream and downstream of the central detector in order to improve the momentum resolution. The silicon tracker is complemented by a cylindrical ToF detector consisting of a scinitillating fiber hodoscope in the central region with a time resolution of few 100 ps. The curling tracks will be measured with scintillating tiles, with a 50 ps time resolution. The granularity of the system (fibers and tiles) will be such to keep the single channel event rate below 1 MHz. The scintillating fibers and tiles will be readout with Si-PMs.

The final sensitivity of Mu3e depends on the ability to reduce accidental backgrounds, which scale with the square of the beam intensity, and irreducible backgrounds such as the $\mu^+ \rightarrow e^+e^+e^-\nu\nu$ decays to a level below 10^{-16}. The former source of background can be efficiently suppressed by excellent timing (~100 ps) and vertex resolution, the latter with a high momentum resolution of the detector ($\sigma E < 1$ MeV).

The Swiss institutions that expressed interest in this experiment (UniGe, ETHZ, UniZ, PSI) are particularly interested in developing the ToF system. These groups will also perform detailed simulations of the detector including background studies, and contribute further to the conceptual development of the detector. Later they will participate in the analysis. The data acquisition including the data management and storage, and the slow control will be taken care of by PSI. A vigorous R&D program is being planned, including the development of Si-PMs, to achieve the desired performances of the ToF system. SiPMs will be readout with the wellestablished waveform digitizing technology (DRS chip) used already in the MEG experiment. The advantage of this technology compared to traditional constant fraction discriminators and TDCs is that pile-up can be effectively recognized and corrected for. In addition, pulse height information becomes available which can be used to discriminate signals. To cope with the high rates expected during the second phase a new version of the DRS chip (DRS5), capable of sustaining continuous rates of 2 MHz, will be developed by the same PSI group.

Links to other projects of this NCCR

The activities described in the field of Lepton Flavor Violation in the charged sector offer great opportunities for Swiss contributions to fundamental questions in particle physics at low energy. The NCCR Universe will ensure a coherent operation of these experiments and enhance exchange of information between them. Technical developments in one experiment can often be used in another one. With the help of the NCCR these synergy effects will be fostered to the benefit not only for the experiments in LVF but even beyond. The DRS4 chip is already now also used in gamma-ray Cherenkov Telescopes, and the DRS5 chip will have even more applications. The development of the high intensity muon beamline described in section 4.3.2 is another example for interdisciplinary efforts enabled by the NCCR Universe.

4.2 THE CHALLENGE OF DARK ENERGY AND DARK MATTER

Coordinating authors: R. Durrer (UniGe) and A. Refregier (ETHZ)

Research question and state of the art

This theme is concerned with 96 % of the content of the Universe: Dark Energy (DE) and Dark Matter (DM). These two mysterious cosmological components have, so far, only been detected via their gravitational action. Dark matter provides about 23 % of the energy density and has been inferred from the rotation curves of dwarf and ordinary galaxies, from the velocity dispersion in cluster, from strong and weak lensing, via structure formation and via the observed anisotropies of the cosmic microwave background. Hence it has been detected on scales ranging from dwarf galaxies to the Hubble scale (i.e. the size of the observable Universe). For DE the situation is more mysterious: even though it provides the bulk part (more than 70 %) of the energy density of the Universe, it has been inferred so far only via cosmological expansion: the observed relation between the redshift and the distance of far away objects is compatible with a homogeneous and isotropic universe (a Friedmann Universe) only, if its expansion is accelerated. Gravity of ordinary matter is attractive and therefore leads to decelerated expansion of the Universe. To obtain the observed accelerated expansion a strong negative pressure is needed so that gravity becomes repulsive. The physics Nobel Prize 2011 has been awarded for the discovery of cosmic acceleration.

If DM is made of particles (a very plausible and well grounded hypothesis), this particle can not be a SM particle (see section 4.2.7). Contrary to accelerator particle physics, cosmological experiments already demand extensions of the standard model. The DE puzzle is related to the most fundamental problems of particle physics (the cosmological constant problem) and gravity. Therefore, any improvement of our understanding of possible nature of these phenomena, e.g. constraints on mass and interaction strength of DM particles, on the equation of state for DE or interaction between them, provides a most valuable input for particle physics

Intended contribution to the NCCR

The simplest proposal for DE is vacuum energy or, equivalently, a cosmological constant.

Other possibilities are a dynamical scalar field (quintessence) or an infrared modification of General Relativity. Another idea is that backreaction from cosmic structure may affect the distance-redshift relation of a homogeneous and isotropic Universe in such a way as to mimic DE. Moreover, only the the total dark energy momentum tensor have been measured so far, which is then conveniently split into a clustering DM component and a non-clustering DE component. It is not clear, whether this is really correct, or in other words, whether DE and DM interact with each other. The project Cosmic Acceleration 4.2.2 addresses all aspects of these questions and are connected with the other projects, especially those concerned with the primary cosmological probes, the cosmic Large Scale Structure (LSS) projects 4.2.3, 4.2.4, and 4.2.5, and the Cosmic Microwave Background (CMB) 4.2.8.

We assume that the observed large-scale structure has grown out of small initial fluctuations from inflation by gravitational clustering. This process is modeled via cosmological perturbation theory and via N-body simulations, see projects LSS: modeling and CMB. To compare calculations with observations (see project LSS: observations) we have to take into account the problem of biasing, and more generically astrophysical systematics (see project LSS: astrophysical systematics): we observe only galaxies while theory predicts only the distribution of DM. How are these related? We can address this biasing problem to some extent by including baryonic interaction (hydrodynamics) into the simulations and on the other hand by inferring LSS power spectra from weak lensing, which is sensitive to the total mass, and by comparing them with those from galaxy surveys. We also want to investigate whether relativistic effects play a role in N-body simulations (so far they have mostly been neglected). LSS simulations and observations are also an important tool to decide on properties of DM: warm DM candidates lead to less clustering on small scales than cold DM. A very strongly motivated DM candidate, sterile neutrinos would provide warm dark matter, while another 'favorite' candidate, a WIMP yields cold DM.

Another interesting aspect of both CMB fluctuations and LSS is non-Gaussianity: the simplest models of inflation, where self-interactions of the inflaton or between several possible degrees of freedom are neglected, predict Gaussian initial fluctuations that are fully characterized by their power spectrum. However, on the next level, taking into account interactions, i.e. higher that quadratic terms in the Lagrangian, inflation also predicts some degree of non-Gaussianity, which usually is very characteristic for the model of inflation. In order to detect it, we first have to compute (and subtract) non-Gaussianities due to non-linear clustering. Non-gaussianities are probably also relevant for the biasing problem, especially on large scales, where they mix with possible DE clustering. Therefore, to understand DE, we also have to study non-Gaussianity which in turn are intimately linked to the physics of inflation, the early Universe, see project Early Universe 4.2.1.

Ultimately, we also want to use cosmological observations to test general relativity, see project Cosmological Tests of Gravity 4.2.6. One example in this direction are the two Bardeen potentials: if gravity is described by general relativity and DE is vacuum energy or a quintessence field, the two scalar gravitational potentials of linearized gravity, the Bardeen potentials, Φ, Ψ, are identical, $\Phi=\Psi$. However, if DE comes from a modification of gravity, they are generically different. Such a difference can be measured by combining weak lensing surveys, which respond to the sum $(\Phi+\Psi)$ with DM clustering observations, which responds to the 'Newtonian potential', Ψ.

Observing CMB anisotropies and polarization and LSS, we have concluded that the initial fluctuations have been generated during an inflationary phase. However, a satisfactory, generally accepted particle physics theory that identifies the inflaton as a physical degree of freedom is still lacking. To make progress in this direction we want to investigate, e.g., whether initial fluctuations contain a gravitational wave component or cosmic strings. It is fascinating that at present our most promising path to physics of the highest energies, GUT scale or the scale of quantum gravity, actually leads through the largest structures of the Universe, the fluctuations and polarization of the CMB.

We also address the challenge of DM 4.2.7: what is DM, how does it interact with ordinary matter? For this we want to detect DM directly, i.e. by other means than through its gravitational interaction. The best strategy for such searches depends on the nature of DM. If it is the most popular candidate, a WIMP (weakly interacting massive particle), this can be done best with direct DM detection experiments as those which are underway now in Switzerland and at LHC. However, WIMPs by no means exhaust the list of possible DM candidates. Although it is usually said that cosmological data favor Cold DM, this actually just means the hot DM (e.g. the standard model neutrinos) are disfavored.

Sterile neutrinos are very strongly motivated from the particle physics point of view, they can play an important role in the Early Universe and be related to baryogenesis, see 4.2.1 below. The hypothesis of sterile neutrinos is also bears connections to our other neutrino projects 4.1.7 and 4.3.8.

Finally, DM may be annihilating or decaying. The search for decaying DM demands for a very different strategy than searching for its annihilating counterpart. One searches for decaying DM by looking for a monochromatic decay line in the spectra of DM-dominated objects. This is a very promising, clean signal. An extensive program of search for a decaying DM signal has already been realized (led by the EPFL group, M.Shaposhnikov, A.Boyarsky). The XMM-Newton satellite delivers the best searching capabilities for the weak extended signal of decaying DM, Chandra, Suzaku and INTEGRAL have also been used.

4.2.1 PROJECT: PARTICLES AND FIELDS IN THE EARLY UNIVERSE

Coordinators: M. Shaposhnikov (EPFL), A. Riotto (UniGe)

Research question and state of the art
Most properties of the Universe we observe today are believed to be determined at very early times by the laws of fundamental physics, most notably by gravity and high energy physics. The list of questions includes: Why is the Universe isotropic and homogeneous at large scales? How are the primordial density fluctuations which seed the formation of structures in the present Universe generated? Why do the cosmological parameters have the values we observe today? Why does the Universe contain more matter than antimatter? What is the nature of the dark matter, observed at present by gravitational effects only? It is already clear that the Standard Model (SM) of elementary particles cannot provide the answers to these questions, meaning that an extension is required. This leads to a number of particle physics questions, such as: What kind of new physics is necessary for addressing these problems? Which particle physics experiments together with cosmological and astrophysical observations can reveal new physics?

Very active theoretical research in this field has started soon after the discovery of cosmic microwave background (CMB) radiation in 1964, with a huge progress over the last years. The theory of the inflationary Universe beautifully explains why the Universe appears so homogeneous and isotropic and, at the same time, is responsible for those inhomogeneities which developed through gravitational instability into the observed large scale structure of the Universe [150].

A number of possible mechanisms leading to a baryon asymmetric universe have been suggested [151]. Inspite of this success, a general unified picture, together with many important details, is missing. We still do not know whether one or several new particles or fields are needed for cosmological inflation. We are ignorant about the precise mechanism responsible for the generation of the inflationary quantum fluctuations. It is not clear what is exactly the source of CP-violation and deviations from thermal equilibrium, leading to a baryon asymmetric Universe. We do not know whether the baryon asymmetry was created at an energy scale testable by current experiments. It is not even clear whether the "dark matter" is a new particle. We do not know whether the observed present cosmic acceleration is due to some new light degree of freedom, dubbed "quintessence", or a manifestation of some modification of gravity (general relativity) at large distances.

Though these questions were around already for quite some time, only now the progress in high energy physics experiments (e.g. LHC at CERN) and cosmological observations (the Planck mission measuring the properties of the CMB anisotropies and current and future galaxy surveys, like the recently selected Euclid satellite mission of ESA measuring the properties of large structure of the Universe) will allow to make a considerable progress in the near future.

Intended contribution of the project

Our primary goal is to take advantage of the impressive flow of data that both particle physics and cosmology experiments will provide in the next decade to learn more about the early Universe dynamics. We will contribute to improve our understanding of the inflationary picture from the CMB anisotropy and large scale structure observations. By studying the statistical properties of the cosmological inhomogeneities in the Universe today, we will characterize the dynamics of inflation and understand the process of quantum Indeed, non-Gaussianity contains information about the interactions of the relevant inflationary degrees of freedom. In this sense, observing primordial non-Gaussianities plays the role of the LHC collider of inflationary physics. We have all the expertise to play a leading role in this line of research [152, 153]. The very same set of data will be also analyzed to furnish crucial information about the present-day cosmic acceleration, possibly confirming and/or ruling out the revolutionary idea that Newtonian gravity is modified on large scales.

Thanks to high energy physics experiments we will possibly identify and study the true mechanism responsible for baryogenesis as well as the true nature of dark matter, which even might be related. For instance, if the LHC provides evidence of that physics beyond the SM, we will thoroughly investigate its properties to understand if baryogenesis can be ascribed to physics close to the electroweak energy scale. At the same time, we intend to make use of observations of non-accelerator experiments testing the flavour structure of the particle content within the SM (e.g. in the neutrino sector) to scrutinize other scenarios of baryogenesis whose energy scale is not directly accessible to colliders and to investigate the possibility that all the observational problems of the SM can be solved without introducing any new energy scale between the Fermi and Planck scales, with a minimal number of new particles and new physics principles introduced [154]. The cosmology and phenomenology of this type of theories will be elucidated, with an outcome for cosmology (properties CMB, of dark energy, and of dark matter) and for particle physics (mass of the Higgs boson and parameters of heavy neutral fermions).

Links to other projects of this NCCR

Reconstructing a fundamental theory of nature from the full body of experimental data is a principal challenge of physics. The investigations of physics of the Early Universe give an indispensable input to particle physics, otherwise hardly achievable. It is at the base of the NCCR Universe that fundamental questions connect to all the LHC experiments discussed in the first challenge (Constituents and Forces), Section 4.1 and to the LSS and CMB experiments, sections 4.2.3, 4.2.4 and 4.2.8 discussed in this challenge (Dark Matter and Dark Energy). Of course also future terrestrial and space accelerators discussed in the third challenge can provide most valuable data to unravel the physics beyond the standard model which is crucial for the early Universe.

Finally, the results of the Dark Matter project 4.2.7 will be most relevant for the construction of the "minimal" extension of the SM with sterile neutrinos. Astrophysical and cosmological studies of super-WIMPs will allow to probe the parameter space of sterile neutrino dark matter. In combination with theoretical investigations that are the objectives of this project, this will allow us to restrict the parameters of heavier sterile neutrinos and make a detailed predictions for the future accelerator (e.g. beam dump) experiments, capable of discovering these new particles.

4.2.2 PROJECT: COSMIC ACCELERATION

Coordinators: M. Maggiore (UniGe), M. Kunz (UniGe)

Research question and state of the art

Understanding the origin of dark energy is one of the most important challenges facing cosmology and theoretical physics. Its discovery at the end of the 90's [155, 156, 157] has led to the Nobel Prize in physics of 2011. Even though the experimental situation is convincing, a theoretical understanding is still completely lacking. The solution of this problem will require a combined approach by theorists and observers, and will certainly require both a significant observational effort as well as the development of new theoretical ideas. For a review see [158].

On the observational side, it is crucial that as much information is gathered as possible. This requires measurements of cosmic expansion and cosmic growth of structure to percent level accuracy and correspondingly tight control of systematic errors. It also requires a robust understanding and careful modeling of astrophysical and instrumental uncertainties, including the effects of non-linear clustering, as they will render the comparison of observations to theory difficult and may hide elusive observational clues about the nature of the dark energy. Additionally, comparing observations to theoretical predictions requires a meaningful parametrization of the space of testable models.

These issues require close collaboration between theorists, data analysis experts, and observers and instrument builders. This NCCR is uniquely positioned to address these problems in a unified manner, since it will unite experts from all these areas. The interpretation of the future experimental evidence will be intensely discussed between the members.

Intended contribution of the project
In particular, we will focus on approaches based on measurements of weak gravitational lensing, galaxy clustering, redshift space distortions, Lyman-alpha and galaxy clusters from a wide range of large scale structure surveys (SDSS, LSST, EUCLID), as well as measurements of CMB anisotropies by Planck, WMAP and suborbital experiments. Several participants in this proposal are involved directly in many of these surveys.

This observational effort will probe the nature of the dark energy at different levels. On the one hand the observations will test the homogeneous cosmology predictions of distance redshift relations. These distances will be measured using standard rulers, e.g. baryon acoustic oscillations in the CMB, large galaxy surveys and the Lyman alpha forest, as well as standard candles like type Ia supernovae. On the other hand, they also provide constraints based on the growth of structure in the universe, such as weak lensing, galaxy clustering, redshift-space distortions, galaxy cluster counts and luminosity functions, Lyman-alpha forest and cross-correlations of the large scale structure with the CMB.

We believe that a more coherent approach to the issue of cosmological data analysis and interpretation is needed not only in the context of Dark Energy, but also of other topics discussed in other sections of this proposal. We have to unify the methodology of data analysis and of statistical reporting and interpretation. By bringing together numerous experts in several of these areas, the proposed NCCR will take on this role. Combining the different data sets to obtain stronger cosmological constraints on dark energy has been one of the main research activities by partners of the NCCR (e.g. V. Desjacques, M. Kunz, J. Lesgourgues, U. Seljak [159, 160, 161, 162, 163, 164, 165]) and we will continue activities in this direction by incorporating the latest data sets, many of which will be delivered by members of our center.

On the theoretical side, there are many crucial open questions. First of all, the ‘simplest solution’, a so called cosmological constant is by no means natural. Experimentally, there is no way to distinguish a cosmological constant from vacuum energy. We therefore think that we should also not distinguish them theoretically. However, the vacuum energy of a quantum theory is not protected from radiative corrections and it scales like the cutoff energy scale to the 4th power. To understand how to ‘fine tune’ it to the measured small value of

$$\rho_{\rm vac} = \frac{\Lambda}{8\pi G} \simeq (2.3 \times 10^{-3}\ \mathrm{eV})^4$$

we probably have to investigate the basis of quantum field theory on a non-perturbative level.

