Research Training in Astroparticle Physics with Multiple Messengers

1 Summary of Intentions

Our main objective is to establish a comprehensive and high level education at the interfaces of cosmology, astrophysics, and particle physics which will enable the graduates to quickly react in their further research career to new developments in these highly dynamic fields. This will provide them with a decisive advantage in this interdisciplinary field where new data from astrophysics currently arrives on a monthly basis and where a major breakthrough in particle physics at the Large Hadron Collider at CERN is expected to also have a large impact on cosmology and astrophysics. The expertise of all three participating institutes overlaps significantly and at the same time is sufficiently complementary to be ideally suited to exploit synergies in training the next generation of scientists at the interface of these fields: The University of Hamburg offers a widely recognized education in particle physics and astrophysics including the study of cosmic rays and astrophysical gamma-rays and neutrinos. The APC is recognized as a leading institute with research and educational focus on all major branches of astroparticle physics including gravitational waves. The University of Oxford has the largest physics department in the UK, and has internationally recognised programmes in the areas of astrophysics, cosmology and astroparticle physics. The development of a joint international graduate programme, including the possibility of double degrees, will thus allow to offer training that goes considerably beyond the expertise of these three institutions separately and covers all aspects at the interface of astrophysics, cosmology and particle physics. Each graduate student involved will spend extended time at the partner institutions. The student will benefit from at least one advisor at both the home and the partner institution whose expertise will complement each other. In specifically designed courses held alternatingly in Hamburg, at APC and at University of Oxford, and broadcast to the partner institutes or held as biannual block courses attended by all participants, the students will be prepared to optimally exploit the resulting synergies to address the central questions in astroparticle physics such as origin and nature of Dark Matter. Excellent students will be won both by utilizing involvement in international experiments, by selecting the best students early on during their undergraduate training, and by involving them in joint research projects at the partner institutes.

2 Research Programme

The guiding theme of the planned international research training group (IRTG) is astroparticle physics, the interface between astrophysics, cosmology and particle physics. This is a highly interdisciplinary research area to which existing research structures and teaching curricula are often still not very well adapted because they often tend to be too compartmentalised following traditional topical divisions. These different communities are often not used to work together and may not even speak the same scientific "language". On the other hand, real progress in this area requires collaboration and common approaches: Many of the main open questions in particle and astroparticle physics are interdisciplinary by nature: Understanding the origin of high energy charged and neutral radiation in the Universe requires on the one hand expertise in plasma astrophysics to understand acceleration processes. On the other hand it needs input from particle physics to model relevant interaction processes, especially for a possible contribution from decaying or annihilating dark matter and at the highest energies. This calls for a multi-pronged approach involving data from particle accelerators as well as from astrophysics ranging from radio observations over the fluxes of electrons, positrons, anti-protons all the way to gamma-ray and neutrino detection. Relevant present and future experiments include the Large Hadron Collider (LHC) in particle physics, LOFAR and Planck in radio-astronomy, VLT, HST, ELT in optical astronomy, JWST, ALMA in infrared astronomy, Chandra, XMM-Newton in X-ray astronomy, H.E.S.S., MAGIC, FERMI and CTA in gamma-ray astrophysics, PAMELA, AMS and ATIC in low energy charged cosmic rays, the Pierre Auger Observatory, the HiRes experiment and the telescope array as well as the planned JEM-EUSO experiment in ultra-high energy cosmic rays, and a planned large underground multi-purpose detector for low-energy neutrino physics and rare processes.

Given the rate at which data arrives currently in astrophysics and astroparticle physics and which is expected to arrive in the next few years from the LHC it is likely that some of the most important open questions in fundamental science will be solved in the near future. Such questions include the nature and origin of the dark sector of our Universe, the origin of the highest energy particles in Nature and the search for the correct fundamental theory of interactions including gravity which can be tested not only at human made accelerators, but also by exploring the most violent processes in the Universe. In order to take advantage of these opportunities, the proposed IRTG aims at going beyond the usual curricula with their often separate training in particle physics and astrophysics and offer a truly interdisciplinary education.

Our research programme will focus on three areas that will lead to close collaboration between the three institutions. These areas, which are also strongly interconnected among themselves, are **1) High Energy Radiation in the Universe**, **2) The Role of Weakly Interacting Messengers in the Universe** and **3) The Search for Dark Matter and Early Universe Relics**. In the following we describe possible projects within these three areas, how they connect the expertise of the principle investigators at the three institutions, and how they are linked to each other.

