# *Particles in an Evolving Universe*

# Contents

# Chapter 1

# Introduction

## 1.1 Dark matter and vacuum energy: grand challenges for modern physics

At the turn of the millenium, the two fundamental fields of physics, elementary particle physics on the one hand, and cosmology on the other, are undergoing a great development. Observational evidence is accumulating that neutrinos have a finite, though tiny rest mass, signifying the need for a revision or extension of the current standard model of particle physics. The next generation of particle accelerators will most likely be able to detect the postulated Higgs particle, which lies at the heart of the connection between symmetry groups and particle phenomenology. Furthermore, the LHC at CERN will reach energies which makes it plausible that the lightest supersymmetric particle can be discovered, thus providing an essential test to this theory which aims at the unification between strong and elektro-weak interaction with the gravitational force, i.e. a theory of quantum gravity.

Cosmology, on the other hand, has undergone a phase transition recently. We are in the process of determining the basic parameters of the cosmological model with a precision unimaginable only a few years ago. To wit, several independent methods converge on the value of the Hubble constant, $H_0 \approx 73 \pm 10$km/s; the very recent baloon experiments BOOMERANG and MAXIMA measured the fluctuation spectrum of the Cosmic Microwave Background (CMB), the relic of the early phase of our Universe, and provided very strong evidence that we live in a spatially flat spacetime. Finally, two independent groups, by studying the population of supernovae (SN Ia) at high redshift, both reported very strong indications for a non-zero value of the cosmological constant $\Lambda$. The era of precision cosmology is lurking around the corner, in the form of extending supernovae studies to even higher redshifts, and future baloon and satellite missions for measuring the CMB flutuations over the full range of angular scales, which will determine the fundamental cosmological parameters to within a few percent.

Already today, there exists very strong evidence for the existence of a non-zero cosmological constant and for the dominance of dark matter in the Universe. The baryon density is strongly constrained by measurements of the light element abundances, most noticibly helium and deuterium, in connection with Big Bang nucleosynthesis. Baryons cannot account for the cosmic matter density as determined by combining the CMB with the SN Ia results, or, completely independently, from the matter density locked up in clusters of galaxies. Both arguments lead to the conclusion that $\sim 90\%$ of the mass in the Universe is in the form of non-baryonic matter. The quest for the dark matter lies at the center of current interest in cosmology, but also poses a great challenge to particle physics – presumably, the dark matter comes in the form of some as yet unidentified weakly-interacting elementary particles. Alternatively, dark matter may be in the form of primordial black holes, presumably formed as a consequence of a phase transition in the very early Universe. In either case, the nature of dark matter can only be understood in the frame of an extended theory of elementary particle physics.

Most surprising is the probable existence of a non-zero cosmological constant, mainly because its value is some 120 orders of magnitude smaller than particle theory would estimate the value of the vacuum energy density. Unless one accepts the idea that we live in a Universe where some as yet unknown physical constants are subject to extreme fine-tuning, an understanding of the nearly-zero value of $\Lambda$ is a most essential step to understanding both cosmology and particle physics. It is possible, perhaps even likely, that the explanation for a non-zero $\Lambda$ and the nature of dark matter are intimately related. These two problems may be seen of the same fundamental nature as that of discrete energy levels before the discovery of quantum mechanics, and their solution will most likely have equally profound consequences for physics.

To summarize, the nature of the dark matter and the non-zero value of the vacuum energy density constitute the most burning and challenging problems of fundamental physics, and it is obvious that they can only be solved in a close collaboration between cosmologists and particle physicists.

## 1.2 Synthesis of Micro- and Macrocosmos

Dark matter and cosmological constant (dark energy) are two of the many phenomena that link the two fields of science that deal with the explanation of phenomena at the largest and smallest scales: cosmology and particle physics, respectively.

Collaboration between these two branches of science becomes so fruitful right now because of the lucky coincidence that both can be described by what is called a standard model, seemingly describing all known phenomena in the field. This indicates that in both fields we seem to be on the right track and can start further explorations from a firm base.

The standard model of particle physics has been formulated in the late sixties and describes physics at subnuclear scales with great precision. Matter is composed of quarks and leptons and the fundamental interactions are mediated by gauge bosons of the underlying gauge theory: $SU(3) \times SU(2) \times U(1)$ for strong, weak and electromagnetic forces. All known microscopic phenomena can be described by this theory. Its prediction concerning the existence and mass of the weak intermediate bosons $W^{\pm}$, $Z$ and the top quark have been confirmed experimentally at CERN 1984 and Fermilab 1995, respectively. The only missing ingredient is the so-called Higgs boson and its search is a major motivation for the construction of large accelerators as LEP and LHC (CERN), the Tevatron (Fermilab) and linear $e^+e^-$ colliders at even higher energies.

The standard model of cosmology is based on general relativity as an expanding Friedmann-Lemaitre universe originating from a so-called hot Big Bang. The evolution of the universe passes through a radiation dominated phase of high temperature followed by today's matter dominated phase. That might enter (or has entered already) in a vacuum energy dominated phase. The theory allows us to understand the appearance of the universe today with its stars, galaxies, clusters and superclusters evolving from a hot particle plasma in the early universe. Its most generic predictions, most notably the existence of the microwave background and the abundance of light elements, have been beautifully confirmed by observations. Most recently the measurement of the energy density of the universe, the observation of fluctuation in the microwave background and its connection to structure formation in the presence of cold dark matter have given further strong support to the standard hot big bang theory. Observations in the near future will allow a more precise determination of the cosmological parameters contained in this standard model.

While these standard models are successful in their description of known natural phenomena, they do not represent a complete theory yet. But they can serve as a solid base for exploring the questions that are still open. Both models contain many parameters that could be (and partially have been already) determined by observations, but the actual values require still some explanation. It turns out that these questions seem to require a synthesis of the two fields. As we have seen above, dark matter and dark energy are such examples. But, as we will argue, there are more phenomena "beyond the standard model" that are of common interest.