One important aspect of the problem is already to understand what is the effect of vacuum fluctuations of quantum fields on the cosmological expansion. This is a domain where cosmology meets quantum field theory on curved space. At a more phenomenological level, it is important to develop field-theoretical models based on extensions of General Relativity, to compare them with the data and to the “standard” ΛCDM cosmological model that at present is consistent with the observations but, at the conceptual level, gives no convincing explanation for the coincidence problem, namely why the dark energy density becomes relevant just at the present epoch of the universe.

These issues require field-theoretical competences, as well as experience in applying these theoretical ideas to cosmological problems, and fall within the domains of expertise of several members of our center (L. Alvarez-Gaume, G. Giudice, M. Maggiore, R. Rattazzi, A. Riotto,

M. Shaposhnikov [166, 167, 168, 169]). In this direction also goes the effort of distinguishing 'standard' dark energy components from modifications of gravity.

The last years have also seen a strong effort towards identifying the degrees of freedom that can be probed by cosmological observations, with the goal of providing a unified parametrized framework within which theoretical predictions can be compared to observational results [161, 162, 163, 164, 165], disentangling the signature of dark energy and massive neutrinos on the growth of structure [170] and performing detailed calculations of relativistic effects relevant for future large surveys [171] as well as of the impact of non-linear clustering [172, 173, 174] (M. Maggiore, A. Riotto, U.Seljak, V. Desjacques). In order to successfully shed light on the physical nature of the dark energy, all these different research strands need to be united into a single, coherent effort. To provide an institutional framework for this work is one of the main goals of the NCCR.

Finally, maybe there is no cosmic acceleration and we are just too naive in applying the distance redshift relation of a homogeneous Friedmann Universe to the real inhomogeneous universe? It has been shown that by modifying the distance redshift relation by as little as 20 %, we can get rid of dark energy and with it cosmic acceleration [175]. But what is the 'real' geometry that induces such a modification? Toy models which cluster non-linearly only on scales up to about 50 – 100 h^{-1} Mpc, as the observed Universe, lead to very small changes in the distance redshift relation, maximally a few percent (see [176] for an example). This is expected, as on large scales the clustering effects should 'average out'. However, since General Relativity is non-linear, this 'averaging process' is not guaranteed to work even on cosmological scales. Hence, despite the negative findings from simple toy models, the problem remains open. Since Newtonian gravity does not lead to significant back-reaction [177, 178], the problem has to be tackled with non-linear GR simulations which we want to perform in collaboration between UniZh (B. Moore, U. Seljak) and UniGe (M. Kunz, V. Desjacques, R. Durrer).

Links to other projects of this NCCR

This project is the theory counterpart of the three sub-projects on LSS 4.2.7 and the CMB project 4.2.8. It is also intimately related to the sub-project on tests of gravity 4.2.6 as the cosmic acceleration might be due to a modification of GR. Finally, there are links to the early Universe project; first of all, also inflation represents a phase of accelerating expansion and secondly, all our LSS and CMB fluctuations measurements depend on the initial fluctuations generated during inflation. Also, the aim of this effort is the find out whether cosmic acceleration is related to a new 'constituent': dark energy, or to the modification of a well known 'force', gravity. In this sense the project is related also to the first challenge of this NCCR.

4.2.3 PROJECT: LSS AS A PROBE OF FUNDAMENTAL PHYSICS 1: OBSERVATIONS

Coordinators: A. Amara (ETHZ), M. Kunz (UniGe)

Research question and state of the art

To address the fundamental questions coming from extragalactic cosmology, we rely on measurements of the large scale properties of the Universe. Four techniques have emerged as standard probes of the low redshift Universe. These are (i) gravitational lensing, (ii) distribution of galaxies, (iii) supernovae and (iv) galaxy clusters. Each one of these measures has its particular statistical power and susceptibility to systematic errors. It is the combination of these probes, with the cross checks that multiple measures allow, that leads to overwhelming evidence that the Universe is currently going through a phase of accelerated expansion. Looking forward to upcoming experiments, weak lensing and the statistics of the spatial distribution of galaxies stand out as the two large-scale structure (LSS) probes with the greatest promise. This is due to both their statistical power and their weak sensitivity to the complicated physical processes that govern galaxy formation.

A large number of experiments are being built, with the next round due to come online in the coming years. In the case of weak lensing, the measurements rely on high resolution, multiband imaging over wide area surveys. In the short term (next five years), data is expected from KIDS, PanSTARRS, DES and Hyper-SuprimeCam.

These large dedicated programs are driven by weak lensing and will image several thousand square degrees to sub arc second resolution. This is a substantial increase over current surveys, such as the CHFTLS and COSMOS, which cover 170 and 2 square degrees, respectively. The next generation of experiments on time scales of 10 years that will follow these survey are also being planned. These include LSST, Euclid and WFIRST. These ambitious missions will take high quality images over roughly half the sky. In parallel to this, studies of the statistics of galaxy distributions rely more heavily on wide area spectroscopy survey. In this respect, the Sloan Digital Sky Survey (SDSS) has had enormous success. The SDSS galaxies cover an area of 1700 square degrees out to a redshift of roughly $z = 0.2$. Upcoming surveys, such as BOSS, DESpec and BigBOSS, Euclid and WFIRST, will extend the galaxies being measured out to redshifts of $z=1$ and beyond. This will greatly improve the volume, and hence the statistical power and allow us to measure the evolution of LSS as a function of redshift. This wide array of exciting experiments will lead to an enormous expansion in this field.

The LSS cosmological probes, developed to study the combined Dark Sector of Dark Matter and Dark Energy are based on large scale surveys of the extragalactic Universe extending out to redshifts $z \sim 2$. They provide a measure of the Universe through the extended epoch during which Dark Energy came to dominate the overall expansion of the Universe. The surveys are intended to provide a three-dimensional view of the development of structure in the Universe to complement the essentially 2-dimensional single epoch “snapshot” that is obtained from the cosmic microwave background at $z \sim 1050$. The implementation of these probes will require a sophisticated understanding of potential systematic effects, both in measurement and astrophysical systematics.

Previous work by the proposers

At ETH-Zurich, A. Amara, A. Refregier, S. Lilly and M. Carollo have played leading roles in the development and analysis of wide field surveys. They have also developed a number of high precision techniques for the analysis of cosmological data and applied these methods to derive statistical properties of cosmic large scale structures and to study the formation and evolution of galaxies. At the University of Geneva, M. Kunz, R. Durrer and V. Desjacques has extensive expertise in theoretical and phenomenological cosmology. At the ISDC, a center of competence for the analysis of space missions part of the Observatory of Geneva, S. Paltani plays a central role in the Swiss Science Data Center for Euclid. His group will fully contribute in the LSS data analysis and interpretation. G.Meylan and his group at the

EPF Lausanne have expertise in strong and weak lensing.

Intended contribution of the project

Development of analysis pipelines: Given the extensive experience that exists in Swiss institutes, we are well placed to develop pioneering analysis pipelines for both imaging and spectroscopic data. These will enable us to perform weak lensing, galaxy clustering (including BAO) and redshift space distortions measurements. The different information that comes from each of these probes is not independent, therefore, it is important to fully understand the cross-correlation to allow for their combination. This is a substantial task that will require interdisciplinary knowledge of each of the probes.

Analysis of current surveys: We will apply our analysis pipelines to existing data that we have access to, these include the SDSS galaxy survey, COSMOS and zCOSMOS. Though these data sets have been extensively analyzed, they still remain excellent repositories that will allow us to develop further our data analysis methods that we plan to deploy on upcoming surveys. The goal here is to provide constraints on cosmological parameters, with special emphasis on dark energy properties (as outlined in the Cosmological Tests of Gravity sub-project, section 4.2.6) with an emphasis on the extra gains from probe combination.

Analysis of upcoming surveys: In the time frame covered by this proposal, we expect to see an explosion of imaging and spectroscopic data. We will directly collaborate on their analysis and provide basic products such as e.g. mass maps and power spectra (density, velocity, lensing potential, etc) for the LSS surveys, both as a function of scale and redshift.

Preparation of future surveys: We are members in a range of future surveys like e.g. Euclid for which the 2014–2017 period will be a crucial development phase. We will provide forecasts for the expected performance of the future surveys, help to optimize their design, and work on the analysis pipeline.

Links to other projects of this NCCR

Of course this project is very intimately linked to the two other LSS projects 4.2.4 and 4.2.5. But LSS observations will also be combined with CMB observations, see project 4.2.8, to best constrain the cosmological parameters which describe the present Universe and the nature of the fluctuations. Weak lensing and Lyman-α forest data are crucial to distinguish between “cold” or “warm” dark matter with severe impact on theoretical understanding of the nature of dark matter. Therefore the control of astrophysical systematics will play a crucial role for the identification of dark matter, project 4.2.7. In combination with the theoretical computations on the physics of the early Universe, project 4.2.1, these data allow to determine the nature of the dark matter particles (e.g. sterile neutrinos) that can be searched in laboratory experiments. The LSS observations will provide the data (density maps and galaxy counts) necessary for the search for decaying dark matter, project 4.2.7

4.2.4 PROJECT: LSS AS A PROBE OF FUNDAMENTAL PHYSICS 2: MODELLING

Coordinators: V. Desjacques (UniGe), U. Seljak (UniZh)

Research question, state of the art and Intended contribution of the project

Measurements of the LSS of the Universe from present and future wide-field surveys will provide strong constraints on the cosmological model. The combination of numerical simulations and analytic methods will enable the development of accurate models, which are necessary to interpret these measurements and to forecast constraints on cosmological parameters.

Previous work by the proposers

At the University of Zurich, B. Moore is a leader in gravitational N-body simulations and U. Seljak is a leading expert in the field of theoretical cosmology. At the University of Geneva, V. Desjacques has a strong expertise in numerical simulations of the large scale structure, and R. Durrer, M. Kunz and A. Riotto are leaders in analytic approaches such as perturbation theory, theoretical and phenomenological modeling of dark energy, as well as the analysis and interpretation of large scale structure data. At ETH-Zurich, A. Refregier and A. Amara have wide experience in the interpretation and planning of high-precision cosmological surveys.

Intended contribution of the project

Numerical simulations of LSS: Numerical simulations bridge the gap that often exist between theoretical models and observational data. They will be used extensively to predict the signal imprinted by viable inflationary models, dark energy or modified gravity, neutrinos and exotic dark matter particles on galaxy clustering and weak lensing data. While pure dark matter simulations combined with models of the Halo Occupation Distribution (HOD) should be enough to accurately predict the signatures in correlation functions of the galaxy distribution on large scales, the interpretation of weak lensing measurements, which aim at measuring the matter power spectrum at 1% accuracy on scales $0.1h\mathrm{Mpc}^{-1} < k < 10h\mathrm{Mpc}^{-1}$, will require hydrodynamical simulations which realistically include the effect of baryons. Series of large-volume simulations will be employed to calibrate the theoretical models, identify parameter degeneracies and estimate covariances in the measurements. Past light-cones will be extracted and “degraded” to account for instrumental noise, photometric errors, flux limits etc., in order to create mock surveys of galaxies. Another important aspect will be the development of numerical codes that can setup and follow the evolution of cosmic structures in non-standard cosmologies, and efficiently compute statistics such as the 3-point correlation functions of galaxies on massively parallel computers.

Analytic models of LSS: On the theoretical side, perturbative expansion approaches and sophisticated extension such as resummed perturbation theory and time-renormalization group methods will be developed to model the nonlinear evolution of the mass density field and the galaxy distribution. These analytic models will provide useful physical insights into nonlinear clustering and help understanding the systematics of the numerical simulations. Their precision and convergence will be tested against the outcome of simulations. Regarding galaxy bias, one of the novel aspects will be to look beyond conventional approaches, in which bias is approximated by a continuous function of spatial location, and consider statistics of point processes. This will help understanding the stochastic nature of galaxy bias and developing optimal methods that can minimize the impact of cosmic variance and shot noise on, e.g., measurements of the growth factor f or the nonlinear parameter f_{NL}. We will also work out all relativistic effects relevant for LSS observations, such as lensing and magnification effects in the galaxy and supernovae surveys. These effects will become measurable with future surveys.

Links to other projects of this NCCR

The LSS project is most strongly connected with the two other LSS projects, 4.2.3 and 4.2.5. It is also linked to the Early Universe project 4.2.1 as especially non-Gaussianities will give us information not only on the nonlinear evolution of gravitational clustering, but also on primordial non-Gaussianities. While the power spectrum is mainly related to the free inflaton field and its cosmic evolution during inflation, primordial non-Gaussianities are related to interactions. They therefore are our access to physical interactions at very high energies which we cannot probe in terrestrial accelerators.

4.2.5 PROJECT: LSS AS A PROBE OF FUNDAMENTAL PHYSICS 3: ASTROPHYSICAL SYSTEMATICS

Coordinators: S. Lilly (ETHZ), M. Carollo (ETHZ)

Research question and state of the art

Of central importance for weak lensing is the estimation of redshifts for huge numbers of galaxies (10^8 – 10^9), which cannot possibly be observed spectroscopically. This necessitates the use of photometrically-estimated redshifts. While the required random uncertainty, $\sigma_z \sim 0.05(1 + z)$ is relatively straightforward to achieve, the required *systematic* uncertainty, of order $0.002(1 + z)$ in the mean redshift of a given set of objects, is very much more challenging. Despite recent progress by ourselves and others, much further work needs to be done to develop photo-z techniques to the point where this level of precision is confidently achievable. One focus will be to improve the ways in which other, non-photometric, information is used in photo-z schemes, e.g. information on the structural morphologies of the galaxies, including possible orientation effects. The other will be to explore more generalized approaches using optimized eigen-spectral energy distributions.

Previous work by the proposers

At ETH-Zurich, S. Lilly and M. Carollo have leading expertise in galaxy evolution, observational cosmology and the analysis of imaging and spectroscopic wide field surveys. A. Amara and A. Refregier have extensive experience in high-precision cosmology, survey planning and systematics treatment.

Intended contribution of the project

One of the most important difficulties is securing spectroscopic redshifts of sufficient quality such that the reliability of photo-z schemes can be accurately characterized. This requires large numbers of highly complete and highly secure spectroscopic redshifts. Spectroscopic redshift surveys, such as zCOSMOS and other similar ones, have been optimized with other considerations and are not sufficient for this task: there are many galaxies where the photo-z and spectro-z are discrepant, some due to photo-z failures and some due to incorrect spectroscopic identifications. It would therefore be very attractive to undertake a dedicated redshift survey optimized for photo-z calibration, e.g. as an ESO Public Spectroscopic Survey using the VIMOS spectrograph, a call for wish is expected in the near future.

In addition to photo-z, there are also formidable challenges to be faced in the measurement of faint galaxy shapes in practical imaging instruments. In addition to the well-known issues surrounding what is effectively a deconvolution of the galaxy image from the instrument point-spread function (PSF), there are a number of more subtle effects to worry about. First, the shapes must be optimally characterized: At first, a simple second moment of the image was taken to yield a “size” and “orientation” [179]. Later, an orthogonal set of “shapelets” was introduced [180], which has the advantage that the effect of a lensing shear distortion can be readily calculated. However, the general shapelet set is non-optimal – in essence too many individual shapelet components are required and they become too noisy to be used [181]. A more optimized basis set, starting around the typical profiles of faint galaxies would be much better – see [182, 183, 184]. There are close analogies here to the “template-fitting” approach to photometric redshifts where one uses similar astrophysical “information” on the spectral energy distributions of galaxies to optimize the information content rather than using a completely general (e.g. Fourier) decomposition.

As a further complication, any practical imaging system will have a PSF that is wavelength dependent. While this could in principle be taken care of by reconstructing the effective PSF for a given galaxy [185], second-order effects will enter if galaxies have internal colour gradients and/or if internal sub-structure has different colours. Both of these are known to be the case. The likely impact of these effects is unknown, nor do we have in place any strategies to recognize and deal with them on a galaxy-by-galaxy basis.

Links to other projects of this NCCR

The aim of this project on astrophysical systematics is to develop those bits of astrophysics that are of most relevance to the measurement and interpretation of the purely cosmological signals in very large surveys of galaxies in the late epoch $0 < z < 2$ regime described in the two other sub-projects of LSS, 4.2.3 and 4.2.4. It can also be useful for indirect detections of dark matter discussed in section 4.2.7 and for the magnetic field project, section 4.3.9 of this proposal.

Furthermore, this research program is also leading to a more sophisticated understanding of how and where galaxies form, which is associated with the cosmological “bias” between the distribution of dark and luminous matter, and in how heating and cooling of the baryonic component leads to redistribution of the baryonic material that is relevant for any study attempting to relate the distribution of these two components.

4.2.6 PROJECT: COSMOLOGICAL TESTS OF GRAVITY

Coordinators: M. Kunz (UniGe),
A. Refregier (ETHZ)

Research question and state of the art

The presence of the dark energy is very puzzling, and one possible explanation is that General Relativity itself breaks down on large scales. But even beyond this crucial question we may ask how can we use cosmological observations to test General Relativity (GR)? On solar system scales GR is well tested by classical solar system tests, like e.g. lunar laser ranging or light deflection by the sun; but also by using data from binary pulsar systems which provide very accurate clocks. These observations have let to the development of the PPN (Parametrized Post-Newtonian) formalism [186] within which deviations from GR are cast in so called ‘post-newtonian parameters’. Since we are now developing similarly accurate cosmological datasets, can we define ‘post-friedmannian parameters’ which in a similar way are sensitive to modifications of GR?