2.1 High Energy Radiation in the Universe

1. Modeling of High Energy astrophysical sources and search for extragalactic magnetic fields.

   The goal of this project is the development of a general code for modeling the fluxes of cosmic rays, photons and neutrinos from acceleration sources. The physics of acceleration is similar to the physics relevant for propagation but in general involves much smaller length scales. Existing numerical codes such as CRPropa which has already been jointly developed at University of Hamburg and APC [1, 2] can, therefore, be partly adapted and extended to simulate astrophysical sources. Those codes can be combined with numerical codes used for modeling of AGN jets [3] and acceleration of cosmic rays near super-massive black holes [4].

   Another complementary direction is connected to search for imprints of extra-galactic magnetic field in the gamma-ray data of FERMI and Cherenkov telescopes. First studies of this kind already point to the existence of non-zero extra-galactic magnetic fields [5]. Within this project we propose to perform a detailed study of FERMI and Cherenkov telescope data on extragalactic sources with existing codes for three-dimensional electromagnetic cascades [6], in order to search for extra-galactic magnetic fields and study of the intergalactic infrared/optical background.

This project lies in the expertise of D. Semikoz and E. Parizot in Paris and of R. Banerjee, A. Mirizzi and G. Sigl in Hamburg and is thus suitable for a PhD project between Hamburg and Paris. It also has links with project (2) on ultra-high energy cosmic rays and directly connects to project (8) on signatures of new light photon-like states in astrophysical spectra and to project (10) on multi-messenger signatures of astrophysical sources.

2. Large-statistics observations of Ultra-High-Energy Cosmic Rays.

   After 7 years of operation of the Pierre Auger Observatory (Auger), the astrophysical sources and physical origin of the ultra-high-energy cosmic rays (UHECRs) remain a mystery. The most recent data point towards a UHE sky that is less anisotropic than had been expected [7], and to the presence of (at least) a substantial fraction of heavy nuclei above $6\,10^{19}$ eV (unless significant changes occur in the hadronic interactions) [8], although this has not been confirmed by other experiments such as HiRes. The major goal of UHECR science remains the identification of individual sources on the sky and the measurement of their flux and spectrum, to constrain their intrinsic power, density, injection spectrum and composition and to understand particle acceleration in extreme conditions. This requires focusing on the highest energies, above $\simeq 80\,\mathrm{EeV}$, well within the so-called GZK-sphere, and increasing the aperture by at least an order of magnitude to compensate for the extremely low UHECR fluxes. The JEM-EUSO mission will explore a new road to achieve this important goal of astroparticle physics and high-energy astrophysics, by observing for the first time the fluorescence light of UHECR-induced atmospheric showers *from space*, with a UV telescope covering a surface of 190,000 km^2 on the ground, using a Fresnel lens of ~ 2.5 m diameter and a focal surface made of photomultiplier tubes with a total of more than 350,000 pixels, sensible to individual photons. Our group gathers experts of UHECR detection (from the Pierre Auger Observatory), shower simulation and reconstruction, as well as the acceleration and propagation of UHECRs in the universe. Important contributions to the development of this promising technique will be made, including the precise characterization of the photodetectors to be used in space, the detailed simulation of the shower development and light transmission across the atmosphere (including the reflection of the Cherenkov peak on the ground or clouds) and through the instrument, the development of powerful algorithms to identify UHE events in the data and reconstruct their arrival direction and energy, the characterization of anisotropies at various angular scales, the search for multiplets and identification of individual sources, and the global modeling of the UHECR phenomenology. This will be done in close collaboration between instrumentalists, experimentalists and theoreticians, to explore and characterize the possibilities offered by the next generation, large aperture UHECR detectors, and how they can be used to solve the long-standing problem of the origin of the most energetic particles in the universe. Synergies with high-energy gamma-rays and neutrino detection will also be developed within our group, from the experimental point of view (through the detailed study of photodetectors, shower modeling, large scale instrumentation, and local and global triggering strategies) as well as from the theoretical point of view (joint and complementary constraints on the physics of the sources, time coincidence and angular correlation analyses, global modeling of the multi-wavelength and multi-messenger emission, and modeling of the source environment at various astrophysical scales).

This project represents expertise of E. Parizot and D. Semikoz in Paris and D. Horns and G. Sigl in Hamburg. It connects with the previous project (1), and with project (3) on hadronic interactions, and therefore suggests itself for a PhD project between Hamburg and Paris.