The motivations to go beyond the standard of particle physics are primarily theoretical. One of them is the quest for the unification of fundamental interactions, including gravity. A second is the search for mathematical consistency of this unified description in the framework of quantum field theory. These considerations lead to the concepts of supersymmetry, supergravity and (super)string theory with various predictions for high energy physics and cosmology, that will be tested in the near future. In fact the notion of a "Supersymmetric Standard Model" has already ermerged. It predicts a host of new particles, the lightest of which is neutral and stable. The properties of this particle are such that it could dominate the matter density of the present universe as cold dark matter. This lightest supersymmetric particle (LSP) is a so-called WIMP (for Weakly Interacting Massive Particle) could be the particle physics candidate for the dark matter seen in astrophysical and cosmological observations. This is of particular importance since by now it is well known that the neutrinos of the standard model, contrary to earlier expectations are not able to play this role.

A further argument to consider physics beyond the standard model is the absence of baryon number violation. This, of course, is very desirable in view of proton stability, but some amount of baryon number violation is needed in the process of baryogenesis: the creation of a baryon-antibaryon asymmetry in the early universe. It cannot be achieved within the physics contained in the particle physics standard model.

Baryogenesis is as well an ingredient of the phenomena beyond the standard model of cosmology. While the baryon-to-photon abundance ratio can be determined from considerations of nucleosynthesis, an explanation of this ratio of $10^{-9}$ is not available within the standard model. Similar statements apply to other cosmological parameters such as the total matter density $\Omega_M$ and the vacuum energy density $\Omega_\Lambda$. The great challenge in this model is the description of the connection of present day astronomical observations to the fundamental parameters in the early universe. Mechanism in astrophysics like star formation, galaxy formation and others will become important aspects in establishing this relation. With the new observational results to come in the next few years, much more detailed questions can be asked and hopefully answered.

These observations will certainly be very important for the field of particle physics as well, in particular since we know by now that neutrinos, although (probably) massive, will not play an essential new role in cosmology, since their contribution to (hot) dark matter will not be important. In fact, from the simple observation that the age of the Universe exceeds $10^{10}$years, from which it follows that the mean cosmic matter density must not substantially exceed the critical value, cosmology yields upper limits on the masses of neutrios ($\lesssim 100$eV), which for the $\mu$ and $\tau$-neutrino are several orders of magnitude more sensitive than laboratory constraints. Other candidates for (cold) dark matter like the above mentioned WIMP-neutralino, axions, gravitinos etc. might become more relevant.

A fundamental question of particle physics is concerned with a mathematical consistent description of quantum gravity. No satisfactory theory has been found yet, although superstring theory might be an important step forward in the right direction. The mysteries of the cosmological constant and the nature of black holes will remain enigmatic as long as this problem is not resolved. Theoretically strings, membranes, extra dimensions are attempts in this directions, but particle physics experiments cannot easily explore these unknown phenomena. It is here that astrophysical observations have to step in. Only these can reveal the possible existence of a cosmological constant, which is such an important ingredient of any theory of (quantum) gravity.

In astronomy the existence of dark matter has been established, but its origin has still be to clarified since a conventional explanation is not available. With the upcoming precision data it has to be seen whether a WIMP as a neutral weakly interacting particle can explain the phenomenon. Direct and indirect WIMP searches are underway and will hopefully resolve these puzzles. Detailed question like e.g. the density profile of dark matter in our galaxy can then be answered with a common effort in the field of astronomy and physics.

In such a way the two standard models of particle physics and cosmology might merge to a unified description of our universe at all the different scales during its evolution.

## 1.3 Observational probes of dark matter

Several deep underground experiments are underway which attempt a direct detection of weakly-interacting massive particles (WIMPs); one of them recently claimed a first signal. Such a detection would provide a major step in the quest for the nature of dark matter, since it would verify that WIMPs, and not primordial black holes or other massive bodies, make up the majority of the dark matter in our Galactic halo. However, it appears that these dark-matter experiments will be able to prove the sheer existence without providing much additional information about the physical properties of WIMPs.

On the other hand, there are no strong astronomical arguments (except Occam's razor) that the dark matter on scales of galaxy halos is the same as that on larger spatial scales. In fact, the baryon density determined from primordial nucleosynthesis is sufficiently high to allow for all dark matter on galactic scales to be in the form of baryonic matter – the detection of a significant gravitational microlensing rate towards the Magellanic Clouds provides some evidence for the presence of massive compact halo objects (MACHOs) in our Galaxy, though the interpretation of these results are far from being obvious. In conclusion, we have no precise idea of how much non-baryonic matter there is in our Galaxy.

Precision cosmology in the above mentioned sense means that the statistical properties of our Universe can in principle be predicted with very high accuracy. As the evolution of weakly-interacting dark matter is governed solely by gravity, very high resolution numerical simulations and, to some degree, analytical models, can provide detailed predictions for the distribution of dark matter and its evolution with cosmic time. In contrast, modelling the distribution and evolution of luminous matter, such as galaxies, is tremendously more difficult owing to the wealth of physical processes which govern the interplay between gravity, hydrodynamics, star formation and feedback processes. Such simulations can be compared with observations to test the underlying theory in more detail, but also to obtain an empirical handle on the evolution of the interplay between dark and luminous matter. In particular, discrepancies between generic predictions of such simulations and observational results will signify gaps in our understanding of dark matter properties.

One of the results of these simulations of hierarchical structure formation is that the dark matter halos of galaxies, and of groups and clusters of galaxies, follow a 'universal' density profile. There is substantial evidence from observations of the rotation curves of low-surface brightness galaxies, which are dominated by dark matter, that their dark matter halo does not follow the universal density profile. To remedy this potential conflict between theory and observations, the concept of self-interacting dark matter particles has been suggested; depending on the cross-section, such self-interactions will affect the central parts of dark matter halo profiles, but leave the outer regions unaffected. If future cosmological evidence supports the idea of self-interacting WIMPs, it would provide an invaluable clue to the nature of fundamental interactions of matter. Very detailed measurements of rotation curves of dark-matter dominated galaxies, combining optical and radio high-resolution data, are needed to verify the discrepancy between true dark matter mass profiles and theoretically expected ones.