At a very basic level, we can measure the geometry of the Universe, or in other words the metric by observing the motion of massive and massless freely falling particles (galaxies and photons). From the metric we can compute the Einstein tensor $G_{\mu\nu}$. If GR is correct then we can use the Einstein equations to infer the energy momentum tensor of whatever is accelerating the expansion of the Universe. But we can do the same computation even if GR is not correct, giving us an effective energy momentum tensor [161, 164],

$$G_{\mu\nu}[H, \phi, \psi] = 8\pi G T^{eff}_{\mu\nu}[\rho, p, \delta\rho, \delta p, V, \pi].$$

In solar system or binary pulsar tests, the energy momentum tensor is vanishing in the part of spacetime under consideration. In cosmology, determining the energy momentum tensor is an important step as it encodes information on the nature of the dark sector. The Einstein tensor depends on the background expansion rate $H(t)$, and the gravitational potentials $\phi(x, t)$ and $\psi(x, t)$ that quantify the scalar metric perturbations (for simplicity we assume a spatially flat Universe because of inflation, and only consider the scalar-type perturbations here, in reality these assumptions would be relaxed). The covariant conservation of the effective energy momentum tensor, $\nabla_\mu T^{eff,\mu}_{\nu} = 0$ allows to eliminate one background and two perturbation quantities, typically ρ, $\delta\rho$ and V. We see that after this elimination, the degrees of freedom of the geometry (one background and two perturbative quantities) match the effective fluid degrees of freedom (also one background variable, the pressure p usually parameterized with the equation of state parameter $w = p/\rho$, and two perturbations, the pressure perturbation δp and the anisotropic stress π). In this formalism both dark energy and possible modifications of gravity are unified, which has the big advantage that we can directly apply it to observations. However, how we can now disentangle the different possibilities? Acceleration today implies $w(t_0) < -1/3$, but to go beyond just the existence of acceleration we have to look at possible models of the dark sector. For example, scalar field dark energy, quintessence or k-essence, generically gives rise to a sound horizon below which the dark energy perturbations are suppressed, which implies a specific functional form of δp. This sound horizon leaves traces in the gravitational potentials, a bit like a finger print of this specific model (see, e.g. [162]). Modifications of General Relativity on the other hand generically produce an effective anisotropic stress [165] ($\pi \neq 0$) that is not present in uncoupled scalar field models.

Intended contribution of the project

In this project we will hunt for the finger prints of gravity and its modifications in the large scale structure data. The only model that leaves no trace at all in the perturbations is a cosmological constant. All other explanations of the accelerated expansion perturb in some specific way the Universe on large scales. For some models these perturbations can, however, be very small, for example the perturbations from scalar field dark energy can only be detected if it is "cold" and has a sufficiently small speed of sound [163]. Deviations from General Relativity, on the other hand, tend to produce much larger signatures.

To identify the physics behind the accelerated expansion and test gravity on large scales, we first have to be able to measure the metric. In practice this means measuring both gravitational potentials, ϕ and ψ. This can done for example by combining weak lensing observations (since light deflection depends on $\phi + \psi$) and the galaxy velocity field (as non-relativistic "test particles" are accelerated by the gradient of the ψ potential alone). Several of the proposers are world experts in these surveys. For example, A. Refregier, S. Lilly and A. Amara of ETHZ have extensive experience in large scale structure surveys, and the Universities of Geneva, Zürich as well as the EPFL are actively involved in the Euclid satellite project.

Based on these measurements we will then derive key variables like the sound speed and the effective anisotropic stress of the dark energy. This in turn places constraints on the space of allowed models. In fundamental physics, the quantity that really describes a physical model is its action, and we will be able to directly measure certain terms in a general action for the dark sector. For example we can start with an Ansatz like

$$S \sim \int d^4\chi \sqrt{-g}\,[\tfrac{1}{2} f\,(\varphi)\,R + K\,(X) - V(\varphi) + \mathcal{L}_m]$$

where $\mathcal{L}_m$ is the matter part of the action, φ is a scalar field with $X \equiv -1/2(\nabla\varphi)^2$ and R the Ricci (curvature) scalar of the action of General Relativity. In this case, the potential $V\,(\varphi)$ is important for modeling the accelerated expansion of the Universe, while the kinetic function $K\,(X)$ will determine the sound speed of the dark energy. The effective anisotropic stress on the other hand is directly linked to the modification of the gravity part part of the action, i.e. to the derivative $f'\,(\varphi)$.

However, there are still many possible dark sector actions to explain the observed effective fluid properties. But, as mentioned above, on “small” scales, e.g. inside the solar system, General Relativity has been extremely well tested. Any viable modification of gravity needs to contain a non-linear mechanism that allows it to revert to GR in high-density regions. Several such mechanisms have been identified e.g. the Vainshtein mechanism of massive gravity or the Chameleon mechanism for scalar fields, see e.g. [187]. If large-scale measurements indicate a likely breakdown of GR, then the precise way in which these deviations are suppressed as a function of scale holds further crucial clues as to the shape of the action that needs to be considered.

The goal of this project is go all the way from cosmological observations through an effective fluid description of the dark energy to inferences on the allowed actions to describe the dark sector. In this NCCR we have been able to assemble a team of the foremost experts in the large-scale structure observations necessary to measure the metric quantities needed (as discussed in the LSS projects), experts of the formalism to infer the fluid quantities from the metric (with M. Kunz of UniGe at the forefront of research in the interpretation of effective dark fluid quantities and co-coordinator of the Euclid theory group), and experts in field theory that links the fundamental description of the dark sector in terms of an effective action to the properties of the dark fluid inferred from observations (especially R. Rattazzi of EPFL and M. Maggiore and A. Riotto of UniGe). In this way we will be able to link cosmological data with the physics of the dark sector and test gravity on large scales that cannot be accessed in any other way.

Links to other projects of this NCCR

This project is of course strongly related to the project of cosmic acceleration, as modification of GR might be at the origin of this observation. Furthermore, most experimental/observational progress is expected via the cosmological probes offered by LSS and CMB observations. Hence there are strong connections to all three LSS projects and to the CMB project. But of course as it is testing one of the fundamental forces of nature, gravity, this project is also related to the challenge ‘Forces and Constituents’.

4.2.7 PROJECT: DARK MATTER: (A) DIRECT AND (B) INDIRECT DETECTION

Coordinators: L. Baudis (UniZh), A. Boyarsky (EPFL), J. Read (ETHZ)

Research question and state of the art

The nature of Dark Matter (DM) is among the most intriguing questions of modern physics. Its resolution will have a profound impact on the development of particle physics. The Standard Model of elementary particles does not contain a viable DM candidate. Therefore, the DM particle hypothesis necessarily implies an extension of the Standard Model. Candidate DM particles in such hypothetical Standard Model extensions differ drastically in their properties (such as mass, interaction strength, clustering properties) and therefore in their observational signatures. By constraining properties of DM particles one can differentiate among extensions of the Standard Model and learn about the fundamental properties of matter.

Swiss groups are leading many important directions in the direct and indirect searches for DM and have extensive plans till 2017, implying close collaborations between cosmology, astrophysics, theoretical and experimental particle physics.

At the largest distances, modern cosmological and astronomical observational data are successfully described by the simplest cold DM model that assumes that DM particles decouple from primordial plasma non-relativistically. Maybe the most popular DM candidates of this class are weakly interacting massive particles – WIMPs. These stable particles interact with the Standard Model sector with roughly electroweak strength. The interest for these candidates is due to their potential relation to the electroweak symmetry breaking, which is being tested at the LHC. To give a correct DM abundance, these particles should have a mass of ~10 – 10^3 GeV. The WIMP searches are important scientific goals of many experiments. One of the main scientific objectives of the Fermi mission is to search for the gamma-rays from WIMP annihilation. Dozens of laboratory experiments are conducted to detect WIMPs in the Galaxy's DM halo by searching their interaction with nucleons. Direct DM detection experiments with leading Swiss participation use the noble liquids argon and xenon as WIMP targets. The ArDM (Argon DM) experiment [188], using 850 kg of liquid argon (LAr) to search for nuclear recoils induced by WIMP scatters, is lead by ETH Zurich (A. Rubbia, spokesperson). ArDM has been constructed and is in commissioning at CERN; it will be installed at the Canfranc Underground Laboratory (Spain) by the end of 2011. The goal is to test the discrimination capability against beta decays from ^{39}Ar, and to probe WIMP-nucleon cross sections down to ~5×10^{-45} cm^2.

The XENON100 experiment [189] is taking science data at the Gran Sasso Underground Laboratory (LNGS) since 2009. It uses 62 kg of liquid xenon in a time projection chamber, surrounded by 99 kg of liquid xenon veto, both viewed by arrays of photo-multipliers capable to detect the primary and secondary scintillation signals after a particle interacts in the active xenon volume of the time projection chamber. Data from the first 100 live-days of DM search showed that the XENON100 background is two orders of magnitude below the one of any other direct detection experiment [190], provided the world's best limits on the spin independent WIMP-nucleon interaction cross section [191] and excluded inelastic DM as an explanation of DAMA [192]. A second science run started in March 2011. Concomitantly, the XENON1T detector, which will feature a total of 2.4 tons of liquid xenon was proposed to be built in a large water Cerenkov shield at LNGS and approved to be installed in Hall B in April 2011. The project, which is led by Columbia (E. Aprile, spokesperson), UZH (L. Baudis, deputy spokesperson) and MPIK Heidelberg (M. Lindner, chair of the collaboration board) is presently in advanced preparation and will start its construction phase in mid 2012, with data science exploration to begin by 2015. XENON100 will probe WIMP-nucleon cross sections down to 2×10^{-45} cm^2, and XENON1T is designed to improve this sensitivity by at least one order of magnitude.

However, WIMPs by no means exhaust the list of possible DM candidates. Cosmological data rule out the possibility that a significant fraction of DM particles remained relativistic up until the matter-dominated epoch (which is the case for the usual neutrinos). Other than that, the mass and interaction strength of DM particles remain largely undefined. We only know (from studies of the phase space density of DM dominated objects) that fermionic DM particles should have a mass above ~400 eV [193].

There is a large class of extensions of the Standard Model, which predict super-weakly interacting DM candidates (super-WIMPs) with much more feeble interaction strength than that of WIMPs. This changes their properties in two crucial ways: (i) a correct abundance of DM may be produced with a mass of DM particles as low as few keV; (ii) super-WIMPs can decay (with a lifetime exceeding the age of the Universe). These particles may be produced relativistic and suppress primordial density fluctuations at sub-Mpc scales. Such models (often called warm DM) fit the CMB and large scale structure data equally well as the ΛCDM "concordance" model [194].

The super-WIMP candidates are also motivated by particle physics. For example, the minimal extension of the Standard Model by three sterile neutrinos, (the *ν*MSM [195]) provides a viable and unified description of three main observed "beyond the Standard Model" phenomena in particle physics – DM, neutrino flavor oscillations and baryogenesis (matter-antimatter asymmetry). The DM in the *ν*MSM should be lighter than 50 keV and is produced with a non-thermal velocity spectrum [196, 154]. This theory is among a very few models that provide testable resolution of the "beyond the Standard Model" puzzles in the situation when no new physics is found at the LHC. However, to achieve sufficient predictive power, the *ν*MSM requires significant input from astrophysics and cosmology.

The search for super-WIMP DM demands a very different strategy. These particles posess a 2-body decay channel, producing a monochromatic photon. The search for decaying DM by looking for a line in the spectra of DM-dominated objects is very promising, as the DM origin of any "suspicious" line can be unambiguously checked. Indeed, the decay signal is proportional to the column density $S = \int \rho_{DM}(r)dr$ along the line of sight and not to the $\int \rho^2_{DM}(r)dr$ (as it is the case for annihilating DM). As a result a vast variety of astrophysical objects of different nature would produce a comparable decay signal [197]. Therefore: (i) one has the freedom of choosing the observational targets, avoiding complicated astrophysical backgrounds; (ii) if a candidate line is found, its surface brightness profile can be measured and distinguished from astrophysical lines (which usually decay much faster in outskirts) and compared among objects with the same expected signal. This promotes the search for decaying DM to a direct detection experiment [198, 199]. An extensive program of search for a decaying DM signal has already been realized (led by EPFL group, M. Shaposhnikov, A. Boyarsky). XMM-Newton delivers the best searching capabilities for the weak extended signal of decaying DM [200]; Chandra, Suzaku and Integral have also been used. The best current results on the searches of signatures of warm and cold+warm DM models in cosmological data (including Lyman-α forest [201, 194]) were obtained by Swiss groups (Boyarsky, Lesgourgues, Riotto, Seljak).

Intended contribution of the project

WIMPS: The two ton-scale experiments (ArDM and XENON1T) will be in their commissioning and construction phases, respectively, starting in 2012. XENON1T will start commissioning in mid 2014, when the construction of the underground infrastructure, of the shield and veto, of the detector and cryostat as well as of the cryogenic infrastructure will have ended. The DM run is planned for 2015–2016.

To convincingly demonstrate the DM nature of a potential signal, and to determine WIMP properties such as its mass and scattering cross section, measurements of the interaction rate with multiple targets and much larger target masses are mandatory [202]. DARWIN [203] is an R&D and design study for a multi-ton scale LAr and LXe DM search facility, with the goal of probing the cross section region below 10^{-47} cm^2, and providing a high-statistics measurement of WIMP interactions in case of a positive detection by one of the aforementioned experiments. Approved by ASPERA [204] in late 2009, DARWIN coordinates the European groups active in the noble liquid DM search field, and runs under Swiss leadership (L. Baudis, project coordinator, A. Rubbia, WP4 leader). DARWIN thus uses techniques which have already been successfully proven in 10 kg to 100 kg prototypes, and which will be studied in ton-scale detectors in the very near future. In conjunction with other WIMP targets, with indirect searches and with the LHC, DARWIN should allow us to learn not only about the WIMP properties, but also about their density and velocity distribution in our local vicinity in the Milky Way. The DARWIN study has officially started in April 2010, and the Technical Design Study is expected to be delivered in 2013. The letter of intent and the proposal for the construction of the facility would be submitted by mid and late 2014, respectively, with the construction and commission phases scheduled for 2015–2016. The period of operation and physics data taking is foreseen for 2017–2020, i.e. during the second period of the NCCR Universe.

Super-WIMPs in high-energy astronomy: As the intrinsic width of the expected decay line is more narrow than the spectral resolution of XMM-Newton, to improve the bounds and advance into the theoretically interesting regions of particle physics models, one needs (i) to combine a large number of archival observations of objects where the strongest signal is expected and (ii) cross-correlate observations of DM-dominated objects (EPFL group). In particular, this will be done for the zCOSMOS (PI S. Lilly, ETHZ) deep field and X-ray diffuse flux measured by the XMM-COSMOS project. If a candidate line is found, deep (~1 Msec) observations of the most promising targets will allow to confirm its nature. Finally, at energies above 20 keV the SPI spectrometer of the INTEGRAL satellite delivers the required spectral resolution [205] (ISDC and EPFL groups).

To resolve the DM decay line one needs an instrument with improved spectral resolution. Two such instrument are planned for the nearest future. The first mission using the new technology (X-ray microcalorimeter) is Astro-H, scheduled for 2014 with an important ISDC contribution. Its observations (including galaxy clusters) will be useful for the combined analysis and a new strategy of search of a weak omni-present line should be developed [200] (EPFL group). Another instrument – LOFT, with contributions from ISCD and DPNC – with very good sensitivity for decaying DM due to its large collecting area and field-of-view was recently selected by ESA as one of the 4 space missions concepts of the Cosmic Vision program.

Super-WIMPs in Structure formation: By 2014 about 160’000 quasar spectra will be provided by the successors of the SDSS survey, drastically improving the sensitivity of the Lyman-α forest method. Weak lensing is another promising tool to probe the imprints of primordial DM properties on structure formation, aiming to measure the matter power spectrum on even smaller scales with a few % precision.

The Kilo-Degree Survey (KiDS) (starts 2011, PI: K. Kuijken, Leiden) should be completed by 2014. The Euclid mission will measure matter power spectrum over large range of scales, ultimately resolving the question of primordial velocities of DM particles.

To take advantage of their high precision, both methods require theoretical predictions at about percent accuracy. These predictions and subsequent data analysis of SDSS Ly-α, KiDS (with Leiden observatory) and Euclid data will be performed by the EPFL and UniZh groups.

The combination of astrophysical X-ray observations, cosmological data on structure formation (EPFL/UniZh), theoretical work on the physics of the early Universe (EPFL, UniGe, see sections on the Early Universe, baryogenesis, and cosmic magnetic fields) will give crucial input for the accelerator super-WIMP searches in “intensity frontier” experiments (e.g. predict the parameters of sterile neutrinos and allow to test experimentally neutrino minimal extension of the Standard Model).

Links to other projects of this NCCR

As described above, observations of LSS can contain information on dark matter, especially whether it might be warm or interacting with itself or with dark energy. This effect, however, should be disentangled from astrophysical feedbacks on matter power spectrum. All LSS projects (observations, theory and systematics, see 4.2.3, 4.2.4 and 4.2.5) are therefore related to the DM question.

Furthermore, there are suggestions that DM might be observable at LHC especially if it is a WIMP. Hence the SUSY searches at LHC are most relevant to DM. Finally, DM might have been generated with the baryon asymmetry in the early Universe, using the cosmic magnetic fields as messengers. This relates this subproject to the projects Particles and Fields in the Early Universe 4.2.1 and to the Cosmic Magnetic Fields 4.3.9.

4.2.8 PROJECT: COSMIC MICROWAVE BACKGROUND

**Coordinators: J. Lesgourgues (CERN),
A. Rassat (EPFL)**

Research question and state of the art

Detailed observations of CMB anisotropies provide one of the most robust and accurate ways to test the standard cosmological model, for a summary of present data see Fig. 2. Starting from January 2013, the Planck collaboration will periodically release new data of unprecedented precision, stimulating a feverish activity for extracting all cosmological information from the maps, challenging the ΛCDM paradigm, and testing its alternatives. Planck will represent the ultimate measurement of temperature anisotropies, but the quest for polarisation anisotropies will go on, in order to extract even more information on the early universe. A particularly exciting challenge will consist in finding the B-mode of CMB polarisation. Detecting B-modes would offer a unique opportunity to test inflation, to estimate the energy scale at which primordial fluctuations have been generated, and to probe other mechanisms leading to gravitational wave production (reheating, phase transitions, topological defects). Polarisation anisotropies will be observed in patches of the sky by several ground-based experiments after Planck (EBEX, POLARBEAR, etc.) and the community promotes a new space-based CMB mission.