3. Hadronic and Weak Cross Sections at Ultra-High Energies.

   The cross sections of inclusive hadron production in high-energy hadronic collisions or neutrino-nucleon deep-inelastic scatterings constitute important inputs to particle astrophysics, in particular to the simulations of air showers, which are produced when ultra-high energy cosmic rays (UHECR) of hadrons or neutrinos collide with nuclei in the earth's upper atmosphere. Currently, the only rigorous way of describing inclusive hadron production is within the framework of the factorization theorem of QCD, for which non-perturbative fragmentation functions (FFs) are essential (for a review, see Ref. [9]). Thanks to their universality, FFs may be reliably determined through global fits to the available data of hadron production in terrestrial particle collision experiments [10]. Such rigorous QCD predictions based on FFs also provide the optimal means to test and tune frequently employed Monte Carlo event generators, which are based on ad-hoc fragmentation models with adjustable parameters.

   The challenge of UHECR experiments for QCD resides in that they probe energy scales Q as high as 10^6 GeV and higher in the center-of-mass frame, far beyond those accessible at current particle colliders. It is, therefore, an urgent task to accordingly improve the DGLAP evolution in Q by including higher-order corrections. In the presence of new physics beyond the standard model such as supersymmetry (SUSY), new particles such as the SUSY partners could modify the DGLAP evolution via loop effects and contribute via their own FFs at energies beyond their production thresholds.

   Unfortunately, the prediction of the UHECR air shower characteristics relies on the knowledge of the FFs at small values of the fraction x of momentum that the produced hadron carries away from the fragmenting parton, and these have been poorly constrained in the past due to insufficient accuracy on the theory side. In fact, the *modified leading logarithmic approximation* (MLLA) [11], which is frequently adopted in this connection, is not fully consistent with the factorization theorem and cannot sufficiently exploit the wealth of experimental data on fragmentation. Fortunately, a complete formalism rigorously based on the factorization theorem now exists [12], which will allow us to describe the UHECR air shower properties in the various models more reliably by using FFs extracted from all available data so as to increase our ability to constrain or rule out these models.

   This project makes use of the expertise on QCD in Hamburg, in particular in the group of B. Kniehl. It has relevance for the detection of ultra-high energy cosmic rays and neutrinos and thus connects to projects (2) and (6) which will be performed in close collaboration between Hamburg and Paris.

4. Search for nearby sources of electrons and positrons using FERMI, LOFAR, and H.E.S.S./CTA.

   This project naturally links with the more theoretical modelling of cosmic-ray propagation and radiative processes. Given the rapid cooling of electrons/positrons, any source of TeV electrons has to be within roughly one kpc (unless additional convective effects or non-isotropic diffusion takes place). The resulting anisotropy from nearby sources of electrons depends crucially on the diffusion coefficient and can be detected with FERMI up to a few hundred GeV and at higher energies with ground based air Cherenkov telescopes (H.E.S.S and CTA). Furthermore, inverse Compton emission on local photon fields would lead to additional large scale emission at energies accessible with FERMI. Finally, low frequency radio observations carried out with LOFAR will probe the accumulated electrons from more distant sources. A joint analysis of the multi-messenger data will provide crucial constraints on cosmic-ray release from sources and on the transport in the solar neighborhood as well as in the Galaxy.

   This project builds on expertise of the groups of D. Horns in Hamburg and provides important information on astrophysical foregrounds for indirect dark matter detection strategies which are the subject of project (11). It will, therefore, be carried out together with T. Bringmann and the group in Oxford, in particular J. Silk. It also has relevance for project (1) on electromagnetic cascades.

5. 3D Radiative Transfer on Cosmological Scales.

   In the last few years, the theory division of the Hamburg Observatory led by Peter Hauschildt has developed a 3D (spatial) radiative transfer framework [13, 14, 15, 16, 17] and incorporated it into the general-purpose setrum simulation code package PHOENIX to create PHOENIX/3D [18]. This framework allows for a highly accurate treament of 3D radiative transfer in moving optically thick media allowing for strong scattering using a non-local operator splitting method, implemented for large scale parallel supercomputing. Currently, additional features are being added such as handling of general relativity and arbitrary velocity fields effects following [19, 20] and [21] and time dependence using a direct extension of the methods presented in [22] and will be completed before the start of the proposed IRTG.

   With this tool, we are in an excellent position to support the projects of the proposed IRTG. We will work to extend the existing (and well tested and verified) 3D framework to cosmological scales and integrate simulations with the other research projects within the IRTG. In order to facilitate this, we will extend PHOENIX/3D to allow for simulations on cosmological scales and to interface with the other theoretical and observational projects. In detail, we propose to extend PHOENIX/3D models to cosmological scales and to directly interface it with project (16) on modeling ionization signatures of dark matter and with project (1) modeling high energy astrophysical sources. Therefore, this is a project suitable for a PhD thesis supervised by P. Hauschild in Hamburg and co-supervised by D. Semikoz in Paris and A. Slyz in Oxford. It will provide a direct interface between the theoretical and observational projects of the IRTG.