Another generic prediction of hierarchical structure formation is the existence of many low-mass dark matter halos around massive galaxies like ours; whereas some 30 faint galaxies are known to exist in the Local Group, this is about a factor 10 below predictions from Cold Dark Matter models. If these discrepancies are confirmed, they would present a serious challenge to our understanding of structure formation, and thus of dark matter.

Whereas on galaxy scales baryonic matter may significantly alter the profile and appearence of dark matter halos, dark matter on larger scales provide cleaner laboratories for investigating the dark matter distribution. Although the defining criterion of dark matter provides the biggest obstacle to its study, namely that it is dark, it is generally assumed that the baryonic processes in clusters of galaxies are sufficiently well understood to allow a detailed investigation of their dark matter profile. One of the goals of near-future cluster observations, using new millimeter instruments for measuring the Sunyaev-Zeldovich effect, the new generation of X-ray telescopes to map the density and temperature structure of the intra-cluster gas, and gravitational lensing observations using the new 8-meter class telescopes and wide-field imaging cameras, will be to compare the mass density in clusters with the universal density profile predicted by theory. A serious discrepancy would provide a smoking gun for CDM models of structure formation.

One of the main goals of modern cosmology is therefore to investigate the spatial distribution of dark matter and its evolution with cosmic time. Whereas the CMB probes the distribution of matter at very early times and on large scales, the dark matter distribution 'closer to home' needs to be studied with very different methods. The most appropriate one is gravitational lensing, since the deflection of light in gravitational fields is independent of the state and nature of the matter which causes them. Hence, lensing will be used

- to study the statistical properties of the large-scale (dark) matter distribution in the Universe at characteristic redshifts of $z \sim 0.3$, by measuring the so-called cosmic shear,
- to measure the mass profile of clusters of galaxies out to large radii, and compare their mass and light profiles,
- to search for matter concentrations with cluster mass which have failed to produce luminous galaxies and which therefore will escape more traditional survey methods,
- to study the mass properties of the dark matter halos of galaxies and groups, employing the methods of galaxy-galaxy lensing, in particular to determine the size of the dark matter halo of galaxies,
- to search for substructure in the mass distribution of galaxies which may signify the presence of the 'missing' satellite galaxies predicted by hierarchical structure formation, by investigating the akward flux ratios of several multiply imaged quasar system.

Recent discoveries of a significant cosmic shear signal, reported by 4 independent groups of researchers, have opened up a new field of research and provided cosmologists with a powerful tool to investigate the dark matter distribution at intermediate redshifts. Recognizing the potential of this new handle on dark matter, serious planning has begun for a dedicated telescope that shall be used entirely or to a large fraction to cosmic shear obsersation. Three such concepts have been widely discussed; the perhaps most promising one is the Dark Matter Telescope, an 8-meter telescope equipped with a 3-degree camera and $(36000)^2$ pixels which was ranked very highly in the Decadel Report of US Astronomy. This ultimate imaging machine presumably can be realized only in an international effort.

Studying the matter distribution in and around our Galaxy is complicated due to the lack of luminous tracers at large Galacto-centric distance. Nevertheless, impressive progress has been made in the past years, owing to the astrometric satellite mission Hipparcos, wide-field multi-color photometric surveys like Sloan, new surveys at 21 cm to map the angular and velocity distribution of hydrogen clouds, and new ultraviolett space missions to study the absorption of gas in our Galaxy. Here we mention two of the highlights resulting from these studies:

The new identification of cold streams of stars around our Galaxy are best interpreted as tidal debris from satellite galaxies which in the recent past have merged with the Galaxy, following the decay of their orbits due to tidal friction. In one case, the tidal stream can be identified with the Sagittarius dwarf galaxy which is currently in the process of merging. These observations thus lend support to the hierarchical process of structure formation in which massive galaxies are built through the merging of less massive entities. In a similar vain, the Magellanic stream seen as a tail of hydrogen trailing the orbits of the Magellanic clouds signifies the slow decay of the Clouds due to tidal interaction with our Galaxy.

The identification of a large number of hydrogen clouds which are approaching our Galaxy with velocities much larger than characteristic orbit velocities has recently been interpreted as being due to gas situated in dark matter halos which are not massive enough to promote significant star formation. This interpretation is supported by UV spectroscopy and the failure to detect molecular (e.g. CO) emission, thus finding that these gas clouds have low metallicity and therefore are unlikely to be of Galactic origin. If true, the high-velocity clouds can be the baryonic tracers of the missing satellite halos predicted in CDM models of struture formation. Testing this hypothesis is therefore of utmost importance to verify, or otherwide, generic prediction of this cosmological model.

Upcoming astrometric satellite missions will provide a quantum leap in accuracy with which we can measure the kinematics of stars in our Galaxy and thus map its gravitational field out to large distances. Already today, the stellar tidal debris provides strong evidence for at most a modest flattening of the dark matter halo of the Galaxy, and these future missions will firm up these constraints. Since the shape of the dark matter halo reveals information about its formation, such constraints are essential for our understanding of the Galactic history. Wide-field imaging surveys will detect further tidal streams and thus allow us to reconstruct the recent accumulation of Galactic mass from satellite mergers. Higher-resolution and more sensitive 21 cm surveys will map the distribution of high-velocity clouds around our Galaxy and thus provide clues to their nature, their origin and their relation to dark matter halos. It is one of the fascinating aspects of modern astrophysics that very traditional astronomical subjects such as astrometry and H I surveys are intimately coupled with some of the most urgent questions of cosmology, i.e. the nature and distribution of dark matter.