Several partners in this NCCR have worked on the foundations of cosmological perturbation theory and on CMB physics for the past twenty years. R. Durrer and U. Seljak have written several pioneering papers in the 1990’s. More

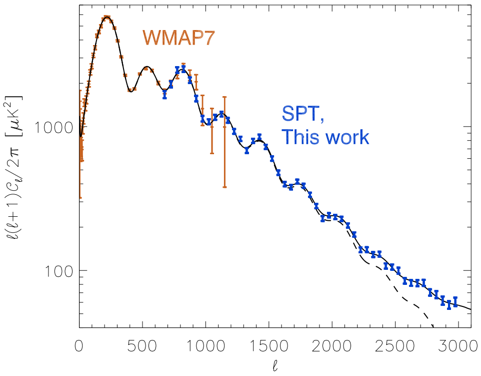

Figure 2: Present CMB anisotropy data from WMAP7 and the South Pole Telescope. Similar precision has been attained with the Atacama Cosmology Telescope. Figure from [206].

recently, many of us have used current CMB observations in combination with other datasets to constrain the parameters of the ΛCDM model, and several of its possible extensions. For instance, members of the NCCR have played a world-leading role in particular topics such as studying the impact of magnetic fields, topological defects and modified gravity (R. Durrer, M. Kunz), constraining inflation or primordial isocurvature modes (R. Durrer, A. Riotto, J. Lesgourgues), testing dark matter candidates and neutrino physics (R. Durrer, J. Lesgourgues). They have played a key role in theoretical developments for predicting or for measuring non-Gaussian statistics in CMB maps (A. Riotto, M. Kunz), for calculating the effect of vector modes (R. Durrer), or for tackling with CMB lensing extraction techniques (U. Seljak, J. Lesgourgues). They have worked on cross-correlation methods of CMB and large-scale structure maps in order to measure the late Integrated Sachs Wolfe (ISW) effect as well as reconstruct ISW maps (A. Rassat, M. Kunz, J. Lesgourgues). They have developed crucial numerical tools for computing CMB anisotropies and derived quantitites, like the famous CMBFAST code (U. Seljak), or more recently the iComso package (A. Refregier, A. Rassat) or the CLASS code (J. Lesgourgues). They are involved in the on-going Planck experiment, and in studying the potential of CMB satellite proposals like CMBpol or CORE (M. Kunz, J. Lesgourgues, U. Seljak).

This NCCR gathers almost all types of expertise on CMB physics, ranging from data analysis up to the most involved theoretical developments. It puts the group in an excellent position for making the best possible use of future CMB data.

Intended contribution of the project

For most topics listed above, rough constraints can be derived from current data, but most of the potential for discovery is contained in future Planck temperature maps, and in post-Planck polarisation maps. It will be fascinating to apply the methods discussed for testing with precision the physics of inflation, or the existence of mechanisms in the early universe generating non-gaussianity, isocurvature modes, vector modes, magnetic fields, topological defects or other CMB-contributing features.

CMB lensing extraction is a technique for probing clustering in the universe up to high redshift ($z = 1$ to 3), in complement to galaxy lensing experiments sensitive to smaller redshifts. This technique just started to be applicable with the South Pole Telescope data. Exciting improvements can be expected with Planck and other future observations, and the team is well positioned for performing such analyses. In order to understand the nature of dark energy, it will be extremely useful to use CMB priors when fitting LSS data from galaxy weak lensing, galaxy redshift surveys, etc. On top of that, by cross-correlating CMB and CMB-lensing maps with LSS maps, one can obtain further information and eliminate systematic uncertainties. The NCCR gathers experts on both the CMB and LSS sides, ready to push these techniques to their limits.

The CMB has little to say about neutrino masses, but encodes lots of information about the amount and the properties of relativistic species in the early universe. Current data show a marginal preference for extra relativistic species. If confirmed, this feature could be connected with particle physics (like recent anomalies in short-baseline neutrino oscillation experiments). The group incorporates experts on this topic, who will explore all indications from the data and possible interpretations.

Finally, CMB observations could provide major surprises like the need to depart from the standard Friedmann model. Current observations provide some (yet inconclusive) hints for large voids, a north-south asymmetry or low-multipole anomalies. By providing better statistics, independent systematic effects and a better understanding of foreground contamination, future data will shed a new light on these issues, and tell us whether they require some fundamental explanation. For a selection of relevant books and papers, see Refs. [207, 208, 209, 210, 211, 212, 213, 170, 214, 215, 216, 217].

Links to other projects of this NCCR

Up to date, the CMB is our most clean and precise dataset from cosmology. This makes it very relevant to all cosmology related questions of this NCCR: the early Universe, cosmic magnetic fields, cosmic acceleration, tests of gravity, just to name some. To exemplify let us outline the connection to primordial magnetic fields. If magnetic fields are generated before recombination they affect the CMB in several different ways: Alfvén waves and magnetosonic waves modify the CMB anisotropy peak-structure, Faraday rotation induces B-polarization and the non-Gaussianity of the magnetic field energy momentum tensor leads to higher order correlations, e.g. a bi-spectrum. All these effects can be used to place limits on primordial magnetic fields, for a review see [218].

4.3 THE CHALLENGE OF PARTICLE SOURCES AND ACCELERATION

Coordinating authors: Lenny Rivkin (EPFL and PSI), Alain Blondel (UniGe), Andrii Neronov (UniGe)

Research question and state of the art

Man-made Accelerators: The main accelerator R&D at CERN is directed towards full exploitation of the LHC physics potential by a fast ramp up to the design parameters and forthcoming upgrades. A multi-TeV e^+e^- Compact LInear Collider (CLIC) is likely to be the next large project, with a Conceptual Design Report issued in 2012 and a Technical Design Report (TDR) foreseen for 2015. Exploratory studies to achieve higher gradients, involving plasma and laser acceleration, are conducted in parallel. Studies related to the high intensity frontier and a neutrino factory complete the medium term plans. Under construction at PSI is the SwissFEL, a hard X-Ray Free Electron Laser based on a 6 GeV linear electron accelerator. It is widely recognized that accelerator R&D at CERN and PSI is curtailed by the need to maintain and upgrade the running accelerators. A large collaboration with European institutions and universities is seen critical to ensure the future of the field. In Switzerland this requires an intensified collaboration between CERN and PSI. Accelerator physics is of course also a science in its own right and should be promoted in Universities. The proposed accelerator R&D will provide excellent additional research opportunities at master, doctoral and post-doctoral level.

Among the novel technologies for accelerators, neutrino factories using decays of muons in a storage ring to produce high unique energy electron-neutrino beams have been proposed. On a much longer time scale, this would open the way to muon colliders allowing very high-energy point-like collisions. Success of these machines depends on the ability to provide multi-MW proton drivers together with the corresponding targets that withstand the extreme thermo-mechanical conditions. PSI's 1.4 MW proton beam is a unique resource that enables PSI to contribute in this field. It is also necessary to cool muons, which is the object of the MICE experiment at RAL, proposed and led by researchers at University of Geneva.

Cosmic Accelerators and Sources: We can only obtain data from cosmic accelerators and sources in the form of different cosmic "messengers", high-energy particles which come from space. These messengers include charged cosmic rays with energies from below GeV up to 10^{20} eV, photons with energies from 10^{-6} eV to 10 TeV and neutrinos with energies from MeV to EeV. These data can be used to understand the physical processes involved in particle acceleration and interactions in cosmic accelerators. These operate in extreme physical environments, which cannot be created in the laboratory, such as extremely strong gravitational and magnetic fields or extremely high matter densities. This opens a possibility to investigate the limits of applicability of the known fundamental physics laws in such unique physical environments. Cosmic scale laboratories are also our unique possibility to study physical phenomena, like gravitational waves and black holes.

The information from gamma-ray messengers might be transformed or washed out on the way from the source to the telescope due to interactions with low energy photons, including starlight, infrared light and CMB. In this respect, neutrino messengers provide a cleaner signal. Neutrinos could come from more compact sources and from larger cosmological distances, enabling the study of cosmological evolution of high-energy activity of sources in the Universe. On the other hand, the interactions of very-high-energy gamma-rays in the intergalactic space can be used to probe the intergalactic medium.

Intended contribution to the NCCR

Man-made Accelerators: The NCCR Universe will closely collaborate with CERN and PSI in research and development of future accelerators. Depending on the nature and energy scale of new phenomena discovered at LHC, several types and specifications of a future high-energy accelerator project may be envisaged. Superconducting linear colliders or two-beam accelerators of the CLIC type may be appropriate, if an electron-positron collider is the right answer to the physics questions of the next generation. Other options include a possible electron-proton extension of the LHC. More unconventional approaches, such as plasma wake field accelerators or a muon collider, may also qualify as options for the future.

A full design study for intense neutrino beams, EuroNU, is ongoing to study and compare cost and feasibility of super-beam, beta-beam and neutrino factory with support from the EU. All possible options for high intensity neutrino beams require a very high-intensity proton source. Such a source would also benefit other aspects of CERN activities, from future luminosity upgrades at the LHC to nuclear physics and even material sciences. Subsequent intensity increases will require the development of many other new techniques to prepare, accelerate and store muons that subsequently decay into neutrinos. An assessment on the technical feasibility and on the costs of such facilities should emerge towards the end of the EuroNU design study around mid-2012.

The MICE experiment at RAL, in which Geneva plays a leading management role, has already commissioned the beam and much of the infrastructure, and will be carrying out the first measurements of cooling starting in 2012. In 2014–2016 measurements including RF acceleration of muons will be performed thus demonstrating the feasibility of an operational cooling channel.

Cosmic Accelerators and Sources: The main focus of research will be the origin of cosmic rays, as well as mechanisms of high-energy particle acceleration and interactions. Measurements of the spectra and anisotropies of components of the cosmic ray spectrum just have started with a space-based AMS-02 detector. These data will be used for the study of cosmic rays with energies up to 10-100 TeV. For higher energies, because of the very low particle flux, satellites cannot be used, one needs to include the Earth atmosphere as part of the detector. The Cherenkov Telescope Array (CTA) will use the technique of imaging Cherenkov light produced by high-energy particle showers in the atmosphere to detect cosmic rays and gamma rays. At still higher energies, the JEM-EUSO space-based detector will image fluorescence emission by particle showers initiated from 10^{20} eV cosmic rays. These facilities will be used in the course of NCCR to obtain the best possible information on the spectrum, composition and anisotropy properties of the cosmic ray flux across all the energy range from GeV to 10^{20} eV. All of these new instruments use technology and concepts inherited from experiments at particle accelerators.

The cosmic ray data will be complemented by multiwavelength photon and neutrino data. CTA will for the first time be able to scan the full sky looking for very-high-energy gamma-rays from cosmic accelerators. Operation of newly completed IceCube will open the field of very-high-energy neutrino astronomy. The sensitivity of IceCube for astronomical sources of high-energy neutrinos will match that of the existing space- and ground-based gamma-ray telescopes, although in a somewhat higher energy range. Work toward the discovery of first cosmic sources of high-energy neutrinos is foreseen in the framework of NCCR.

Cosmic scale laboratories will also be used to explore the nature of relativistic gravity with two complementary probes. Strong, non-perturbative gravity effects will be probed via the study of environments of astrophysical black holes, using X-ray and gamma-ray astronomy. The LISA space-based gravitational wave detector will aim at the direct detection of gravitational waves from merging stellar binary systems and relic gravitational wave background from the Early Universe.

4.3.1 PROJECT: HADRON AND LEPTON COLLIDERS

Coordinators: L. Rivkin (EPFL and PSI), T. Garvey (PSI)

Research question and state of the art

The European Strategy for Particle Physics, adopted by the CERN Council in 2006 recognized that in order to fully exploit the physics potential of the LHC "a subsequent major luminosity upgrade, motivated by physics results and operation experience, will be enabled by focused R&D". The first year of LHC operation exceeded the integrated luminosity goals of 1 fb^{-1} by a factor of five. It is planned to attain the ultimate luminosity by 2020 and to accumulate a total of 3000 fb^{-1} by 2030, collecting yearly 300 fb^{-1}.

Strong international R&D effort on the high luminosity LHC upgrade with significant contributions from Swiss universities, in particular from EPFL as part of the FP7 High Luminosity Large Hadron Collider Design Study, is on the way. The operational experience with the LHC has pointed out some promising directions towards increasing the integrated luminosity of LHC. These include luminosity leveling, new designs of the interaction region optics, flat beams collisions as well as a "crab-waist" scheme using additional sextupole magnets around the interaction point.

Pushing the energy and luminosity frontier beyond the LHC requires an advanced accelerator R&D for e^+e^- linear colliders. The CLIC two-beam high gradient acceleration scheme has the potential to extend the energy reach of linear colliders towards multi-TeV region. In the framework of the CLIC Collaboration EPFL and PSI are contributing to the development of high gradient X-Band RF accelerating structures. There is substantial interest in such development for the future light source projects and in particular for the SwissFEL project at PSI.

Intended contribution of the project

LHC High Luminosity Upgrade: The integrated luminosity of the LHC can be significantly increased by implementing the so-called luminosity leveling. It consists of maintaining the luminosity in the detector at a constant level by adjusting continuously the beam parameters in order to compensate for the decay of the beam current. One such method, utilizing relative transverse beam displacement, was successfully implemented at the LHCb experiment last year. Detailed analytical and simulation studies, verified by dedicated experiments will be performed as part of the luminosity upgrade to be implemented in all the LHC detectors. Crab cavities are planned both for compensation of the crossing angle and for luminosity levelling, allowing for optimum integrated luminosity during the collision run without the need of excessive peak intensities.

Several promising ideas and their combination are under consideration for luminosity upgrade. The first is a large “Piwinski angle”, the second is flat-beam collisions and the third a so-called “crab-waist” collision scheme. The latter has recently been successfully tested at the DAϕNE e^+e^- collider in Frascati. Flat beams and large Piwinski angle by themselves could boost the luminosity of the existing collider as built, but are also prerequisites for a crab-waist scheme that suppresses the non-linear betatron resonances and increases the beam-beam interaction limit, allowing for additional luminosity increase. Included will also be a study of options for correcting chromatic aberrations from the optics focal system near the experiments.

High gradient X-Band accelerating structures: The CLIC Test Facility-3 (CTF3) is a prototype accelerator complex which has been built by the collaboration to demonstrate that many of the key accelerator and technology challenges which would be required for CLIC can indeed be met. EPFL has contributed to CTF3 through the participation of doctoral students.

The CLIC concept is based on the use of accelerating structures operating at an unusually high frequency and high accelerating gradient for a given level of RF power. The use of higher frequencies also favors improved efficiency as the energy in the structure, which is not extracted by the beam, is dissipated as heat. Therefore, higher frequency structures, with their reduced volume, are more efficient. CLIC aims to operate with “X-band” (12 GHz) structures at a gradient of 100 MV/m. Their development is a considerable technical and scientific challenge. PSI and EPFL, supported by FORCE funding, are already contributing to such studies.

There are numerous difficulties with the development of an acceptable X-band structure for CLIC. Although higher frequencies permit an increase in accelerating field they also increase the strength of the so-called “higher-order-modes” (HOMs). This implies that the structure’s “wake-fields” will also be increased. The design must, therefore, include features to reduce the strengths of the wakes if the collider is required to accelerate several bunches per RF pulse. This latter condition is necessary to meet the luminosity requirements of the collider.

One approach to the reduction of wake-fields is to reduce their strengths by "damping" them with lossy ceramic material built into the structure. Such material can be built into slots machined into the cell volume perpendicular to the structure's axis. The HOMs would propagate into the slot and be damped by the ceramic. Simulations indicate that the quality factor of such modes has to be reduced below ten. Care must be taken in the choice of damping material. Candidate materials are available from industry but their RF properties at high frequencies are not well known. It is important for the design of the structure to have accurate experimental determination of the frequency dependence of the loss tangent and dielectric constant of the materials at high frequencies.

PSI and EPFL, in collaboration with CERN, are currently performing a survey of possible materials and measuring their properties. With the support of SNF funding PSI is currently working on the design of what would be the "base-line" CLIC accelerating structure.
It is important to experimentally verify the strengths of the wakes by performing tests with beams. As part of our contribution to this project we are working on the design of a "multi-purpose test structure" (MPTS). This structure would correspond to the design of the CLIC base-line but would be machined from aluminium (as opposed to high quality copper for the real structures). We propose to perform experiments in which the wakes are excited in a sequence of structures by a "drive" bunch and the strengths of the wake is indicated by its effect on a trailing "witness" bunch. Such tests could be performed at the Facility for Advanced Accelerator Experiment Tests (FACET) at SLAC. This facility uses part of the SLAC linac to provide beams for such tests.

An important question is: what is the effect of introducing damping slots on the breakdown rate? A new program of structure testing is one of the highest priorities of the CLIC collaboration for the coming years to address this and other questions. Recently a consortium of three laboratories, CERN, PSI and Sincrotrone Trieste (ST), has financially supported the development at SLAC of a 50 MW klystron operating at 12 GHz. Four such klystrons have now been built and each laboratory will soon have the potential to test CLIC structures. This activity represents an important synergy between the Free Electron Lasers, such as PSI's SwissFEL and CLIC for X-band structures.

Our contributions to the NCCR would thus consist of an optimization of the design of an X-band structure for CLIC. The work would consist of several aspects: experimental determination of the RF properties of possible lossy ceramic materials for the HOM dampers; electromagnetic structure design taking into consideration the properties of the ceramic materials studied; realization of prototype structures for low power RF measurements of the frequencies and Q's of the HOMs; numerical and experimental tests of the wake-fields generated in prototype structures employing test beams on FACET.