2.2 Weakly Interacting Messengers in the Universe

6. Search of cosmic neutrino sources with ANTARES [23] and characterisation of the optical detection units of the next generation neutrino telescope.

   Neutrino telescopes rely on the instrumentation of large volumes of water (or ice) with photomultipliers (PMTs) to detect the Cherenkov radiation emitted by charged leptons (mainly muons, but also electron- or tau-induced showers) induced by cosmic neutrino interactions with the transparent target medium, inside or near the instrumented volume. PMT signals (timing and amplitude) are used to reconstruct the muon trajectory and the energy of the parent neutrino. In order to reduce the background due to the intense flux of down-going atmospheric muons present at ground, such detectors are buried deep under the surface. Moreover, since the Earth acts as a shield against all particles but neutrinos, their design is optimized for the detection of up-going muons produced by neutrinos which have traversed the Earth and interacted below the detector, with the consequence that one neutrino telescope can efficiently monitor only one half of the sky.
   ANTARES is today the most sensitive detector in its hemisphere, thus providing an unprecedented sensitivity to the Southern Sky, in particular for TeV galactic sources. The APC group in Paris is strongly involved in the analysis, coordinating different working groups within the ANTARES collaboration. The group has particular interest in the search for cosmic neutrinos in coincidence with other messengers. The goal of such a multi-messenger approach is to maximize the discovery potential of ANTARES by developing joint analyses based on timing and/or direction coincidences with other messengers (thus reducing the associated backgrounds) such as gamma-rays, UHECR and gravitational waves. Such combined studies are strongly supported by the collaboration which has signed several agreements for data exchange with other experiments (e.g with the LIGO Scientific collaboration searching for gravitational waves). Following this spirit, a Ph.D. student in the IRTG would have the opportunity to develop original studies and collaborations with other experiments.

   A more technical aspect of the work being carried out by the high energy astronomy group at APC, Paris is related to the construction and the exploitation of a test facility dedicated to photodetection. The APC group is setting up an optical test bench able to measure the acceptance of photomultiplier tubes and optical detectors with unmatched accuracy. One measurement will use a light source tuned to single photons and a motor which enables to perform measurements all over the detection surface and for all incident angles separately. Another measurement will make use of a $2{\times}2{\times}2\text{m}^3$ water tank and a muon hodoscope to characterize the response of the photodetector in realistic conditions. The two devices are developed as part of the R&D efforts carried out for the construction of the next generation neutrino telescopes (KM3NeT). A PhD student with hardware skills could paticipate to the development and exploitation of such test benches.

   This project centers on the participation of the group of A. Kouchner at APC, Paris in the ANTARES experiment. Together with project (9) on gravitational wave detection it provides the experimental background for the multi-messenger studies in project (10). In this context it will be performed in close collaboration between Hamburg and Paris. It is, however, also relevant for the indirect dark matter detection studies (11) planned between Hamburg and Oxford.

7. Theoretical and Experimental Aspects of large Underground, Liquid Based Detectors.

   This thesis project is proposed in the context of studies and developments in view of the next-generation very large volume underground observatories searching for rare events and studying various terrestrial and extra-terrestrial sources of neutrinos.

   Such detectors will answer fundamental questions of particle and astroparticle physics: they will search for a possible finite lifetime for the proton; they will measure with unprecedented sensitivity the mixing angles between neutrino mass and flavor eigenstates and unveil through neutrino oscillations the existence of CP violation in the leptonic sector, which could provide an explanation of the matter-antimatter asymmetry in the Universe; they will also study astrophysical objects, in particular our Sun and Supernovae, using the neutrinos as messengers from their sources [24].

   The construction of one or more large scale detectors devoted to particle and astroparticle physics in Europe is currently investigated by the Large Apparatus studying Grand Unification and Neutrino Astrophysics (LAGUNA) collaboration [25]. This project is one of the priorities of the AstroParticle ERAnet (ASPERA) [26] roadmap from 2008.

   One of the most reliable techniques for neutrino detection is based on the Cherenkov light emission in water by the final state particles resulting from neutrino interactions. This faint light is detected by a very large number of photomultipliers positioned on the surface of the water container. The possibility of building a water-Cherenkov detector with a fiducial mass of about 500 kton (20 times larger than SuperKamiokande, the largest ever built presently in operation in Japan) observed by about 200,000 photomultipliers is currently being investigated by different groups around the world, and for different underground sites. While water is a cheap medium, the size of such detectors is limited by the cost of excavation and of the photomultipliers.