The observational evidence for dark matter could be of great relevance for elementary particle physics. It might find its explanation in the existence of new fundamental particles. Typically such particles should be neutral and weakly interacting, since otherwise they would have been observed already in particle physics experiments (as long as the are not too heavy). They should be stable (or long lived) to be still around today to account for dark matter. They are classified in *hot* and *cold* dark matter, according to whether they are relativistic or nonrelativistic at their freezeout temperature. Light neutrinos would contribute to hot dark matter, while WIMPS are cold. The present observations greatly favour cold dark matter that clumps at smaller (e.g. galactic) scales.

Particle Physics candidates for dark matter are manifold and fall into 3 different classes: (i) those particles that are known to exist (e.g. light neutrinos), (ii) those that have been conjectured for reasons other than dark matter considerations and (iii) others. The existing neutrinos are not likely to contribute much to dark matter (contrary to earlier expectations), because their masses do not seem to lie in the relevant range and since hot dark matter would clump predominantly at larger scales than observed. The second class (ii) contains already many candidates. Most of them are connected to the supersymmetric extension of the standard model. Supersymmetry predicts many new particles that should be in the range of TeV or below. A consistent supersymmetric extension of the standard model requires a new symmetry (usually called R-symmetry or R-parity) to assure a long lifetime of the proton. Such a symmetry implies that supersymmetric particles can only be produced in pairs: *thus the lightest particle (LSP) has to be stable.* This is very similar to fermion number conservation: it is at the origin of the stability of the electron. The LSP should be neutral: depending on the model it could be the gravitino (partner of graviton), neutralino (partner of gauge boson), higgsino (partner of higgs boson), sneutrino (partner of neutrino) etc. In the minimal model (MSSM) it is the neutralino: the partner of the neutral gauge boson Z and/or $\gamma$. Its mass should be in the range of 50 - 300 GeV with weak interactions. It could easily lead to dark matter with the required abundance $\Omega_M \sim 0.3 - 0.4$. At the moment this seems to be the most likely WIMP candidate. It is searched for by current particle physics experiments e.g. at LEP at CERN (Geneva), that provide the current lower limit on its mass of around 50 GeV. Future searches will extend this bound to higher energies. Other experiments search for neutral particles in our environment (galaxy), one of which (DAMA) claims to have found a signal, but this observation is still controversial.

Another cold dark matter candidate in class (ii) is the axion, a very light pseudoscalar boson. Its existence was conjectured in connection with a solution of the strong CP-problem. Now it could serve as cold dark matter as well. Its supersymmetric partner, the fermionic axino might as well be a realistic candidate for cold dark matter.

In the third class (iii) of candidates there is not much predictive power since these particles have been conjectured for the purpose of dark matter considerations. Here we might find heavy neutrinos, heavy neutral scalars, ultra heavy particles (like Wimpzillas), just to name a few.

Very often particle physics models tend to predict an embarrasingly large contribution to the matter density of the universe. In string theories and theories with extra dimensions, for example, we usually find a host of new candidates: the so-called moduli fields that parametrize the vacuum degeneracies of these theories. In fact, very often they might contribute too much to the energy density of the universe, a property that might be shared by gravitino as well. More detailed calculations are needed to clarify these questions, as these problematic abundances might originate from a nonthermal production in the early universe, a mechanism that is not yet undestood very well.

## 1.4 The young Universe

The past five year have witnessed an impressive widening of our visible horizon into the early phases of the Universe:

- By now, nearly a thousand galaxies have been detected at redshifts $z \sim 3$, demonstrating that galaxies were alive and well at a time where the Universe had only $\sim 15\%$ of its current age. Already by then, galaxies were strongly clustered and the precursors of current day massive galaxy clusters were in place.

- Similarly, about 100 galaxies with redshifts $\sim 4$ are known, some of which have been studied with great detail, partly making use of natural telescopes provided by the gravitational lens action of intervening clusters of galaxies.

- These findings have allowed the reconstruction of the cosmic star formation history, yielding that most of the stars have been formed well in the past; the Universe was a more exciting place back then.

- Sub-millimeter surveys have uncovered a population of deeply dust-enshrouded galaxies, probably very actively forming stars.

- Galaxies and quasars with redshifts close to 6 have been discovered, showing that the Universe is transparent at least out to these distances (i.e., reionization must have occurred at even earlier epochs) and that it found a way to form massive galaxies and supermassive black holes merely one billion years after the big bang.

- Gamma-ray bursts, these mysterious flashes of very high-energy photons, once believed to origin on the surface of neutron stars in the backyard of our Galaxy, are now known to occur at very high redshifts, implying energies apparently exceeding the rest mass energy of a whole star.

This, by no means exhaustive, list of achievements demonstrates that the young Universe can be studied in detail, thus allowing us to obtain the history of structure formation from very early times on. Presently, though, these findings raise more questions than provide answers: When did the first galaxies form? Why was star formation more efficient in the past than today? Why does there exist a 'quasar era', i.e. why is nearly all quasar activity confined to a brief time period aound 2 billion years after the big bang? How do massive black holes form? What is the relation between dark matter halo formation, galaxy formation, and the formation of black holes which seem to reside at the center of almost every galaxy?

The last question may bear the answer to many of the previous ones. Since dark matter cannot be probed directly at high redshift, one has to rely on understanding better than today the relation between dark and luminous mass to use galaxies as markers of the underlying dark matter distribution. But progress is rapid: the new 8-meter class telescopes will allow the measurement of the rotation curves of high-redshift galaxies and therefore study their dark matter halo profile. The same telescopes, together with a new generation of instruments on the Hubble Space Telescope, will identify the optical counterparts of sub-millimeter sources. The sub-millimeter sky itself will be reopened with ALMA, the sub-millimeter array to be in operation in 2005, after which sub-millimeter astronomy will achive similar sensitivity and resolution as optical astronomy. High-redshift clusters will be found, using the Sunyaev-Zeldovich effect, the X-ray emission from intracluster gas, or weak lensing signatures.