Links to other projects of this NCCR
There are numerous links, through common methodology and technology, to the projects 4.3.2 and 4.3.3. The requirements governing this project mainly come from the outcome of the Challenge 4.1.

4.3.2 PROJECT: HIGH INTENSITY BEAMS AT PSI

Coordinators: L. Rivkin (EPFL and PSI), M. Seidel (PSI), P.-R. Kettle (PSI)

Research question, state of the art and intended contribution of the project

Intensity limitations in cyclotrons: Cyclotrons are today the most cost effective and energy effective solution for generation of high intensity beams of protons up to 1 GeV. The 35 year old PSI cyclotron produces the highest intensity proton beam in the world and represents an ideal test bed for studying the fundamental intensity limitations in cyclotrons.

For operational reasons the extraction losses in a high intensity proton accelerator should be kept very low, typically at or below 100 W. High beam power e.g. on the order of 10 MW thus requires achieving 10 ppm relative losses. The present PSI accelerator has so far demonstrated losses below 100 ppm.

The loss is caused by beam tails, generated by beam dynamics effects such as space charge, coupling/beam mismatch and/or by unfavorable initial phase space at the source. Better understanding of tail generation mechanisms is necessary for further improvements of the PSI facility or extrapolation to other cyclotron designs.
The goal of this R&D is to understand the tail production mechanisms at PSI operating conditions via

- analytical studies;
- numerical tracking studies using High Power Computing;
- experimental studies and verification at the operating PSI cyclotron.

The results will be used to propose measures for further improvements (loss reduction) at the PSI High Intensity Proton Accelerator (HIPA). They will also be used to propose key aspects of a next generation very high power cyclotron facility.

High intensity muon beam line: The high-intensity frontier coupled with precision-type experiments is an excellent candidate for enabling the search for new physics beyond the Standard Model (SM). Specifically, the search for "rare" decays, which can manifest themselves in signatures hidden to the complementary direct searches at the energy frontier, are those suitable candidates, providing high enough beam intensities can be achieved.

The muon as a laboratory for this type of search is still the most sensitive tool within the frame-work of lepton decays and the study of flavor physics, see Section 4.1.9. Of the three "golden" lepton-flavour violating (LFV) channels, namely, $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\mu N \rightarrow eN$, the first two, being coincidence experiments, are particularly suited to a DC machine structure such as that of the PSI ring cyclotron. This is due to the lower instantaneous rate, which reduces the accidental background, one of the main limitations of such experiments.

Currently, the most sensitive limit to date on the LFV-decay $\mu \rightarrow e\gamma$, has been achieved using the world's most intense source of low-energy muons from the PSI PiE5-channel and associated MEG beam line. However, for the next generation of experiments, such as the planned $\mu \rightarrow 3e$ experiment at PSI or the $\mu N \rightarrow eN$ conversion experiments Mu2e at Fermilab and COMET and PRISM/PRIME at J-Parc, far more intense muon beams are required to reach sensitivities of 10^{-16} and beyond. This in turn requires the development of new high intensity muon sources and transport systems.

One new, yet simple idea of P.-R. Kettle, that of producing a high-intensity source of surface muons (muons obtained from stopped pion decay at the surface of a target) could be achieved by using a spallation neutron source, such as PSI's SINQ source as a production target. Initial muon flux estimates have been confirmed by use of realistic Monte-Carlo simulations and show that enhancement factors of two-to-three orders of magnitude might be possible compared to the current primary target situation. The enhancement is four-fold: the increased number of primary proton interactions, the increase in the pion production cross-section for backward production angles, the increase in the pion production cross-section due to the higher-Z material of such a spallation target and finally the enhancement due to the increased capture probability for higher-energy pions stopping in the spallation target window.

Furthermore, the utilization of part of the upward, incoming proton beam line, in the reverse direction to allow the extraction of the same charged-sign muons via the final proton beam dipole magnet, into an already present underground bunker, to be used as the front-part of the high-intensity surface muon beam line, would technically simplify such a solution.

The impetus for such a high-intensity source at PSI is also confirmed by the need for a multi-GHz muon beam for a phase II $\mu \rightarrow 3e$ experiment with a goal of achieving a sensitivity of 10^{-16}. The collaborative synergy between experimental partners and PSI towards the design and construction of such a muon beam line would help maintain the current world class muon beam facilities at PSI, also in the future, with muon intensities similar to the far more complex facilities at Fermilab and J-Parc.

Links to other projects of this NCCR

Proof of principle demonstration of extremely low losses in a High Intensity Proton Accelerator facility like the PSI cyclotron is an essential step towards the future facilities based on high intensity and brightness muon beams.

4.3.3 PROJECT: INTENSE NEUTRINO BEAMS AND FACTORIES

Coordinators: A. Blondel (UniGe), A. Rubbia (ETHZ)

Research question and state of the art

Neutrino beams are essential for the study of neutrino oscillations, in particular for the search and measurement of CP violation and the determination of the neutrino mass hierarchy. The observation of CP violation requires an appearance measurement. Two types of beams can be considered. i) the conventional neutrino beam from $\pi \rightarrow \mu\nu_\mu$ decays; ii) storage ring neutrino sources, from muons (Neutrino Factory), or beta-decaying ions (beta beam), in which the decay of the stored particles produce pure and well understood neutrino beams.

Conventional neutrino beams operate presently near maximum capacity, but offer still some possibility of optimization [110]. Studies exist, past [108] and ongoing [111], [112] for the storage ring sources, as well as intensive R&D programs.

The present state-of-the-art conventional neutrino beams [219] are the NUMI beam at Fermilab, the CNGS beam at CERN and the T2K beam at J-PARC. The most relevant performance parameter is proton beam power on target. The neutrino beam energy and baseline L are chosen such that L/E_ν is near the oscillation maximum. The number of oscillated events scales like neutrino cross-sections, linearly with neutrino beam energy.

In Japan [220], the T2K beam operates presently with a power of 150 kW, and will progressively increase to achieve the design value of 750 kW in the next 5 years. Eventually a beam power of 1.66 MW is hoped for. For the T2HK upgrade a new near detector station will be required.

At Fermilab, [221], the NUMI beam operates presently with a beam power of 320 kW, which will be upgraded to 750 kW for the NOvA experiment in 2014. For the DUSEL project a new beamline is designed, with beam power to be upgraded with the 2MW superconducting proton linac known as ‘project X’. The NUMI near detectors are small scale replica of the far detectors, respectively of MINOS and NOvA.
CNGS operates presently at 350 kW on average [222]. There is no near detector station. Improvements in the SPS beam power should allow 750 kW. CERN studies a north area neutrino beam up to 2 MW optimized for neutrino beam energy of 4.6 GeV, matching the CERN to Pyhasalmi 2300 km baseline. A near detector station will be mandatory.

The CERN to Pyhasalmi baseline [223] is very suitable for a Neutrino Factory [224], [225]. Matter effects are well understood [226]. The Neutrino Factory flux can be predicted better than 1%, for all four neutrino flavours of interest for appearance and disappearance experiments. The detector is a magnetized iron detector for the $\nu_e \rightarrow \nu_\mu$ ‘wrong sign muon’ detection. A magnetized fine grain (e.g. liquid argon) detector is needed for the other oscillation channels. The Neutrino factory is a challenging accelerator, to a muon collider. A critical R&D experiment is the Muon Ionization Cooling Experiment (MICE) presently in progress at RAL (UK) [227].

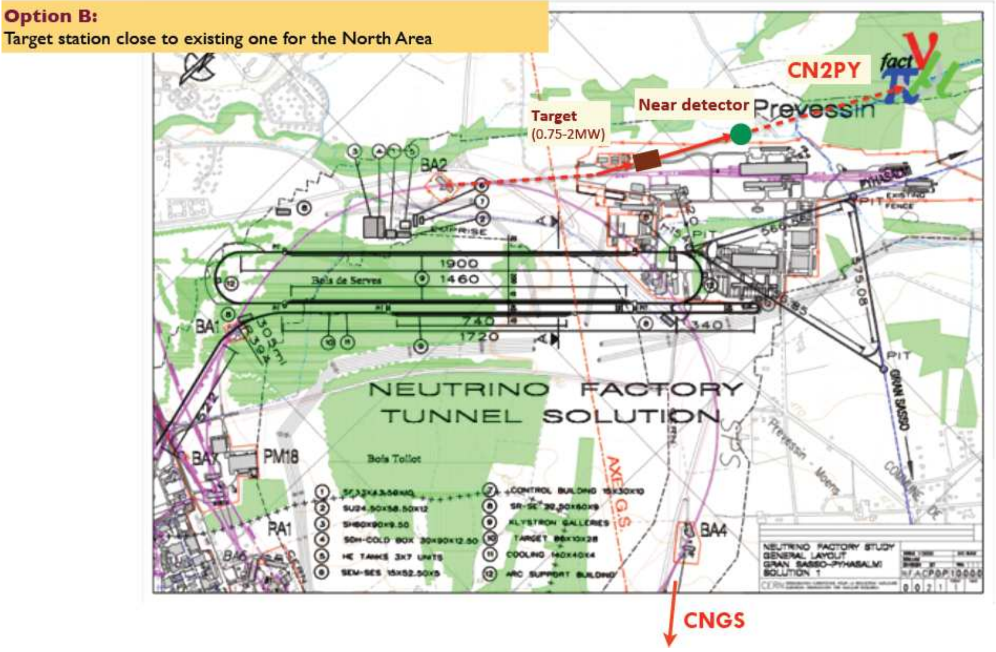

Figure 3: Possible scenario for development of beams at CERN [228] [229].

Intended contribution of the project

The contributions to the project will be structured as follows:

- ETHZ: global design and optimization of SPS neutrino beam from the CERN North Area to Pyhasalmi (C2PY).
- UniBe, ETHZ, UniGe: physics studies for the far detector: Mass hierarchy, CP violation, sterile neutrino searches and tests of unitarity.
- UniGe: design of near detector for C2PY, and evaluation of small scale muon storage ring for measurements of cross-sections.
- UniBe, ETHZ, UniGe: measurement of particle production off neutrino targets, evaluation of needs and possible improvements for future projects.
- All groups: submission of proposal by the end of LAGUNA LBNO design study in 2014.
- UniGe: MICE experiment, completion in 2016; international design study of the neutrino factory (IDS-NF).

These experimental activities will be complemented by associated theoretical and phenomenological work with the theoretical groups at EPFL and UniBs.

Links to other projects of this NCCR

The neutrino beam project is, clearly, of great importance for the neutrino oscillation project. Hadro-production measurements are important input for the description of cosmic ray air showers. Through the deep underground far detector, the project has considerable synergy with other deep underground physics including proton decay searches, detection of supernovae and detection of atmospheric neutrinos.

The excellence in accelerator technologies related to neutrino beams is synergetic with other aspects of the NCCR: high intensity beam technology for neutrino production is synergetic, especially in the beam handling and high intensity target area, with the development of high intensity muon beams at PSI and uses similar technologies. The development of a new accelerator technique, muon ionization cooling, in the MICE experiment for the neutrino factory is clearly of great interest for a muon collider either as a Higgs factory or a high energy frontier lepton collider.

The LAGUNA-LBNO and MICE projects will greatly benefit from the NCCR accelerator physics projects and reciprocally.

4.3.4 PROJECT: GALACTIC COSMIC RAYS

Coordinators: A. Biland (ETHZ), A. Neronov (UniGe), T. Montaruli (UniGe), M. Ribordy (EPFL)

Research question and state of the art

Most of the Cosmic Rays (CR) reaching the Earth have energies in the 0.1 to 10 GeV range. They are produced by (unknown) particle accelerators in the Milky Way and are playing an important role in the physics and chemistry of the interstellar medium (ISM). The CR flux is affected by extinction in the Heliosphere, so that the locally measured CR spectrum is not identical to the Galactic CR spectrum in the ISM. Deflections of CRs by Galactic magnetic fields preclude the possibility of localization and study of galactic CR particle accelerators. CRs diffuse through the ISM and spread only over distances less than about 1 kpc from their sources during the typical lifetime of 10^7yr. Nearby Supernova Remnants (SNR) and Pulsar Wind Nebulae (PWN) are conjectured to be the main candidate CR acceleration sites. However, a direct proof of this conjecture is missing.

Localization of the CR sources and understanding of the physical phenomena involved in their acceleration becomes possible only now, due to the progress in the domains of γ-ray and neutrino astronomy. Observations by a new generation of space- and ground-based γ-ray telescopes Fermi, AGILE, HESS, MAGIC and VERITAS have revealed numerous sites of particle acceleration in the Galaxy. The newly discovered VHE sources include known source types, like shell-type SNRs, PWNe and binary systems with black holes or neutron stars. However, the nature of the largest part of Galactic VHE sources is uncertain. These unidentified sources are the brightest and hardest spectrum sources in the Galaxy. Their energy output is dominated by emission in the γ-ray band, as expected from the “hadronic” sources powered by interactions of high-energy protons and nuclei.

Measurements of the properties of the CR flux at low energies are done with particle detectors mounted on balloons or spacecrafts. ETHZ and UniGe participate in the AMS-02 CR detector which was installed on board of the International Space Station in 2011. AMS-02 will provide precise information on the elemental composition, spectral characteristics and anisotropy of the CR flux penetrating into the Solar System, in the energy range up to 10 to 100 TeV. EPFL and ETHZ are involved in a next-generation balloon based CR detector PEBS optimized for the high-precision measurement of the electron/positron component of the CR flux.

The Galactic CR spectrum is believed to extend up to the “knee” energy range at 10^{15} eV. In this energy range the Earth atmosphere is used as particle detector. CRs penetrating the atmosphere initiate Extensive Air Showers (EAS) which can be detected either with particle detectors on the ground of via imaging of Cherenkov light from EAS particles at high altitudes. The best available measurements of the spectrum and composition of the CR spectrum in the knee region are done using surface detectors, like KASKADE-Grande. Higher statistics measurements in the energy range above the knee will be done in the near future with a setup which combines the IceCube neutrino telescope with the IceTop surface array of km^2 collection area. Research groups from EPFL and UniGe participate in IceCube/IceTop experiments.

Complementary measurements can be done via imaging of the Cherenkov light from EAS. This measurement technique will be used by CTA. The Cherenkov light imaging technique is sensitive to the chemical composition of the CR flux because the intensity of Cherenkov emission by the primary CR particle at the top of the atmosphere and the shape of the EAS image depend on the particle charge and mass. Swiss experimental astroparticle groups from EPFL, ETHZ, UniGE and UniZh have joined forces to contribute to CTA in a visible way. The main focus of activity of the Swiss groups is development of the focal surface instrumentation based on the novel type of high photon detection efficiency photosensors and the setup of the CTA Data Centre.

Intended contribution of the project

Different approaches should be considered to solve the problem of the origin of CRs in different energy bands and for different components of the CR flux. The four projects described below will are aimed to find the origin of the bulk of the CR flux (1-100 GeV energies), of the CR electrons/positrons and of the PeV energy CRs.

Origin of the bulk of Galactic CRs: Discreteness of the CR source distribution should lead to appearance of distinct features in the spectrum and/or angular distribution of CR species. We will look for such features in the spectra and angular distribution of individual components of the CR spectrum (protons, nuclei electrons/positrons) using AMS-02 detector. The CR spectrum and angular distribution are modified during CR propagation in the Heliosphere. The AMS-02 data on the spectra and time variability of the fluxes of CR species will be used to study the Heliospheric distortions of the CR flux. This should allow to deconvolve the spectral and anisotropy features due to the propagation in the Heliosphere from the intrinsic features of the Galactic CR spectrum. This will also lead to a better understanding of the structure of our Solar System, in particular, of the largely uncertain properties of matter and magnetic fields in the outer part of the Heliosphere.

Measurement of CR distribution in the local Galaxy: Measurement of the Galactic CR spectrum not affected by the effect of Solar modulation can be done in an indirect way via the detection of γ-ray emission from interactions of galactic CRs with large mass concentrations, like Giant Molecular Clouds, or with diffuse local ISM. Study of γ-ray emission from the entire Milky Way and from structures within 1 kpc distance will provide information the shape of Galactic CR spectrum and possible variations of the CR density with the distance from the local CR source(s). Such a study can be done with Fermi and AMS-02, below several 100 GeV (probing the distribution of TeV CRs) and at higher energies, up to 100 TeV, with CTA.

Origin of CR electrons and positrons: CR electrons and positrons cannot travel far from their sources. Compared to nuclei, electrons and positrons suffer from strong energy losses by inverse Compton and synchrotron emission. Strong energy losses are expected to introduce a sharp high-energy cut-off in the CR electron/positron spectrum. Detection of such a cut-off with AMS-02 will provide a measurement of the distance to the nearest source of high-energy electrons/positrons. A measurement of the anisotropy of the electron/positron flux with AMS-02 will provide a hint on the location of this source on the sky. Measurements of the positron spectrum by PAMELA reveal an “anomaly” in the positron flux above ~10 GeV. The existence of this anomaly will be clarified with AMS-02, which will provide the measurements of the positron flux with much better precision. If real, the peculiarity of the positron spectrum provides an important clue on the nature of the nearby electron/positron source. Complementary information will be obtained with CTA, which will detect γ-ray emission accompanying acceleration/production of electrons in the source and their propagation in the ISM.

Origin of the knee of the CR spectrum: It is not clear if our Galaxy hosts accelerators powerful enough to accelerate protons and nuclei up to the knee energy (10^{15} eV). The origin of the knee is equally uncertain. It might be related to a high-energy cut-off in the Galactic CR spectrum, or to a change in propagation of CRs in the Galaxy. We will use the high-statistics measurement of the CR spectrum, composition and anisotropy with IceCube/IceTop and CTA, to clarify the origin of the knee. This will be done via a measurement of composition of the CR flux as a function of energy. Complementary study will be done in the γ-ray and neutrino channels with CTA and IceCube: (non) observation of cut-offs in the spectra of Galactic sources in the 100 TeV band will tell if the knee corresponds to the limiting energy attainable in particle accelerators in the Milky Way.