   The MEMPHYS project is being discussed for deployment in an extended LSM-Fréjus laboratory, at the border of France and Italy, which for low energy beam neutrino studies is located at an optimal distance from the CERN accelerator complex. The team of the APC laboratory has a leading role in the MEMPHYS project, including the lead of the project (T. Patzak), the construction of a small-scale prototype -MEMPHYNO- to test technical solutions and several simulation studies to optimize the detector performances and investigate its physics reach.

   The student will perform realistic simulations based on theoretical predictions to study detector sensitivity. Based on this work, the student will participate on the detector R&D, particularly on light sensors and electronics and simulating physics impact on detector.

   Based on the success of liquid-scintillator devices on the kton scale such as KamLAND and Borexino, the construction of LENA (Low-energy Neutrino Astronomy), a liquid-scintillator detector on the scale of 50 kt is also being considered in Europe as next generation neutrino observatory. LENA's physics objectives comprise the observation of astrophysical and terrestrial neutrino sources as well as the investigation of neutrino oscillations. In the GeV energy range, the search for proton decay and long-baseline neutrino oscillation experiments complement the low-energy program. The Ph.D. student will, therefore, also have an opportunity to get involved in design studies such as LAGUNA which compares alternatives for future Megaton-size Detectors.

This project centers on involvement of both Hamburg (A. Mirizzi and C. Hagner who will be associated to the IRTG) and APC, Paris (T. Patzak) in studies on a future Megaton-detector project.

8. Novel weakly-interacting particles in astrophysics.

   In the last years it became clear that a variety of low energy experiments, in particular optical ones such as ALPs at DESY [27] and SHIPS at the Hamburg Observatory can search for new physics related to a possible hidden sector that is extremely weakly coupled to the Standard Model. String theory provides motivations for such WISPs (weakly interacting slight particles). In particular, string models often predict different types of light axions, hidden-photons and millicharged particles [28, 29]. WISPs would be invisible to conventional collider detectors, but could affect astrophysical and cosmic environments, and might give us valuable and complementary information about important open fundamental questions, like the hierarchy problem, unification, dark energy, dark matter, and the strong CP problem.

   In this context, a well-motivated physics case is the one of axion-like particles (ALPs) with a two-photon vertex. This photon-axion coupling may produce peculiar features in the spectra of distant gamma-ray sources, due to photon-ALP conversions in the large-scale cosmic magnetic field. Therefore we plan to perform a systematic study of possible signatures of ALPs in different gamma-ray observations such as gamma-ray bursts and the X- and gamma-ray diffuse backgrounds. Moreover, recently photon-ALP conversions in extragalactic magnetic fields have been suggested to play a possible role in the explanation of the observed transparency of the Universe to very-high energy photons [30, 31]. We intend to analyze this mechanism, studying in detail the spectral deformations expected for observed sources at different redshifts and for different models of the extragalactic background light.

   The main expertise for the particle physics aspects of this project is found in Hamburg (A. Mirizzi and A. Ringwald who will be associated to the IRTG), whereas the astrophysical aspects will be developed within project (1) on electromagnetic cascades in collaboration between Hamburg and Paris.

   A complementary research topic will focus on the role of WISP emission for anomalous energy losses in stellar evolution, allowing to set bounds on WISP properties. Valuable astrophysical probes for this research are constituted by solar measurements via neutrinos and helioseismology, and by the observational lifetime of helium-burning stars in globular clusters.

9. Data Analysis for LISA : Gravitational Wave imaging.

The LISA mission aims at detecting gravitational wave (GW) signals coming form a wide variety of sources including Super Massive Mass black hole coalescence, EMRI (Extreme Mass ratio Inspiral), Galactic binaries and other objects. One of LISA's end product will be a limited number of (3 year) data streams (1Hz) which can be transformed into two-dimensional Time-Frequency matrices.

The standard data analysis procedure is to extract the different signals using minimization schemes, as for example Monte-Carlo Markov Chain, based on model waveforms for the above sources, assuming they are sufficiently correct to not bias the searches. Our aim is to complement these methods using image-analysis techniques as the Time-Frequency matrix mentioned above can be easily compared to a very noisy image containing straight or curved lines that represent the expected signals during short time intervals. Note that although the time integrated Signal to Noise ratio of a given source could be in excess of 10, this is not true for smaller time periods. Based on modern techniques used to improve/modify optical images and on the minimal information defining a GW signal, this Ph.D work will study a number of possible algorithms which would allow to extract the physical signals contained in the matrix. The Ph.D will also study how data analysis techniques used for modern High Energy detectors could apply to this type of data.