Concerning the X-ray detection of high-redshift clusters, the current generation of X-ray telescopes will measure the brightness and temperature profiles of many high-redshift clusters. Since clusters provide perhaps the cleanest probe of dark matter, these new observations will allow us to measure the dark matter profile of halos at $z \sim 1$, thereby enabling one to test the universal dark matter profile at earlier times. The following generation of X-ray telescopes will have the sensitivity to measure clusters out to redshift $z \sim 5$, if they exist, thus probing the tail of the density contrast population and its Gaussian nature, as predicted by inflationary theories. However, these measurements are hampered by absorption from Galactic gas: Even the iron-K line at $\sim 6.4$keV is then redshifted to below 1 keV, making it difficult to unambiguously identify it as such. In order to make best use of these future facilities, the angle-dependent absorption, i.e. the distribution of column density of Galactic gas, needs to be understood in great detail, and a new all-sky survey at 21 cm is badly needed.

The evolution of the quasar population with redshift directly probes the formation of supermassive black holes. To understand the relation between galaxy formation and black hole formation, the formation and merging of dark matter halos needs to be understood in much more detail than at present. Are supermassive black holes formed in the process of galaxy mergers, or are they formed in the first generation of galaxies? If so, what is the fate of the individual black holes in merging events? In order to answer questions like this, the census of quasars must be further extended to fainter flux limits, as is already happening with the very first data from the Sloan survey (which yielded several quasars with redshift $\geq 5$). In parallel, quasars need to be searched from radio surveys, as traditionally they have yielded the highest redshift examples of this energetic phenomenon. Whereas the relation between galaxy and black hole formation is currently not understood, it is most likely that a very tight connection exists; this connection can then be used to study galaxy mass-scale dark matter halos to larger redshifts than possible with the stellar light from galaxies alone.

## 1.5 The very young universe

Whereas the standard model of cosmology, obtained through combining the laws of General Relativity with known particle physics, has been extremely successful and can be regarded one of the greatest triumphs in physics, there are questions which need to addressed before we can understand the origin of the Universe:

- Why is the Universe so close to being spatially flat?
- Why is the CMB so incredibly isotropic?
- What is the origin of the density fluctuations seen in tiny CMB temperature fluctuations, from which all structure in the Universe developed?
- Why is the cosmological constant so much smaller than generic predictions for the vacuum energy density?

All of these questions can be attributed to special 'initial conditions' at a time when $T \sim 10^{13}$K, but a more scientific view would be a natural explanation of these phenomena through physical processes in the very early universe by extrapolating as yet unknown physical laws further back in time.

The fundamental scale of the particle physics standard model is the scale of electroweak symmetry breakdown: a few hundred GeV, and the physics beyond the standard model deals with energies of a TeV or larger, as e.g. the grand unified scale $M_X \sim 10^{16}$ GeV or even the Planck scale of $M_{\rm Pl} \sim 10^{19}$ GeV. These phenomena will be relevant for the very early universe with temperatures $T \geq 10^{15}$ K or redshifts $z \geq 10^{15}$. Todays astronomical observations cannot directly probe these phenomena and only provide indirect information about the nature of the electroweak phase transition, baryogenesis, leptogenesis, just to name a few. Nonetheless today's universe is believed to originate from such a hot universe and we should find ways to connect the different phases of evolution. One of the past successes of the hot big bang scenario is the prediction of the microwave background as well as the prediction of the abundance of light elements in the framework of nucleosynthesis, which e.g. is very sensitive with respect to the number of light neutrino species. In fact one of the strong constraints on the physics of the early universe is the requirement that the successful predictions of nucleosynthesis should not be spoiled by new phenomena.

A key ingredient of the connection between the early and the late universe is the mechanism of structure formation. It should provide the seeds of density perturbations and describe their evolution to the structures observed today: galaxies and clusters of galaxies.

It is the mechanism of inflation that is at the basis of this description; the generic predictions of inflation address several of the aforementioned problems so that it by now has become part of the 'standard model' of cosmology, despite our lack of understanding of its details. One assumes a phase of exponential expansion in the early universe. Originally this conjecture was made to solve some conceptual problems of the naive hot big bang scenario, such as the flatness and horizon problem. New degrees of freedom (as e.g. a scalar field called inflaton) are needed to implement this mechanism. The inflationary expansion takes place while the inflaton field is dislocated from the minimum of its potential and the total energy of the universe is stored as potential energy of this field. At the end of inflation this potential energy is transformed into radiation energy of a reheat temperature $T_R$. Possible values of $T_R$ range from 100 GeV to $10^{19}$ GeV. After the inflationary phase the universe will then enter a radiation dominated expanding universe with starting temperature $T_R$.

The inflationary scenario makes some definite general predictions of which the most important one concerns the energy density of the universe: $\Omega_{\mathrm{M}} + \Omega_{\Lambda} = 1$, i.e. critical total density, implying a spatially flat universe. Recent measurements conducted by balloon experiments, BOOMERANG and MAXIMA, seem to confirm this prediction: a big support to the theoretical conjecture of an inflationary early universe.

In addition, the inflationary scheme gives rise to seeds for structure formation. Quantum fluctuations in the very early universe (before the inflationary epoch) lead to density perturbations. During inflation these pertubations leave the event horizon due to the fast expansion. As a result their size is not washed out but frozen in. After inflation they will eventually reenter the event horizon and provide the seeds for structure formation with a Harrison-Zeldovich type of spectrum. A first sign of these perturbations can be seen as the tiny fluctuations in the cosmic microwave background spectrum as first observed in the early 90's by the COBE experiment.