Links to other projects of this NCCR
Transversal links are established with numerous projects, most notably with the project 4.3.6, which will adress the problem of the origin of CRs using the methods of γ-ray and neutrino astronomy. Similar nature of the problems of the origin of Galactic and extragalactic CRs implies a tight connection to the project

4.3.5. CR propagation is influenced by cosmic magnetic fields (project 4.3.9). Study of the peculiarities on the spectra and angular distribution of CRs might reveal the products of decay/annihilation of DM (project 4.2.7).

4.3.5 PROJECT: ULTRA-HIGH ENERGY COSMIC RAYS

Coordinator: A. Neronov (UniGe)

Research question and state of the art

Maximal energies of CRs reach ~10^{20} eV (a factor of 10^7 higher than the particle energies at LHC). It is not clear what physical processes make acceleration to ultra-high energy (UHE) possible. The sources of ultra-high-energy CRs (UHECR) are not known. Energetic considerations suggest several candidate UHECR source classes: supermassive black holes, jets or radio lobes of radio galaxies, γ-ray bursts (GRBs) or galaxy clusters.

The main obstacle for identification of the sources of UHECR is the intergalactic (IGMF) and Galactic (GMF) magnetic field. The effect of the GMF on the spectrum and anisotropy of UHECRs is reasonably small (100 EeV protons are typically deflected by just 1 to 3 degrees). This opens the possibility to identify UHECR sources via back-tracing of the arrival directions of the individual UHECR events. It is not clear if the UHECR could simply stream freely through the intergalactic space, or they diffuse through the IGMF. If the IGMF strength is close the known upper bound (~1 nG), the CR gyroradii reach values comparable to distances of nearest extragalactic CR sources (e.g. the closest radio galaxies) only for energies above 10^{20} eV. Deflections by GMF and IGMF are further increased if UHECR are heavy atomic nuclei, rather than protons. In this case identification of UHECR sources should be possible via a study of energy- and charge-dependent deflection patterns of UHECR around individual sources. Such a study requires high statistics of events above 10^{20} eV.

The UHECR flux is suppressed above 10^{20} eV. It is not clear if the suppression is due to the effect of propagation of UHECR through the intergalactic medium (IGM) or it is due to the limitations of the Nature-made particle accelerators. Higher statistics of UHECR events is needed to distinguish between the two possibilities.

The statistics of UHECR events is limited by the effective area of UHECR detectors (1 UHECR hits an area 100 km^2 every 100 yr). Largest effective areas are reached by the currently operating UHECR detection facilities: Pierre Auger Observatory (PAO) and Telescope Array (TA). Both experiments use a combination of surface particle detectors (water tanks in PAO, scintillators in TA) on the ground with the air fluorescence telescopes detecting UV emission from excited air molecules along the path of UHECR induced EAS in the atmosphere. An increase of collection area will be achieved with JEM-EUSO, a fluorescence telescope which will be installed at the International Space Station (ISS) in 2017. UniGe and CSEM are involved in JEM-EUSO.

The nature of the high-energy suppression of UHECR spectra could be clarified via the search for UHE neutrinos (UHEν). EPFL and UniGe participate in the IceCube neutrino telescope which has a sufficient sensitivity for the detection of the neutrino signal from UHECR protons interacting with the CMB with a multi-year exposure. Measurement of UHEν flux with IceCube will provide information on the cosmological evolution of UHECR sources. A complementary search of UHEν will be done with JEM-EUSO. JEM-EUSO measurements will provide information on the maximal energies to which CRs are accelerated in Nature.

Intended contribution of the project
The identification of UHECR sources requires a higher UHECR statistics and the knowledge of the GMF and IGMF. These are the main subjects of research in the sub-projects described below.

High-statistics measurements of UHECR flux: JEM-EUSO will observe UHECR across a 400 km size region below the ISS, providing an effective collection area > 100 times larger than that of PAO above 10^{20} eV. Contrary to existing experiments, JEM-EUSO will have an all-sky coverage, important for the analysis of large angular scale UHECR distribution. JEM-EUSO will use the Earth's atmosphere as an UHECR detector. Detailed knowledge of this detector is required for the interpretation of the fluorescence signal from EAS. Some 70 % of UHECR events seen by JEM-EUSO will occur in cloudy sky conditions. We will develop a system of monitoring of the atmosphere, to measure UV transmission and scattering properties of clouds and aerosol layers in the JEM-EUSO field of view. These measurements will be used to correct the UHECR data for atmospheric effects and to retain the events occuring in the cloudy sky for further analysis. This will be possible because a significant part of the fluorescence signal is typically produced above the low-altitude clouds in the Troposphere.

We will study anisotropy patterns of UHECR detected by JEM-EUSO to search for UHECR sources. If UHECR particles are protons, the sources will appear as excesses on the scale of the angular resolution of JEM-EUSO telescope (~1°). If a significant fraction of UHECR is heavy nuclei, more complicated energy-dependent patterns of the UHECR distribution around sources are expected. In this case, sources could be identified via a search of energy-dependent template angular distributions of UHECR determined by the GMF and IGMF.

Galactic and intergalactic magnetic fields: Knowledge of the GMF is necessary for a proper understanding of the angular distribution of UHECR. We will use the data of new radio telescopes, LOFAR and (in the near future) SKA to obtain a precise three-dimensional model of the GMF derived from the measurements of Faraday rotation and dispersion measures of emission from a large number of pulsars. Based on the model, we will calculate the distributions of UHECR events around the sources, as a function of the source position.

UHECR data will be used to measure or to impose constraints on the IGMF strength and correlation length. Absence of IGMF induced distortions of the angular distribution of UHECR will impose a limit on IGMF at the level of $\sim 10^{-11}$ G, two orders of magnitude better than the known upper limits. If the IGMF is in the range $10^{-11} - 10^{-9}$ G, deviations of the angular distributions from those produced by the GMF will be found.

Measurement of the deviations will provide a measurement of IGMF strength. Still weaker IGMF will be probed by observations of UHECR induced cascades in the IGM using γ-ray telescopes, in particular, CTA. UHECR and γ-ray measurements will be used together to constrain the nature of the recently discovered IGMF.

Ultra-high-energy neutrinos are produced by UHECR interactions in the IGM. Neutrinos are not absorbed during propagation through the IGM and could be detected from sources at cosmological distances, thus providing information on the cosmological evolution of UHECR sources and on the maximal energies attainable in particle accelerators in the Universe. We will search for the UHE*ν* signal from UHECR interactions (both inside UHECR sources and in the IGM) using IceCube and JEM-EUSO. The two telescopes are sensitive to the neutrino flux in adjacent energy bands, from 10^{17} eV up to 10^{20} eV. Similarly to UHECR, UHEν initiate particle cascades in the atmosphere. UHE*ν* air showers can be distinguished from UHECR showers, based on the depth of the first interaction. The first interaction point of UHE*ν* could well be not in the atmosphere, but in the ice layer surrounding the IceCube. If the UHE*ν* flux will not be detected by IceCube and JEM-EUSO, this will imply that significant part of the observed UHECR flux consists of heavy nuclei, rather than protons.

Complementary information on the interactions of UHECR in the IGM will be obtained from the measurement of diffuse extragalactic *γ*-ray background above 100 GeV by CTA and Fermi. UHECR interactions induce electromagnetic cascades with most of the released energy finally emitted in the 100 GeV band. The flux of the 100 GeV *γ*-rays from UHECR interactions is comparable to the flux of UHE*ν*, so that constraints on the extragalactic *γ*-ray background in the 100 GeV range can be used to constrain the expected UHE*ν* flux.

Links to other projects of this NCCR

This project is related to the project 4.3.4 which will concentrate on the search for the sources of lower energy CRs. The multi-messenger approach to the source identification (via CR, *γ*-ray and neutrino channels) will be also in the focus of the project 4.3.6. Nuclei of active galaxies, powered by supermassive black holes are possible sites of UHECR acceleration and will be a subject of study in the project 4.3.7. Interpretation of the UHECR data requires knowledge of the interaction cross-sections above 10 TeV, an information which is obtained from LHC, which is in the focus of the Challenge 4.1. The IGMF measurement is also a subject of the project 4.3.9.

4.3.6 PROJECT: COSMIC SOURCES IN A MULTI-MESSENGER STRATEGY

Coordinators: T. Montaruli (UniGe), A. Neronov (UniGe), M. Ribordy (EPFL), A. Biland (ETHZ)

Research question and state of the art

The project concerns the understanding of the highest energy phenomena in the Universe and of the nature of extragalactic and galactic sources of high energy particles through the combination of information from photon, neutrino and cosmic ray (CR) experiments. Our current knowledge of these sources comes from photon observations in the optical, radio, X-ray and *γ*-ray regions. Most of the observed photon signals are compatible with emission from high-energy electrons, but solid evidence exists that a part of the power of these sources goes into proton and nuclei acceleration. As a matter of fact, we observe CRs from GeV to about 100 EeV. It is not evident at today what are the acceleration sites, the mechanisms of conversion of such power into matter acceleration and its efficiency. These are the goals of this project and of high-energy *γ*-ray, *ν* and CR facilities.

Switzerland is involved in: the IceCube neutrino telescope operating above 100 GeV (EPFL and UniGe), the space-based soft *γ*-ray telescope INTEGRAL in the sub-MeV range (UniGe), the ground-based *γ*-ray telescope MAGIC operating above 50 GeV (ETHZ). A new generation facility for ground-based *γ*-ray astronomy, the Cherenkov Telescope Array (CTA), is now in design phase moving to construction phase. The array, a mixture of small, middle and large-size telescopes, will improve the sensitivity of the current generation of telescopes by about a factor of 15. Moreover, it will extend the energy reach down to about 20 GeV, to overlap with Fermi, and it will cover the still unexplored region of up to 100 TeV where hadronic acceleration may become evident. New technology based on Geiger-mode Avalanche PhotoDiodes (G-APDs) has been successfully employed by the prototype telescope FACT. This is the first working proof of this high photon detection efficiency technique in γ-astronomy. The G-APD camera of FACT was developed by ETHZ with participation of EPFL. EPFL and UniGe are involved in the first cubic kilometer neutrino telescope IceCube which uses about 6000 PMTs in the Antarctic ice to measure the Cherenkov light from muons and showers produced by high-energy neutrinos. It will unequivocally prove hadronic acceleration in sources by observing neutrinos produced by high-energy protons interacting with matter or ambient photons in cosmic sources. A proposal exists to extend the reach to lower energies with a denser core of PMTs inside IceCube. UniGe is also developing a γ-ray polarimeter POLAR to be launched in 2014 to measure polarization of γ-ray burst (GRB) prompt emission.

Intended contribution of the project

We define 4 projects dedicated to the search and identification of sources of extragalactic and Galactic CRs among Active Galactic Nuclei (AGNs), GRBs and supernova (SN) related phenomena. The observed power in the spectrum of UHECRs is compatible with the energy density of observed populations of GRBs and AGNs. Similarly, below the knee of the CR spectrum at 10^{15} eV, SN remnants are considered as the main galactic CR candidate sources.

Jets and supermassive black holes in AGNs: The goal is to understand what causes flaring activity of AGNs (from minutes to days) during which observed fluxes may rise by up to a factor of 10 to 100. Flares can unravel hadronic phenomena due to protons accelerated in the jets through neutrino detection since the time tag helps rejecting the atmospheric backgrounds. Orphan flares in the TeV band not accompanied by X-ray flares are are not naturally explained by leptonic models, where photons are produced by Inverse Compton on high energy electrons that also produce synchrotron emission at lower energies. We aim at establishing an online search for AGN flares using IceCube data and light curves from Fermi and other experiments. These can be used to establish the long-term behavior of sources while indicating the relative importance of flaring states. This program will profit of the long-term monitoring with the FACT telescope and later with CTA that will provide precise spectra in a wide energy range. This will clarify if such minute-scale variable emission from blazars is produced by a small accelerating region at the base of the jet or by intrinsic small scale instabilities at large distances from the black hole. Since neutrinos are not absorbed during their propagation from and inside sources, their observation will provide information on cosmological evolution of AGNs, on the maximum energy achievable in sources and on the nature of accelerated hadronic components.

Gamma-ray bursts: GRB duration indicates that they are produced by two different populations of sources: short bursts (≤ 1s) by binary mergers and long bursts (~1 to 1000 s) by core-collapse of massive stars. These hypotheses are yet not fully verified as well as the mechanism of GRB broad band emission. The goal of this task is to clarify the origin of the GRB phenomenon and investigate particle acceleration in GRBs. The “prompt” emission in the MeV range could be due to synchrotron or inverse Compton from non-thermal electrons or thermal emission form the GRB “fireball”. The polarization measurement of the MeV prompt emission by POLAR will provide information on this aspect. Observations by Fermi have revealed the existence of an additional power law component of the prompt GRB emission reaching up to 30 GeV whose origin can be clarified through the measurement of the spectrum at higher energy. This could be possible with CTA with faster pointing, lower energy reach and large number of telescopes. The role of hadrons in GRB phenomena, and hence possible significance of GRBs as CR sources, is assessed via IceCube observations. Its stringent limits exclude the possibility that GRBs are the dominant sources of UHECRs or that hadrons are efficiently accelerated in fireballs. Moreover, we will conduct a continuos monitoring of neutrino emissions in coincidence with bursts detected by Fermi, SWIFT, INTEGRAL and other detectors.

Galactic cosmic ray sources: CRs with energies above TeV, which were produced by sources over the last ~30 kyr, fill regions of ~100 pc around them. Interactions of CRs with the interstellar medium in such extended regions lead to detectable γ-ray and neutrino emission. We will search for degree-scale extended γ-ray and neutrino sources in the Galactic Plane using CTA and IceCube. We will test the hypothesis that the extended CR regions are the bright unidentified Galactic sources revealed by the H.E.S.S. Galactic Plane survey and find the points of recent injections of CRs in the Galaxy. Having precise information on the source spectra and morphology from CTA to ~100 TeV, we will optimize IceCube analysis to search this potentially extended neutrino signal. IceCube, when using upgoing neutrinos, is exposed to part of the galactic plane containing important regions such as Cygnus where PeVatrons have been observed by Milagro.

Supernovae: The end of a star life is one of the richest physics laboratories, as illustrated by the detection of cosmic acceleration and of neutrinos from SN1987A. The few neutrino events observed from SN1987A contained information on the mechanism of gravitational collapse, on neutrino mass and unitary matrix and led to strong constraints on some of Nature's fundamental symmetries. IceCube will have unprecedented statistics of inverse beta-decay events induced by supernova electron anti-neutrinos. It will reconstruct the neutrino lightcurve, determine the t_0 of the collapse with time precision of ms, produce an alert to other neutrino and optical detectors at the level of 3-10 sigma (pre-trial) for a SN in the Large Magellanic Cloud and at more than 25 sigma for a SN in the Galaxy. The coincident observation between detectors would be unequivocally evidence for SN collapse neutrinos. UniGe and EPFL will participate to this SN monitoring with IceCube.

Links to other projects of this NCCR

The above program highlights activities that enhance the potential of various experiments employing different techniques to observe cosmic messengers. The understanding of how cosmic accelerator works may open unexpected options to power terrestrial accelerators. The new means of observation of the universe, gravitational waves and neutrinos, will be the new observational window in the sky, while the high precision gamma astronomy will enable their discovery and provide the details on sources. This project is correlated to the projects in 4.3.4, 4.3.5, 4.3.7 (neutron stars and black holes are objects governed by relativistic gravity) and the project on SN physics 4.3.8.

4.3.7 PROJECT: RELATIVISTIC GRAVITY

Coordinators: S. Paltani (UniGe),
Ph. Jetzer (UniZh)

Research question and state of the art

Three out of four known fundamental interactions can be studied at particle colliders (electromagnetic, weak and strong). Gravitational interaction is not directly accessible in this way. Instead, the main tool for the study of the nature of relativistic gravity (RG) is astronomical observations. Our knowledge of RG is constrained to the weak field and/or mildly relativistic regime, in which the effects of RG appear as corrections to Newton's theory. Existing data are consistent with predictions of General Relativity (GR), which is the main candidate for the RG theory. GR has not been tested at very large, cosmological, scales and in the strong field, non-perturbative, regime. Testing the GR in the strong field regime is of the highest importance, since possible deviations of the true RG theory from GR might be related to the Dark Matter and Dark Energy problems.

GR makes particular predictions on the structure of space-time near strongly gravitating systems: black holes (BH) and neutron stars (NS). Tests of GR can be done using observations of phenomena related to supermassive BHs in the nuclei of galaxies and smaller mass BHs and NSs in stellar systems. Another prediction of GR is on the properties of gravitational waves (GW). Search and detection of GW expected from various sources, from binary stellar systems to the Early Universe, will be a strong test of GR.

ETHZ and UniZh are involved in the construction of the LISA-Pathfinder satellite, scheduled for launch in 2014, with the aim to test the technical feasibility of the LISA mission. LISA will be a space-based GW detector which will use measurements of GW induced variations of distance between several satellites to detect low frequency GWs (0.1–100 mHz). Such GWs from merging BHs will produce a very clean signal, measurable with high precision with LISA. Alternative RG theories influence the dynamics of such mergers and hence LISA is expected either to directly see the imprints of certain alternative theories or to put severe constraints on them. Apart from the GWs from the merging systems LISA will be able to detect or put strong constraints on the primordial gravitational radiation, which is, just as the cosmic microwave background, a leftover from the Big Bang. At present, LISA is under study as an ESA only mission of the L-class.