This project centers on the expertise of P. Binétruy, E. Plagnol and G. Auger in Paris. Together with the project (6) on high energy neutrino detection it provides the experimental background for the multi-messenger studies in the project (10) discussed next. In this context it will be performed in close collaboration between Hamburg and Paris.

10. Multi-messenger studies with photons, neutrinos and gravitational waves.

A promising thesis topic consists of studying sources and mechanisms that involve both detectable high energy radiation and gravitational wave fluxes. One of the proposers has studied the case where the gravitational wave emission is linked to the high energy neutrino emission from core collapse supernovae [32] or to the electromagnetic output of accretion disks around supermassive black holes [33]. This should be extended to study detection prospects of fluxes of all four messengers, namely charged cosmic rays, photons, neutrinos and gravitational waves as well as their time variability from X-ray binaries, core collapse supernovae, active galactic nuclei (AGNs), and gamma-ray bursts. We will here benefit from the involvement of APC in the gravitational wave detector projects VIRGO and LISA. The fluxes of some blazars in GeV and TeV gamma-rays have been observed to vary on minute time scales which severely limits the size of the region where this emission can be produced. If the emission is produced in the accretion flow onto the central supermassive black hole powering the blazar, this short-time variability may probe gravitational effects very close to the supermassive black hole. The potential pay-off of multi-messenger source studies is large due to the many experiments involved. Detecting powerful sources such as blazars can also have considerable spin-off for fundamental cosmology since they can be seen out to very large redshifts where they can probe the expansion history of the Universe and thus, among other cosmological parameters, dark energy.

This project links the projects on electromagnetic cascades (1), and high energy neutrino (6) and gravitational wave detection (9) and develops the phenomenological and theoretical background. It centers on expertise of several senior physicists at Hamburg and Paris (D. Horns, A. Kouchner, E. Plagnol, D. Semikoz, G. Sigl).

2.3 The Search for Dark Matter and Early Universe Relics

11. Indirect detection of dark matter.

    This project will exploit a probe of dark matter that utilizes indirect detection of massive weakly interacting particles (WIMPs) that thermally decoupled in the very early universe and now fill our galactic halo. They are visible by their continuing annihilations into high energy gamma-rays, neutrinos, positrons and antiprotons. Crucial to this work is the coordinated interdisciplinary approach of astronomy and particle physics in order to separate out known astrophysical foregrounds. Theoretical predictions will be refined to pursue the quest for dark matter by both direct and indirect techniques using novel types of telescopes, both terrestrial and in space, that could detect high energy neutrinos, gamma-rays and cosmic ray antiparticles via deep underground direct detection of WIMPs, deep underwater (or ice) detection of high energy neutrinos and gamma-rays via satellite or air Cerenkov telescopes, and high energy positrons and antiprotons via satellite and balloon experiments.

    Improved calculations will be performed that include positron and antiproton diffusion, and implement templates designed for Planck foregrounds, to distinguish between the astrophysical and dark matter origins of any excess diffuse galactic synchrotron emission. Predictions will be made for the FERMI satellite which measures gamma-rays from inverse Compton emission by high energy electrons and positrons as well as the final state gamma-ray emission from annihilations. Forecasting will be done for existing air Cerenkov telescopes as well as for future projects such as CTA. Potential smoking guns include detection of gamma-ray line emission and confirmation of annihilation signals associated with nearby dwarf galaxies, with the Galactic Centre, and in dark matter cusps around massive black holes, by both spectral and spatial resolution. One novel signal is a sharper spectral cut-off than produced by cosmic ray propagation models.

    With the wealth of incoming data, it will be particularly important to cross-correlate the information from the various detection channels (both in wavelengths and messengers) – not only because any compelling claim of a dark matter detection will have to involve evidence from at least two independent observations, but also because this would allow to pinpoint the detailed properties of the dark matter particles much more precisely. In this context it is, in fact, important to realize the complementarity of these channels: while antiprotons [34], e.g., probe a much larger region of the galactic halo than positrons and therefore tend to be more suitable to constrain dark matter models, the latter could, in some cases, exhibit interesting *spectral* signatures [35] that would allow the discrimination of dark matter candidates; even more compelling spectral signatures are expected in the case of gamma-rays [36] – unlike for radio signals whose angular distribution, on the other hand, provides an interesting *spatial* signature which is quite different from the one in gamma-rays.