At later time these fluctuations will grow and turn into galaxies and clusters of galaxies. This mechanism of structure formation depends, of course, very much on the parameters of our universe. As such, it can be used as an indirect tool to determine these parameters. At the moment it is believed that cold dark matter must be present to give a satisfactory account for structure formation. This is an argument for cold dark matter independent of the astronomical observations explained earlier. More detailed studies of this mechanism will most probably reveal new insights in particle physics, astrophysics and astronomy.

Thus the inflationary paradigm gives us a mechanism that links the very early universe to today's astronomical observations, one of the examples that makes the synthesis of particle physics and cosmology so successful.

## 1.6 Supermassive black holes

The discovery of quasars some 37 years ago, and studies of their properties quickly led to the hypothesis that they are powered by accretion onto a central, supermassive

($\sim 10^8 M_\odot$) black hole. Only much more recently, mainly due to high-resolution observations with HST, came the realization that basically every spheroidal galaxy, or spheroidal galaxy component (such as the bulge in spiral galaxies) contains a supermassive black hole. The latest evidence convincingly shows that the mass of the black hole is very tightly correlated with the velocity dispersion of the spheroidal stellar component in which it is contained. This remarkably tight correlation may provide important hints on the nature of dark matter:

As numerical simulations predict a cuspy density profile of dark matter halos, the mass distribution in the center of a newly formed galaxy will initially be dominated by dark matter; hence, the current density profile and the corresponding velocity dispersion must have originated from the initial dark matter profile which determined the fate of the baryonic, star-forming material. Also, the initial dark matter profile, in conjunction with (as yet not understood) baryonic processes, must have led to the formation of supermassive black holes. The observed tight correlation between black hole mass and the kinematic properties of the stellar population requires a joint explanation for their formation and their evolution, e.g. in the merger processes of subhalos.

The formation of supermassive black holes is far from being understood; a dense central (neutron?) star cluster could become dynamically unstable and collapse to a black hole; alternatively, a stellar mass black hole could grow via accretion of baryonic material, and supermassive black holes are formed by merging the holes of the progenitor galaxies in galaxy merging. If the dark matter particles are self-interacting, black hole growth can also occur via accretion of WIMPs, without the emission of electromagnetic radiation.

## 1.7 The highest-energy cosmic rays

Some of the most energetic phenomena in the Universe occur in the direct vicinity of black holes. Many Active Galactic Nuclei (AGN) have been found to emit very hard $\gamma$-radiation, which varies on time scales of days or even shorter. Since this type of AGN is expected to host black holes with mass $\sim 10^8 M_\odot$, the variability time scale is not appreciable larger than the event horizon crossing time, so the radiation, or better: the radiators, must come from very close to the Schwarzschild radius. The processes leading to these $\gamma$ rays are not understood in detail, but it is likely that they originate from very high energy electrons. Since the energetic particle production process in AGNs has not yet been uniquely identified, it is unknown whether there exists a corresponding population of ultra-energetic protons, but for many acceleration processes, protons are more easily accelerated than electrons.

In any case, it is clear that near the black hole of AGNs there exist a production site of particles with energies unattainable in any of the future man-made accelerators. Direct evidence for such a production is provided by the highest-energy cosmic rays with $E \geq 10^{11}$ GeV. Although their flux near the Earth is too small to allow controlled experiments with them, near their production site they undergo interactions which can be observed – e.g., the TeV emission from AGNs. The current revolution of astronomical intrumentation will rapidly improve our capability to observe these accelerator sites and to study the high-energy processes occurring therein.

The origin of the most energetic cosmic rays remains one of the big puzzles. Whereas cosmic rays with energies $\lesssim 10^{17}$eV are believed to be produced by shock acceleration in supernova explosions in our Galaxy, those with $E > 10^{19}$eV are of different origin. One suggestion for their origin is the production in energetic radio galaxies; however, cosmic rays at such high energies cannot propagate through intergalactic space without dramatically loosing energy through photon-pion pruduction through collisions with the CMB photons. Owing to their high energy, these cosmic rays are not substantially deflected by magnetic fields, so that their arrival direction should point towards their source, but no obvious candidate sources have been identified within $\sim$ 100Mpc.

An alternative explanation for the origin of ultra high energetic cosmic rays employs particle physics beyond the standard model. For example, they may be generated by the decay of some supermassive 'X' particle. If the 'X' particle is a metastable relic from the inflationary phase, its decay time should then be comparable to the age of the Universe and may be one of the dark matter candidates. Alternatively, the 'X' particle could be produced by topological defects, like cosmic strings of magnetic monopoles, that were created at a phase transition at the end of inflation.

If these cosmic rays have an astrophysical origin, e.g. being produced near the event horizon of a spinning black hole, the study of their arrival direction and the energy-dependent arrival times can be used to put constraints on magnetic fields outside of our Galaxy about which very little is known.

## 1.8 Challenges in theoretical physics

Mostly cosmological constant and quantum nature of black holes...

Could get new input from cosmology that is not available otherwise...

Strings and extra dimensions...... brane worlds and cosmological consequences.

## 1.9 The necessity for founding an SFB

## 1.10 Timing

As argued above, we are currently witnessing the completion of a great milestone in particle physics and astrophysics, where in both areas 'standard models' have been developed and verified within their range of validity, owing to very recent observational, experimental, and theoretical progress. By reaching this important milestone, several new fundamental physical questions have been uncovered whose solutions will most likely affect the foundations of modern physics. At the same time, prospects for a thorough investigation of these questions are most favourable, given the current outline for future observatories and experimental facilities (such as a whole new generation of collider experiements, vast advances in detector developments, new astronomical observatories in space and on the ground).

Progress in uncovering the nature of the dark matter and of the vacuum energy, and the puzzle of the highest energy cosmic rays, can undoubtedly be made only in a close interaction and collaboration between experimental physicists, theoreticians, and astronomers. The insights contributed by each of these groups, whereas valuable on its own, must be combined in order to attack the aforementioned fundamental questions.