UniGe is involved in research on astrophysical BHs and NSs. Activity of astrophysical BHs and NSs induces a range of thermal and non-thermal phenomena and is accompanied by electromagnetic emission. Observations in the X-ray band provide diagnostics of phenomena in the strong gravitational field near the BH horizon. BHs generate (via an uncertain mechansim) relativistic jets spreading high-energy particles over very large (megaparsec-scale) distances. EPFL, ETHZ and UniGe are involved in the development of the CTA components. The focus of activity of UniGe group is observations of BH and NS systems in X-rays and γ-rays with existing telescopes (INTEGRAL, XMM-Newton, Fermi and others) and development of next generation instrumentation for the X-ray (Astro-H, LOFT, POLAR) and γ-ray astronomy (CTA, together with EPFL and ETHZ).

In the stellar mass BHs and NSs the characteristic time scales are shorter than 0.01 s, meaning that the GR effects reveal themselves in variability at > 100 Hz in the Fourier space. In this frequency range, quasi-periodic oscillations (QPOs), have been discovered by RXTE. Physics behind these high-frequency QPOs is governed by the RG effects, which are not clearly understood. A massive step toward understanding of the nature of the high-frequency QPOs will be done with the LOFT, an ESA Cosmic Vision M-class mission. UniGe is co-leading this project, together with SRON, the Dutch space agency, and is actively contributing to the development of silicon-based X-ray sensors that can be deployed over large areas (> 10 m^2).

Intended contribution of the project

LISA and LOFT missions are planned to be launched after 2020, so that the data will be available toward the end of the NCCR project. Main efforts within NCCR will be devoted to the preparation of the missions and to research on the physics related to LISA and LOFT. CTA will start operation within several years. The CTA-related part of the project will concentrate on the analysis of fast-variable γ-ray emission from AGN and its implications for the mechanism of activity of supermassive BHs and for the origin of relativistic jets.

Gravitational waves: A study of the effect of alternative RG theories on the GW signal from a range of sources will be done. Measurement of the parameters of the merging binaries from the GW signal in LISA could be done only when a number of the relevant physical processes is taken into account. This includes precession of the orbital angular momentum and of the individual spins of components, the spin-orbit and spin-spin couplings as well as orbit eccentricity. Signatures of alternative RG theories could be revealed only when all these factors are taken into account. These signatures will appear as corrections to the phase and amplitude of the GW signal. The Fisher matrix approach used so far for the calculation of these effects could be used only when the signal-to-noise ratios are high. Development of a new Markov Chain Monte Carlo simulation code, better suited for the lower signal-to-noise ratios, is planned. A range of alternative RG theories predicts extra GW polarizations. The existence of such extra polarizations would immediately put GR into question and favor proposed alternatives. Such additional degrees lead to faster energy loss in compact binary inspirals. We will build a framework which accounts for such effect in parameter estimates for binary inspirals.

High-frequency quasi-periodic oscillations: Nature of the high-frequency QPOs could be constrained by the measurement of light-curves of X-ray binaries with ms time resolution. This will be done with LOFT, which will have large enough collection area to achieve sufficient signal statistics. Before the start of operation of LOFT, constraints on the nature of fast QPOs will be imposed via measurement of coherence time scale of QPOs. Constraints on the coherence times in the range of 0.1 s challenge currently existing theoretical models in which clumps orbiting the BHs are destroyed on much shorter time scales by the differential rotation. Study of the coherence time scale will reveal the possibilities of testing the GR using X-ray timing data. GR makes testable predictions on the location of the innermost stable circularorbit (ISCO) around BH. The location of the ISCO could be found from the measurement of the period of rotation around it and from the gravitational redshift of the signal (X-ray line emission). Deviations from GR would affect the location of the ISCO and hence produce an observable signature in the timing and spectral properties of X-ray emission. Signatures of the alternative theories in the X-ray data could be identified only when the degeneracy with the system parameters (the BH spin and mass, radial density profile of the accreting matter etc) is resolved. This will require accurate continuum shape and line profile and timing measurements, possible with the LOFT.

Fast variable *γ*-ray emission from AGN: Observations of *γ*-ray emission from AGN reveal fast variability on the time scales comparable or shorter than the period of rotation over the ISCO. The nature of such fast variability will be clarified with the systematic characterization of its properties in a large number of sources. We will perform a monitoring of large number supermassive BHs powered sources with CTA to collect information on the fast variability of

γ-ray emission. Based on this information, we will determine whether the observed fast variability is produced by the high-energy particles injected at the base of the jets, close to the BHs. If confirmed, the fast variable emission will provide a new source of information on the processes in the direct vicinity of the BH horizon and give a clue for the understanding of formation of the BH jets.

Links to other projects of this NCCR
Study of the nature of RG is important in the general context of understanding of both the known elementary constituents and forces of Nature, which is central to the Challenge 3.1 and in the context of Dark Matter / Dark energy problems considered in the Challenge 3.2. BH and NS powered systems work as particle accelerators and are considered as possible sources of CRs which will be studied in projects 4.3.6, 4.3.4 and 4.3.5.

4.3.8 PROJECT: NEUTRINOS FROM SUPERNOVAE

Coordinating authors: F. Thielemann (UniBs), T. Montaruli (UniGe), M. Ribordy (EPFL)

Research question and state of the art
All stellar burning stages of massive stars start with an initial central contraction, causing a density increase and a temperature increase due to released gravitational binding energy, until ignition sets in when the kinetic energy of the major reaction partners is sufficient to overcome their Coulomb repulsion. Si-burning results in an Fe-core and, as nuclei around Fe possess the highest nuclear binding energies, no further energy release or burning stage is possible. Thus, the final evolution of massive stars leads to a core-collapse which is not halted until nuclear densities are attained. For stars with initial masses between 8 and $\approx 25\,M_\odot$ the subsequent evolution is expected to lead to – besides the dense/compact central object, a proto-neutron star – an explosive ejection of the outer layers, observed as supernova (SN), optically and in neutrino emission, if occurring close enough.

The major part of the released gravitational binding energy from core-collapse is released in neutrinos that can escape within seconds and are direct witnesses of the explosion mechanism. Neutrino properties impact the dynamics of the explosion and the composition of the ejecta. Neutrino physics has also a large impact on the dynamics and the cause of the explosion and the composition of the ejecta.

The observation of neutrinos from a supernova event can address a number of still open aspects in the explosion mechanism: (1) The nuclear equation of state plays an essential role in the initial bounce and the dynamics thereafter. A transition to strange quark matter at relatively low densities would e.g.lead to a second bounce, causing an explosion and a second neutrino burst [230, 231]. (2) After the initial bounce at nuclear densities, a phase of matter accretion onto the proto-neutron star precedes the final explosion [232, 233]. (3) Core collapse with rotation leads to large rotational energy in the proto-neutron star which causes the build-up of magnetic fields. If these fields are strong enough, they alone can cause an explosion with jet ejection along the polar axis [234] with a still to be determined neutrino signal.

Standard supernova models do not yet include neutrino flavor oscillations, but they are now clearly established from solar and atmospheric neutrino observations and from terrestrial long-baseline experiments. The mass ordering between the 3 neutrino mass eigenstates, $m_1 < m_2 < m_3$ (normal hierarchy) or possibly

$m_3 < m_1 < m_2$ (inverted hierarchy), depends on matter effects in 13 oscillations. This is addressable directly via terrestrial long baseline experiments. However, the mass ordering can also be determined from the observation of the neutrino signal of a future galactic SN in IceCube or in a future LAGUNA experiment because of resonant matter-oscillation effects in the SN mantle and envelope [235]. A further effect which can only occur in high density "neutrino plasma", as established in SN cores, is related to neutrino flavor transformations in the presence of neutrino self-coupling. The latter effect has been termed "collective neutrino oscillations" [236].

All of the aspects addressed above will manifest themselves in neutrino emission related patterns, their flavors, their spectra and their total luminosities. Thus, the observation of neutrinos from SNe can provide a direct link to the explosion mechanism and the conditions deep inside the stellar core as well as lead to new insights into fundamental neutrino particle properties [237, 238, 239].

Intended contribution of the project

Simulations which are required to predict neutrino signals need to follow the fast (dynamical) contraction of the Fe-core and to consider large sets of weak interactions (especially neutrino production and scattering) and a general relativistic treatment of the dense neutron star at the center of the collapse plus possible transitions to a quark phase. The treatment of rotation and magnetic fields requires to solve the equations of (ideal) magnetohydrodynamics in 3 dimensions. A good spatial resolution permits detailed 3D models, similar to cosmology and large scale structure simulations, but with a more complex set of input physics, coupling the hydrodynamics to radiative neutrino transfer.

The difficulty is to reliably quantify the energy transfer that occurs from the small coupling of the large energy reservoir in the proto-neutron star to its surface layers that have densities of $10^{10} - 10^{8}$ g cm^{-3}. In the neutrino-driven explosion mechanism the energy is transferred by neutrinos. The energy deposition rate depends on their spectra and propagation angles in the layers that are close to the energy-dependent neutrino-spheres, located at densities $\approx 10^{11} - 10^{12}$ g cm^{-3}, beyond which they can escape freely. Typical dynamical time scales in this less dense regime outside of the neutrinospheres are of order of several 10 ms. In the case of a successful explosion, after several 100 ms, the density may drop from the compact remnant to densities of 1 g cm^{-3} in the ejecta.

In the past the Basel group has addressed these questions with computational spherical symmetric SN models, including general relativistic Boltzmann neutrino transport and detailed nuclear and weak interaction input physics [240, 241] and three-dimensional approaches, including a consistent evolution of fluid instabilities with magnetic fields and sophisticated spectral neutrino transport approximations [240, 242]. In addition to current supernova models targeting the explosion mechanism, we need to implement a scheme for treating collective neutrino oscillations, which is a major part of this project. Besides leading to a better understanding of neutrino physics, the effect of ν flavor oscillations and spectral swapping may feed back on the SN shock evolution and on the nucleosynthesis of ejected matter and it is important for understanding SN explosions. Further code improvements and applications to a large variety of SN progenitor stars are to be done.

In the event of a SN core collapse in our galaxy, supposedly occurring at a rate of 2 ± 1 per century, a clear signature mainly from CC $\bar{\nu}_e$ interactions would be recorded by the IceCube and manifest as a sudden increase of the global "noise" rate in the detector. Provided a sufficiently large $\sin^2 \theta_{13}$, matter effects would show up in the light curves of the ν_e signature during the short neutronization burst and $\bar{\nu}_e$ signature during the subsequent ν emission phases. The Multi-Messenger program (Sec. 4.3.6) includes monitoring SN collapses, sharing information with other detectors [8]. Recently, the EPFL IceCube group has conceived and developed an alternative method for SN detection with IceCube, which has additional potential, enabling the disentanglement of the $\bar{\nu}_e$ flux from its average energy $(E_{\bar{\nu}_e})$. Work will be done to: (i) a refine IceCube analysis based on this new experimental data stream (e.g.to resolve the galactic SN distance from the measurement of $(E_{\bar{\nu}_e})(t)$); (ii) study performance of various configurations of a future densely instrumented core of IceCube. We will study for a SN neutrino burst event and the atmospheric neutrino beam the mixed effects of earth matter oscillations (and subsequent access to the neutrino hierarchy) and core collapse dynamics. Further we will study the distance reach for extra-galactic SN detection. Should it be in excess of several Mpc, several detections during the detector lifetime would be guaranteed.

Links to other projects of this NCCR

Neutrino observation with high statistics of a future galactic SN, done in a Multi-Messenger strategy, offer a huge scientific harvest on SN physics. The neutrino measurement from a SN collapse could reveal the nature of the neutrino mass hierarchy and provide constraints on Θ_{13}. Observation of oscillation effects imply different spectra of different flavors, which need to be determined from neutrino transport simulations. Possible Earth effects would manifest themselves in a SN neutrino energy-dependent modulation or by a difference between the measured SN signal in a detector and in another shadowed by the Earth. Collective neutrino oscillations will need to be implemented in core-collapse SN simulations. The NCCR will allow to fund this program with manpower and facilitate exchanges of researchers and students.

4.3.9 PROJECT: COSMIC MAGNETIC FIELDS

Coordinators: A. Boyarski (EPFL), R. Durrer (UniGe)

Research question and state of the art

Magnetic fields are ubiquitous in the Universe. Fields of several μGauss are observed in nearby and high redshift galaxies. Also in galaxy clusters μGauss fields are found. Somewhat smaller fields have been observed even in filaments [243, 244, 245]. Recently, it has been argued that the absence of GeV radiation from blazars, which emit TeV gamma rays, requires magnetic fields even in voids with an amplitude of at least 10^{-16} Gauss, if the coherence scale is 1 Mpc or larger [246, 247]. Suggestions how the observed large scale coherent magnetic fields in the Universe might have formed range from late formation during structure formation in galaxies [248, 249] over formation during phase transitions in the primordial Universe [250] to inflation [251, 252].

If the fields have been formed during galaxy formation, it is difficult to understand how such fields could have been expelled into intergalactic space to fill out the voids. One may suggest that they have formed before galaxy formation, when fluctuations were still relatively small. However, as long as fluctuations are small, magnetic field generation is suppressed: it is second order in perturbation theory, since vector perturbations are needed.

The fields generated are of the order of 10^{-28} Gauss [253, 254]. These very small fields are most probably not sufficient even if galaxy formation leads to a strong amplification of primordial fields by dynamo action. It has been estimated that for dynamo amplification to be successful in generating the observed magnetic fields also in galaxies at redshifts $z = 1$ to 2, one needs seed fields of the order of at least 10^{-22} Gauss [255].

Another suggestion has been that magnetic fields form during the electroweak or the QCD phase transition. The problem with this process is that purely from the fact that magnetic field generation is causal, one can conclude that the magnetic field spectrum after the phase transition is very blue [256, 257]

$$\frac{d\rho_B\,(k)}{d\log k} = \rho_c\epsilon(k/k_*)^5, \quad \frac{d\Omega_B}{d\log(k)} = \epsilon\Omega_r\left(\frac{k}{k_*}\right)^5 \qquad (3)$$

for all $k < k_*$, where k_* is the (comoving) correlation scale of the magnetic fields and $\epsilon < 1$ in order for the magnetic fields not to overclose the Universe. Certainly, k_* is smaller than the Hubble scale at the transition, but more likely it is of the order of the largest bubbles at the end of the phase transition which gives $k_* \sim 100 H_*$, where H denotes the comoving Hubble parameter. If no inverse cascade is active and the magnetic fields on large scale evolve passively, this leads to very small fields on large scales. For the electroweak phase transition with $k_* = H_* \simeq 10^{-4}$ Hz, we obtain an upper bound for magnetic fields on large scales, say $k_1 = 10/\mathrm{Mpc}$, of $B(k_1) < 10^{-29}$ Gauss. Somewhat more realistic values for k give even more stringent bounds. For the QCD phase transition these bounds are relaxed by about 3 orders of magnitude but the resulting fields are still much too small to yield the observed fields in galaxies, even via very optimistic dynamo amplification. If the magnetic fields are helical, an inverse cascade is expected [258, 259]. This can mitigate the limits somewhat, but it will still not be able to generate 10^{-16} Gauss fields on Mpc scales [260].

These results lead us to consider inflation as the most promising mechanism for magnetic field generation. Inflationary magnetic fields can have different spectra. Depending on the coupling strength one can even obtain a scale invariant magnetic field spectrum [251]. The magnetic field is then constrained e.g. by the CMB yielding

$$d\rho_B\,(k)/d\log k = k^3 P_B/2 \lesssim 10^{-6}\,\rho_{\mathrm{rad}}.$$

In terms of magnetic field amplitude this requires $\sqrt{k^3 B^2} \lesssim 10^{-8}$ Gauss. Depending on the measurement considered, this limit can become somewhat more stringent [218, 261]. This limit applies only on very large scales relevant for CMB anisotropies.

Recently, some of us [262] have demonstrated that magnetic fields generated during inflation contribute to the Bardeen potential in such a way that the Universe becomes rapidly strongly inhomogeneous and anisotropic after inflation. This result probably rules out inflationary magnetic field generation altogether. However, it has been proposed, that the chiral anomaly of the standard model might lead to a strong inverse cascade, moving small scale power of magnetic fields to much larger scales [263].

Intended contribution of the project

In a first project we want to study quantitatively whether the mechanism proposed in [263], may help to resurrect magnetic fields generated during phase transitions. Can it move sufficient power to sufficiently large scales so that these fields become viable? What exactly are the equations that govern the evolution of magnetic fields in the highly conducting Universe filled with relativistic particles? We also want to investigate the influence of this evolution on CMB constraints.

A second project is to take into account the effects of magnetic fields on structure formation. This project is already under way, but it is still in its infancy.

Last but not least, we want to make progress on the experimental side: the lower limit on magnetic fields in voids originally comes from a Swiss group [246]. We want to improve this limit from both sides: by simulations which compute the expected cascade radiation with higher accuracy and by observations, best simultaneously in the TeV and GeV range for the same object.

Links to other projects of this NCCR

Our project is obviously related to the numerical simulation of large scale structure, project 4.2.4, and to the CMB project 4.2.8. But also to the high energy gamma-ray observations as the large scale magnetic fields in voids are detected in this way. Magnetic fields can be produced in the early Universe, e.g. during the electroweak phase transition and baryogenesis (see section 4.2.1 on the early Universe). Such primordial magnetic fields, would affect every important process in the early Universe (baryo- and lepto-genesis, DM production (see sections 4.2.1 and 4.2.7), can change the nature of the QCD phase transition (see Ref. [263]). A correct description of a magnetized Early Universe is important to derive reliable conclusions about beyond the Standard Model particle physics from cosmology. If these primordial fields can survive until now and if they can be related to the observed large scale magnetic fields, their theoretical and experimental study might open a new window to the early Universe and provide a new tracer of these fundamental phenomena. This is the core of this NCCR: observing and understanding the Universe, can teach us about fundamental physical interactions, testable with particle physics experiments.