The complementarity of indirect and direct dark matter searches has recently been demonstrated to be important even in the long run [37]; this is in general true also for accelerator searches for missing transverse energy – though of course the first results of the LHC already begin to add important, and independent, input to the quest of determining the nature of dark matter.

With the aid of theorists bringing interdisciplinary skills from astronomy and particle physics to bear on these forefront problems, we hope to strengthen confirmation for the WIMP paradigm and to constrain specific models over large regions of parameter space.

This project is based on the expertise of senior scientists T. Bringmann, J. Silk, G. Sigl (indirect detection), D. Horns (indirect detection with radio and gamma-rays) and A. Kouchner (high energy neutrino detection) at all three institutions.

12. Dark matter detection with clusters of galaxies.

    Clusters of galaxies are known to contain large amounts of dark matter. While dark matter itself is invisible, the baryonic matter can be used as a tracer of dark matter. Most of the baryonic matter in Clusters of Galaxies (hereafter cluster) is at temperatures above 10^6 K and therefore emits strongly in X-rays. In order to obtain the best estimates for the dark matter content of a cluster of galaxies, it is necessary to obtain the temperature structure as accurately as possible. The best X-ray spectra to date are still obtained with grating spectrometers, however, the extended nature of the clusters is not ideally suited for X-ray grating spectroscopy since all current X-ray observatories are equipped with slit-less spectrographs and each individual line produces an image of the object in the dispersion/cross-dispersion plane. Therefore, the lines are "geometrically" broadened in addition to the instrumental line profile.

    On the other hand, the CCDs on-board of the current X-ray satellites provide a low-resolution spectrum at each position of the cluster but lack the high spectral resolution of the gratings. It is clear that for spatially concentrated X-ray emission, the smearing of the spectral lines is sufficiently small and the spectral resolution of the grating remains much higher than that of the CCDs. Still, for clusters with a sufficient core concentration the reflection grating on board XMM-Newton can still be used, in particular with the cooler Fe lines at 15 Å. Since the grating spectrometer of XMM-Newton usually operates simultaneously with the imaging CCDs (EPIC) and the imaging data can be used to compute the expected line profiles of the extended sources, the spatial information required for this task is actually present in the data. In order to compute the additional (geometric) broadening of the line profile, the extraction region of the RGS needs to be projected onto the EPIC CDDs and the emission distribution around the projected zero-point of the RGS can be derived. The extended nature of the emission of the clusters prevents the extraction of a source free background region in the RGS. However, usually a small part of the CCDs is not exposed to direct light from the source and can be used to scale the template backgrounds to the estimated background count rates.

    The feasibility of this approach has been tested by us with the availble XMM-Newton data on A 2957 and shown to work successfully. We propose to analyse all suitable clusters of galaxies observed by XMM-Newton to derive chemical abundances from line ratios, construct temperature and density profiles and determine the dark matter content.

This project centers on the observational expertise at Hamburg Observatory (J. Schmitt) and complements the expertise at Oxford (J. Devriendt, J. Dunkley, P. Ferreira). It is also directly related to the three following projects (13), (14) and (15) on the role of dark matter for the cosmological large scale structure.

13. Galaxy formation and dark matter structure.

    The project will consist of running and analysing GALACTICA, the most detailed cosmological simulation of the formation of our Galaxy ever achieved to date. This will feature constrained initial conditions with more than an order of magnitude more constraints than previously used in the field, allowing the influence of the environment of the Galaxy to be accurately captured up to distances of 200 Mpc. Moreover we will include for the first time baryonic physics (hydrodynamics, gas cooling and supernovae feedback) at unprecedented resolution ($10^{5-6}\,M_\odot$ in mass and 50-100 pc spatially) to assess its impact on the dark matter structure. This should allow us to make more realistic predictions for direct and indirect dark matter detection signals than what has been achieved before. The Ph.D. project would be to analyse the results of GALACTICA in order to perform these predictions. At Oxford, this project would be directed by J. Devriendt in close collaboration with the experts on indirect dark matter detection (T. Bringmann and J. Silk) at Hamburg and Oxford.