In contrast to the need of close interactions between physicists and astronomers is the lack of a strong tradition in Germany for such collaborations. Cross-disciplinary research is often difficult to carry out as they do not fit well within the current structure and organization of research. To mention one example, only recently did experimental astro-particle physics become part of the Verbundforschung. (Could mention here labs like Gran Sasso and Kamiokande to illustrate the activities in other countries...)

Given the large attention that the interplay between physics and astrophysics receives in several other countries (e.g., the USA and UK), measures are needed to allow German scientists to contribute to the big endevour that will eventually lead to the understanding of the origin, nature and properties of dark matter. The SFB-375 in Munich (where to of us have been involved decisively) has been a fruitful example how an SFB can positively affect the research of formerly unrelated research groups. At the time of its creation, the quest for the properties of neutrinos has been the key question which combined experimental physicists, theoreticians, and astrophysicists. The impressive progress made demonstrates the positive effects the installment of the SFB had.

Similarly today, the time is ripe to make a coherent effort towards dark matter research. The planned SFB will be centered around this basic theme, and is intended to catalyze cross-disciplinary research in this and closely related areas. It will strongly encourage to create collaborations between currently separated teams and to capitalize on their joint expertise, and it will be invaluable in making optimized use of the current and near-future research facilities. The SFB is not centered on funding new experimental hardware, at least not initially, but on 'brainware', in an effort to maximize the scientific output from experiments in which the applicants are involved.

Given the large public outreach effect questions related to fundamental interactions, cosmology, and dark matter have, the SFB will have a positive impact on the attractiveness of the physics program at the University of Bonn. With the current dramatic decrease in the number of physics students, attracting young and talented people will be essential to keep up the scientific standards of research on fundamental physics. The SFB will provide a framework for joint seminars and discussions to achieve a mutual understanding of hitherto separated research fields and to obtain a common ground for future research, in particular also for young researchers like postdocs and PhD students.

## 1.11 Location

Bonn hosts one of the biggest concentration of astonomy and physics research in Germany, together with Munich and Heidelberg. The physical research at the University of Bonn covers a wide range of areas, including elementary particle physics and field theory, nuclear physics, applied physics ....HP.... Likewise, astronomy in Bonn covers a large diversity of fields, including cosmology, galactic and extragalactic research, star formation and evolution, cosmic ray physics, active galactic nuclei, interstellar chemistry etc. Bonn hosts the only two radio-astronomical institutes in Germany, one being the Max-Planck-Institut für Radioastronomie which operates the 100-m antenna in Effelsberg. Researchers within the SFB are centrally involved in major national and international research projects, including ZEUS at HERA, OPAL at LEP, ATLAS at the LHC at CERN ....HP....., and on the astronomical side, ALMA, the large millimeter array in the Atacama desert in Chile, DIVA, a German astrometric satellite recently approved by DARA ...

The traditionally excellent relations between physicists and astronomers in Bonn provides an ideal framework for our research program. The recent appointments of two former members of the Munich SFB (H.P. Nilles and P. Schneider) has brought additional experience in inter-disciplinary research and its coordination to Bonn. In addition the presence of K. Menten as a Director of the Max Planck Institute and the newly appointed professor H. Dreiner at the PI strengthens the program (should we mention NF Dietz?).

Recognizing the importance of dark matter research, several courses and seminars on cross-disciplinary topics have been organized, including a seminar on astro-particle physics (U. Klein & N. Wermes) and a lecture course on this topic (H.P. Nilles). In agreement with what was mentioned above, these attracted large and active participation by students.

# Chapter 2

# Proposals

### 2.0.1 Star Formation in the Early Universe

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**Abstract**

The rapid development of millimeter and sub-millimeter bolometer array technology has recently lead to the detections of abundant thermal dust emission from galaxies and quasars at high redshifts, at epochs where the first galaxies and black holes formed. In this project we propose to utilize present and upcoming sensitive bolometer arrays to study the nature of these submillimeter and millimeter background objects. We plan to perform unbiased searches for such objects in square degree blank fields, and to study the uncovered sources in detail through follow-up radio, optical, near-infrared, and X-ray observations, in order to clarify their relation to known classes of objects, and to examine their redshift and spatial distribution. We supplement the unbiased surveys with deep pointed observations of know galaxies and quasars. Our aim is to trace the star and black hole formation history of the Early Universe.

### Current status of research

Among the fundamental cosmological questions being asked today are: when did galaxies and massive black holes form in the early Universe, and how did they subsequently evolve? Modern telescopes, operating from radio through optical wavelengths are now detecting galaxies out to redshifts beyond 6, thereby probing the "dark ages" where the first stars and black holes may have formed (Rees 1999).

The most luminous starburst galaxies in the universe are difficult to observe at optical wavelengths, since much of the stellar light is typically obscured by dust, which absorbs the radiation and reradiates the energy at infrared wavelengths. The emission from galaxies at large distances is redshifted, so that the far-infrared (FIR) to millimeter (mm) wavelength region is best suited to detect and study such galaxies. This has motivated deep searches at submm and mm wavelengths with existing ground-based instruments such as SCUBA and MAMBO, and in the future with the space observatories SIRTF (to 160$\mu$m) and FIRST.

A most puzzling discoveries in high-redshift astronomy was the recent identification of compact (sub)mm background sources, objects that are estimated to be at redshifts 1 to $> 5$. The bolometric luminosities of these sources are similar to those of quasars, but the ratio of (sub)mm to optica/IR flux shows that at least 99% of the emission is coming from dust. The relation between metal production and background radiation (Eales et al. 1999) then implies that roughly 25% of all the stars ever formed have formed in extreme objects like this. Apparently high obscuration makes these sources inconspicious at optical and near-IR wavelengths, although many of them can be detected in deep VLA radio images (Barger et al. 1999; Carilli et al. 2000). The lack of clear optical identifications leaves unclear to what class of objects these sources belong. It is not yet clear whether they represent the bright end of star-bursting Lyman break galaxies (Chapman et al. 1999; Adelberger & Steidel 2000), or whether they correspond to dust-obscured quasars (Guilloteau et al. 1999; Carilli et al. 2000), to spirals or ellipticals in their formation phase, to lensed galaxies, or a composite of the above. The small number of current identifications does not yet permit firm conclusions about their nature.