5 INTERNATIONAL NETWORKING

International networking and cooperation is one of the strongest assets of the proposed NCCR Universe. It is the much-needed catalyst linking together tightly all existing initiatives from international organizations, institutions and associations (such as CERN, PSI and CHIPP), and international projects (such as ATLAS, CMS, LHCb, Euclid, Planck and AMS). It is the essential initiative, which will help increase the coherence and outreach of fundamental research in particle physics. Switzerland becomes the common destination for data, analysis and research of all international projects in our field.

Beyond our borders, Swiss particle- and astrophysics collaborates dynamically in various international scientific activities of the Swiss confederation through the Swiss Infrastructure Roadmap, the European Strategy Session of Council, the European Commission FP7 programs (LAGUNA, AIDA, CTA, the ITN “Cosmology with Large Surveys”, etc.), and international space agencies as ESA (Europe), NASA (USA), JAXA (Japan), and GESSA (China).

The Swiss groups also play a leading role in the international networking for future neutrino facilities. They have been strongly involved in the organization of the yearly international workshops NUFACT, for future neutrino beams, and NNN for large underground detectors for neutrino and nucleon decay; the 2011 events were organized in Geneva (NUFACT11) and Zurich (NNN11). The EPFL astrophysics lead the international effort COSMOGRAL (COSmological MOnitoring of GRAvitational Lenses). Swiss particle physicists lead the European networking activities in the framework of the FP7 EUCARD program for future accelerators and are taking an important role in the organization of the contributions for the upcoming European Strategy Process.

Scientists by tradition use an extensive international network to support, enable and critique their work. By bringing complementary disciplines together, it triggers, leverages and breeds new approaches. NCCR Universe’s challenge to unite scientists in cosmology, astrophysics, particle physics and theoretical physics on common research projects, thus not only creates additional links, but offers a new dimension to our international networks as well. It allows us to extend our networks from individuals or groups to institutions. It thus establishes stronger and more sustainable forms of international collaborations through, for example, exchange programs for students, hosting of postdocs or invitations to leading scientists.

These initiatives find strong encouragement and support in Geneva as its University goes through a reorganization and development of its branches of physics, mathematics and astrophysics. The project includes specific developments towards education and training, international forums and conferences, as well as a multimedia infrastructure permitting remote attendance to international events. To the schools organized by this NCCR, we shall not only invite international lecturers but we shall also open the schools for participation by PhD students from abroad.

Particle Physics and Cosmology being international by nature, Swiss researchers have long collaborated individually or in groups not only with their international research collaborators but also with associations such as ECFA, NUPECC, ApPEC and Aspera. The establishment in 2003 of the national centralizing body CHIPP, supporting the active Swiss community in particle physics, offers the added benefit of gathering individual international networks in a common pool. It also demonstrates the experience and know-how of those scientists in leading national and international programs to outstanding results. With over 400 professors, researchers and students, CHIPP's commitment to NCCR Universe strengthens our ability to sustain a rich and productive activity with international recognition and support. Combining this experience with our vision of developing particle physics through new Challenges, NCCR Universe is ready today to institutionalize a sustainable methodology for managing international research projects linking instrumental, theory and academic units.

6 KNOWLEDGE AND TECHNOLOGY TRANSFER, ADVANCEMENT OF YOUNG RESEARCHERS AND WOMEN, COMMUNICATION

Questions on the fundamental nature of the Universe, its origin and future, are not concerns of scientists only. Whether philosophically, religiously or socially, it is a genuine curiosity of human nature to explore these matters and interpret what they see and hear. As the research fields concerned with these questions, particle physics, cosmology and astrophysics have since always been encouraged to outreach. NCCR Universe thus naturally takes on the responsibility to build bridges with the various actors of society, whether industry, general public, students or more particularly women. Efficient communication and bespoke education are the tools allowing us to maintain the bridges in a sustainable fashion. The networking of our activities in these areas by combining outreach programs or developing new initiatives should greatly strengthen the community's understanding of what is done in particle physics, of its role and responsibility to society and its development. As co-leading house of NCCR Universe, the PSI, with its recognized experience in the field, will take on an active role in managing the outreach and developing new programs. Offering a more academic and nationally targeted complement to CERN's efforts, as well as benefiting from CHIPP's framework, will be important assets to take into account.

6.1 KNOWLEDGE AND TECHNOLOGY TRANSFER

Particle physics, accelerator and detector technology have demonstrated over the past decades an enormous potential for technology transfer and spin-off companies to the benefit of the economy and society as a whole. Some common examples include the development of medical accelerator technology, gamma, X-ray and particle detection systems for imaging techniques, monitoring and medical diagnostics, fast data acquisition and information distribution systems for a variety of applications. All partners involved in this proposal have offices for technology transfer from the respective university or institution to industry. The University of Geneva recently established the Geneva Creativity Center, which reinforces the upstream efforts of the existing Unitec support to spin-offs. The PSI technology transfer office is also represented in a CERN based HEPTECH network for technology transfer from high-energy physics. We plan to establish a TT & IC node and implement especially IC at an early stage of each experimental project. The goal is to establish contacts between the research institutions and potentially interested companies at an early planning stage of R&D efforts. TT can work in both directions and certainly also the projects will gain from the IC effort. It is very desirable to coordinate this in a node on Swiss scale because of a considerable effort to maintain industry and research group contacts simultaneously and pooling specific field related knowhow. Conflicts between offices of individual institutions will be prevented by clear agreements in particular on intellectual property rights and their exploitation. Without identifying explicit spin-offs yet, this NCCR will improve the efficiency of knowledge and technology transfer in a sustained way.

6.2 EDUCATIONAL SUPPORT

The success of particle physics and cosmology research in Switzerland largely results from the highly qualified and innovative scientific and technical teams within Swiss institutes. This NCCR will not only maintain that quality, but innovate by educating our students in both particle physics and cosmology, and especially the strong connections between these fields. A solid education in particle physics, astrophysics and cosmology in undergraduate physics curricula is mandatory to prepare the next generation of students for the challenges of tomorrow in our field. Despite the existing efforts to coordinate the undergraduate and doctoral programs in particle physics in Switzerland, a large diversity persists. NCCR Universe will work towards ensuring a good standard of undergraduate education in particle physics, astrophysics and cosmology. It will further coordinate and streamline the existing doctoral programs in the interrelated fields. As far as specialized education in particle physics is concerned, CHIPP initiated a ProDoc program to improve the offer and access conditions of PhD students all over Switzerland to the local and regional doctoral programs. The CHIPP Winter School, the Zuoz Summer School and the CERN School of Physics play an important role in this program. “Universe Schools” will complement the program to educate the students in the NCCR especially in cosmology and astroparticle physics. Access to all courses will be granted to all Swiss PhD students free of charge and credits be granted on an equal footing. The present doctoral program in particle and accelerator physics (funded through ProDoc and integrated in the Center for Advanced Studies in Particle Physics C15) will be further developed on the basis of existing resources and at the Swiss level. We shall also give all Universe-PhD students the opportunity to spend a semester or even a year at another Swiss University, which collaborates on the same project.

6.3 ADVANCEMENT OF FEMALE RESEARCHERS

Physics in general, and particle physics and cosmology alike, sees a remarkable asymmetry between male and female researchers. The source of the problem seems to be rooted in University education or even earlier. Although progress has been made in the last years to attract female students to studies in “hard sciences”, the level of female beginners in physics stagnates at a low level. This asymmetry is then propagated into an unsatisfactory female fraction of physics PhD, post-docs and professors. This indicates that the problem needs to be addressed at an early stage in the scientific career of women. NCCR Universe will establish a program of tutorships for beginners especially tailored for bachelor and master level female students. The tutors will be advanced female physics students, post-docs and researchers, recruited at all levels. They will provide their younger colleagues with personalized help with their studies and act as role models for younger students. A system of fellowships will support this action at the levels mentioned. Permanent jobs are very rare and are obtained only rather late, often at the age of 40. The lack of dedicated facilities for parents discourages over-proportionally many women researchers. Special attention will be given to organize childcare facilities during conferences and schools so that researchers and students caring for small children can participate as well.

6.4 INTERNAL AND EXTERNAL COMMUNICATION

NCCR Universe will coordinate a more active information exchange among communicators and work towards a higher level of public awareness in our field. Many Swiss groups at their Universities and at PSI pursue outreach activities. A coordinating effort is already made by the CHIPP Outreach Group, bringing together people from all Swiss research sites involved in particle physics to discuss individual and common activities to exchange ideas and contacts. A representative from ASPERA establishes the link within the astroparticle community, and an observer from SER brings in advice from a higher-level research and education perspective. Targeted at high-school teachers and students, a number of excellent activities, reports and documentation have been produced by the various members of our NCCR, many of which coordinated by the CHIPP Outreach Group's websites and fact-sheets about the Swiss participation in the LHC experiments by CHIPP; European Physics Master classes in Bern, Geneva and Zurich; master class events, special guided tours at CERN and other Swisslabs, PhysiScope Genève, Kinderuniversität Zürich, PSI Forum and iLab, etc. To ensure further developments, the NCCR will establish a global communication strategy on particle physics in Switzerland. Through the use of the latest communication technologies and enhanced websites, we can not only provide information but engage with our various stakeholders as well. These new tools will push the boundaries of our science and our country far beyond our actual borders.

7 STRUCTURAL GOALS OF THE HOME INSTITUTION

In its long term strategic planning [265], the Rectorat of the University of Geneva identifies the physical sciences, enlarged to astrophysics and mathematics, as one of its priorities during the period 2011 to 2015, in the form of a pôle d'excellence in research. This priority confirms the support the physics department of University of Geneva had already received during the previous four-year planning period, due to its excellent performance during this time. This strategic direction of development is also reflected in the *Convention d'objectifs quadriennale 2012–2015*, which the University is in the process of concluding with Geneva cantonal authorities.

In spring 2011, the physics section together with the astrophysics department of Geneva University inaugurated CAP (their Center for Astro-Particle Physics) which aims to strengthen activities at the center of this NCCR, bringing together members of the Department of Theoretical Physics (DPT), the Department of particle physics (DPNC) and the Department of Astrophysics. All members of CAP shall actively work on this proposal. In total there are 12 professors with their research groups involved in topics covered in this NCCR.

University of Geneva in fact has ambitious plans for the mid-term future of its mathematics, astronomy and physics departments. A new project uniting these branches of science in a common effort is in an advanced planning process. Supporting this planning, the scientists concerned have developed an innovative usage concept, aiming at liberating the synergies between these sciences much in the same way as this NCCR proposal. In parallel, the education in basic sciences and its services to all students of the Faculty of Sciences is being rethought. At the undergraduate level, new cross-disciplinary branches like biophysics or climatology are installed or in the planning, setting an example for the educational branch of the NCCR Universe.

For PSI, particle physics and accelerators are key components of its strategic planning. PSI is at the forefront of accelerator development with its new SwissFEL project, with the SLS, with the medical cyclotron and with the world's most powerful proton accelerator, the PSI ring cyclotron. PSI is providing such large research infrastructure to national and international users and is at the same time developing this important technology further. The Development Plan for 2012–2016 has "Particle Physics and the Structure of Matter" as one of its 5 thematic areas of legal PSI responsibilities and places a strong emphasis on its user lab function. The PSI laboratory for particle physics runs a research program "Precision and discovery physics at low and high energy" with a major contribution to LHC activities within the Swiss LHC consortium and with unique precision physics experiments at PSI. PSI has over the past few years built a new facility for ultracold neutrons and continues to run and improve its world highest intensity muon beam lines. High-visibility particle physics experiments are supported on these facilities and will be in the future. PSI particle and accelerator physics activities are responsible for major developments and spin-offs into the whole of PSI and very often had fertilizing influence. PSI expects this to continue and promotes both the investigation of the most fundamental questions to nature and its positive coupling to other fields. It is committed to high-level education and has a considerable effort in, both, scientific education mostly on the level of doctoral student education and training of apprentices, which, e.g. for electronics, is located in the laboratory for particle physics.

The long-term commitment of the CHIPP partners to the research themes of this NCCR ensures the sustainability of the planned reinforcement beyond the lifetime of the NCCR itself. The partner institutes regularly replace retiring professors in the field concerned by eminent young researchers. The Universities of Bern and of Geneva have recently created new chairs in astroparticle physics, one of the central themes of this NCCR. The implementation report of the CHIPP road map contains a detailed record of the achievement of its members in recent years. All project and sub-project coordinators regularly obtain important funding from the SNSF, cantonal and federal authorities, as well as the European Commission and other international funding bodies.

The University of Geneva has demonstrated its ability to ensure the proper administration and accounting for several NCCRs in basic sciences. Its *Section de physique* has very successfully run the NCCR MaNEP during the past 12 years.

8 ORGANIZATION OF THE NCCR

Figure 4 displays organs and functions of this NCCR. The **Governing Board** consists of the participating professors. It defines the NCCR's scientific policy, approves projects and monitors their progress. It discusses and approves the yearly report of the Directorate, takes note of the results of evaluation by the SNF and the **Advisory Board** and monitors implementation of their recommendations. The Advisory Board is composed of internationally recognized experts in particle physics, cosmology and astrophysics not participating in the NCCR. It holds a yearly meeting, hears and discusses reports from NCCR directorate and project coordinators. It also provides an independent view on the progress of the NCCR as a whole and of its parts. Their written conclusions are transmitted to the Directorate and included in its yearly report. The NCCR Directorate consists of the Director, the Deputy Director and the coordinators of the NCCR's three challenges. During the first four years period of the NCCR, the Director will be Prof. Martin Pohl of University of Geneva; the Deputy Director will be Prof. Klaus Kirch from PSI and ETHZ. During subsequent periods, it is foreseen that the Director's appointment rotates among the leading houses. The Directorate is responsible for the implementation of the NCCR's scientific policy. It distributes the budget. It takes on all administrative duties with respect to the leading houses and the SNF and reports to them on a regular basis. In particular, the Directorate prepares and transmits the yearly report on scientific and financial matters. After approval by the Governing Board and the SNF, the yearly report is published. The Directorate will design and implement through the NCCR an organization methodology fostering the multidisciplinary approach of a sustainable platform aggregating cosmology, astrophysics and particles fundamental research. Part of the implementation will consist of enabling collaboration and transparency, as well as supporting the engagement of the stakeholders. This open approach should and will permit to broaden the commitment of new partners or financial sponsors over time.

The **Staff of the Directorate** comprises a dedicated **NCCR administrator**, a part-time **outreach coordinator**, a coordinator for the **advancement of women**, a half-time **communications officer** and a **coordinator for education**. The **NCCR administrator** supervises all administrative tasks of the NCCR, including contractual, personnel and budgetary issues. He/she reports to the Directorate and will be assisted by a full time **secretary**. The **outreach coordinator** takes care of promoting pubic awareness of the NCCR's work, its results and their relevance to society. He/she organizes public events and publications directed towards the general public and collaborates closely with the outreach coordinators of the participating institutions and of international partners in the field. Communications professionals from the Leading Houses take care of the external communication of the NCCR progress and results through a coordinated effort. The NCCR finances an additional half-time position of a **communications officer**, dedicated to these tasks. He/she supports the Director with the global external relations strategy including internal communication. The coordinator for the **advancement of women** is responsible for gender aspects in organization and work of the NCCR. Networking among female participants, proposing innovating solutions and coordination of special fellowships are part of his/her responsibilities. The relevant offices of the leading houses will coordinate **Technology Transfer**. The general strategy of outreach to industry is coordinated with the Directorate. The **coordinator for education** will organize the doctoral program of the NCCR in collaboration with existing organizations like the CRUS and CUSO doctoral program in physics. He/she also makes supporting material available for professors teaching undergraduate courses in the fields covered by the NCCR and will be responsible for publishing a complete catalogue of relevant courses available in the participating institutions. These courses will be open to all students working in the fields covered by the NCCR. The coordinator will also organize the exchange of students among participating institutions.

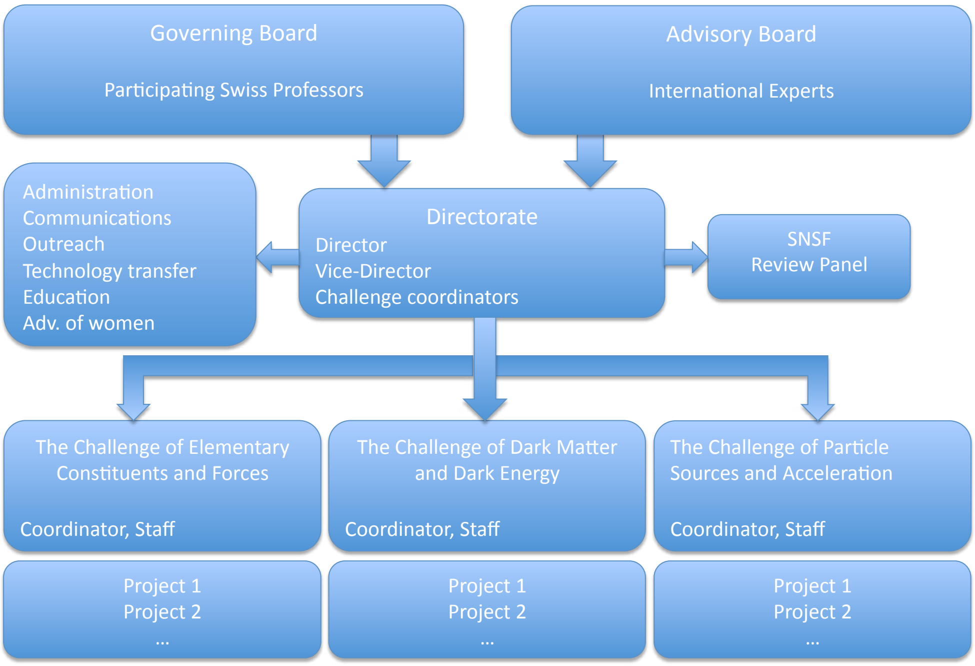

Figure 4: Organizational chart of the NCCR Universe.

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