14. Signatures of dark matter in the microwave background.

    This project will investigate dark matter in light of Planck observations of the microwave background. Dark matter can leave an imprint on the primordial Cosmic Microwave Background (CMB) signal, and can also generate microwave emission from the Galaxy in the frequency range probed by CMB experiments. The injection of secondary particles produced by dark matter annihilation at high redshift ($z \sim 1000$) affects the process of recombination, leaving an imprint on CMB anisotropies and polarization. In this project we will investigate the constraints this places on dark matter models with Planck and ACT/ACTPol. In addition, the small-scale CMB is a sensitive probe of neutrino properties, and we will use new data to test for additional relativistic species and probe modifications to the coupling. The project will also exploit Planck data to search for indirect Galactic signatures of dark matter models in the microwave, including polarization of synchrotron emission from the dark matter halo. At Oxford this project would be directed by J. Dunkley, complemented by the particle physics expertise in Hamburg (B. Kniehl, A. Ringwald, T. Bringmann). It is also linked to project (11) on indirect dark matter detection with high energy radiation. Finally, its relevance for neutrinos builds a link to project (7) on low energy neutrino studies with future large scale underground detectors.

15. Large scale diagnostics of the nature of dark matter.

    The growth of structure in the Universe is a particularly powerful probe of the nature of dark matter. The Ph.D. project will be to perform a thorough analysis of how the properties of dark matter (interactions, mass, etc) affect the growth rate of structure, both linear ad non-linear. With an analytic understanding of the growth rate at hand, the task will then be to see how it affects cosmological observers, from the shape of the power spectrum to the effect of redshift space distortions and correlate them with measurements of the large scale properties of space time (such as luminosity distances and probes of the expansion rate). The hope is to find a "consistency" relation between the large scale observables and probes of growth which can be used as a dark matter diagnostic. At Oxford this project would be directed by P.G. Ferreira. It will be performed in close collaboration with the other projects on the large scale distribution of dark matter at Hambug and Oxford.

16. Dark matter annihilations as a source of ionisation in molecular clouds, and implications for primordial and current epoch star formation.

    The project will focus on the role of dark matter annihilations as a source of ionization in molecular clouds, both primordial and in the current epoch. Dense molecular cloud ionization levels control the coupling with magnetic fields and thereby the processes of fragmentation, accretion and feedback that are an essential part of star formation. This is obviously important for the first generation of stars, but may also be relevant for current epoch star formation especially in regions where the dark matter density is high, such as near the Galactic Centre. In collaboration with Patrick Hennebelle (Saclay), this will be studied via numerical magnetohydrodynamical simulations. In Oxford we have been running a suite (called the "Nut" suite) of extremely high resolution (parsec scale in the densest regions) Adaptive Mesh Refinement (AMR) cosmological resimulations of a high redshift galaxy. At high redshift ($z \sim 9$) the galaxy is a high surface density, rapidly rotating, gravitationally unstable disk with an ever-evolving population of high density molecular clouds. Through a collaboration with J. Blaizot and his Ph.D. student J. Rosdahl, researchers at the CRAL, Lyon, we have been implementing radiative transfer from ionizing photons into the AMR code. With this project, the sources of ionizing photons may be for example the first generation of massive stars, but equivalently we could assume they originate in dark matter annihilations and explore the impact of this source of ionization on molecular cloud formation and the first and later generations of star formation. At Oxford this project would be supervised by A. Slyz and it strongly links to project (5) on radiative transfer so that it could be co-supervised by P. Hauschildt in Hamburg. It is also complementary to project (11) on indirect dark matter detection with high energy radiation.

17. Non-Gaussianities in the Cosmic Microwave Background fluctuations.

    Cosmic Microwave Background (CMB) radiation results from the decoupling of matter and radiation in the early Universe. Weak anisotropies and polarization of the CMB are a major probe of the primordial Universe. The period of inflation in the first fraction of second after the Big-Bang, wich results from extremely high energy physics, can be constrained by the study of non-Gaussianities of CMB fluctuations. Very soon, the Planck satellite of ESA might be able to detect primordial non-Gaussianities for the first time. We propose to work on the development of tools for extracting non-Gaussianity informations from the maps of CMB anisotropies in the frame of the Planck mission, in which APC is largely involved. The student will also work on the induced constraints on the inflation potential. This project is at the interface between phenomenological theory and observations and would be directed by G. Patanchon at APC, Paris and co-supervised by one of the theorists in Hamburg.

As particularly suitable for a start we identify the three projects (1) Modeling of High Energy astrophysical sources and search for extragalactic magnetic fields, (4) Search for nearby sources of electrons and positrons using FERMI, LOFAR, and H.E.S.S./CTA and (11) Indirect detection of dark matter, which at the same time have a high potential to exploit the synergies and added value between the three institutes. Project (1) will be carried out mostly between Hamburg and Paris, project (4) is relevant for all three institutes, and project (11) will mostly be carried out between Hamburg and Oxford. The research oriented task of the scientific coordinator for whose funding we also apply in this proposal will be to get involved in the research topics of the three students.

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