The high luminosities and star formation suggest that these objects might be ellipticals seen during their formation phase, in which a significant fraction of their stars are forming (Smail et al. 2000; Tan et al. 1999; Blain et al. 1999). If so, then (sub)mm surveys would have found a population which has been looked for in vain at optical wavelengths for several decades. If the (sub)mm sources are "proto-ellipticals", then the basic question one would like to answer is whether ellipticals form at very high redshift by the collapse of individual primordial clouds, as the ages of stellar populations in low-redshift ellipticals suggest (Bower et al. 1992), or whether they form over a range of redshift by the gradual hierarchical merging of smaller systems (Baugh et al. 1998).

To address this question, (sub)mm observations have proven to be powerful probes of early galaxy formation because the dramatic "negative K-correction" enables very deep and essentially distance-independent surveys of thermal sources. Because the rest frame SED peaks at 60-100 $\mu$m, the colors derived from (sub)mm measurements also provide a rough redshift discrimination, which is important since for nearly all the (sub)mm sources found so far, a spectroscopic redshift cannot be determined because of their optical/near-IR faintness.

A new generation of bolometer arrays now build at the MPIfR for the IRAM 30 m telescope and for the upcoming MPIfR/ESO *Atacama Submillimeter Telescope* (AST) will vastly improve the sensitivity of deep and wide field mapping surveys to detect galaxies and quasars at the earliest epochs of galaxy formation. One major goal of deep, large-area (sub)mm surveys is the determination of extragalactic source counts as a function of flux density. These measurements can be compared with theoretical model predictions. Depending on the evolutionary model used (e.g., monolithic collapse vs. hierarchical merging), the number counts can be quite different. SCUBA and MAMBO surveys have take the first steps in establishing statistics on the (sub)mm background sources. Detailed comparisons with model predictions are however limited by the small number of sources detected, by the small areas surveyed (typically 4 arcmin$^2$ for SCUBA and 100 arcmin$^2$ for MAMBO maps), and by the lack of accurate redshifts.

One important result from the SCUBA and MAMBO surveys was the appearance of a turnover in the (sub)mm background source number counts above $\sim$ 5 mJy at 850 $\mu$m. The cause of this turnover is unclear, but one could envision several interesting possibilities. The prodigious star formation rates implied by the luminosities of the brightest background sources suggest correspondingly large gas supplies, and a limit to the star formation rate could be due to the limited gas supply within the galaxy. A turnover in the luminosity function of these galaxies might then trace the spectrum of density fluctuations in the early Universe. Alternatively, a limit to the starburst luminosity may be due to an internal feedback mechanism that inhibits stronger starbursts.

SCUBA and MAMBO can only map a limited area to adequate depth; the statistical significance of the apparent turnover in the luminosity function therefore remains marginal. In the near future, wider field surveys –initially with the 117-element MAMBO at the IRAM 30 m telescope, and in two years with a large 850$\mu$m bolometer array on the AST (and at shorter wavelengths with SIRTF)– will vastly improve the significance of the source brightness distribution. Detailed follow-up radio and optical/near-IR studies of the luminous (sub)mm background sources will also clarify the effect of lensing on the count statistic.

Wide field imaging will also reveal source clustering. If the (sub)mm background sources are indeed the precursors of present day elliptical galaxies, then they should cluster on typically 10 arcminute scales, which would be detectable with future mapping capabilities. Large-scale mapping surveys have already shown hints of variations in the source brightness distribution from field to field. However, considering the still large systematic uncertainties, this evidence remains marginal, but does point at noticable large-scale structure due to "cosmic variance."

At present an interesting puzzle is the connection between high-redshift AGN and the thermal (sub)mm sources, which are thought to be powered by starbursts. It was noticed in nearby galaxies that the mass of galactic bulges correlates well with the mass of supermassive black holes (Magorrian et al. 1998). This indicates that the growth of black holes and the formation of the first stellar populations are closely linked. The discovery of strong thermal dust emission in high-redshift quasars (McMahon et al. 1994; Omont et al. 1996, 2000; Carilli et al. 2000), and the recent observation that a large fraction of the X-ray background sources are obscured by high columns of dust and gas, indicate that galaxies with active nuclei could contribute noticably to the FIR to mm background. In fact, two of the three SCUBA submm sources for which optical emission lines were detected show signs of an active nucleus, and the two brightest sources in recent blank field surveys with MAMBO (Bertoldi et al. 2001) and SCUBA (Knudsen et al. 2000) are intermediate-redshift quasars. On the other hand, recent Chandra observations failed to detect most of the targeted SCUBA sources (Bautz et al. 2000; Fabian et al. 2000; Hornschemeier et al. 2000). Right now, a connection between starbursts and AGN is evident but unclear.

**Own experience**

During the past three years, Dr. Bertoldi has coordinated the bolometer scientific programs, observing campagnes, and the bolometer data processing development at the MPIfR. Before joining the MPIfR, he has worked on the theory and observations regarding the physics and chemistry of the interstellar medium in star forming regions. Recently, he has coordinated numerous international collaborative efforts for observations of star forming galaxies and of AGN using MAMBO at the IRAM 30 m telescope, the VLA, and SCUBA. This includes deep blank field surveys to resolve the millimeter background, high-redshift quasar surveys, the study of radio galaxies and gamma-ray bursts, and also of comets and asteroids.

### Goals of the project

To further our understanding of dust-obscured high-redshift starburst galaxies and AGN seen at mm and submm wavelengths, to establish how they fit into the broader picture of galaxy evolution, we propose the following strategy.

- Using the new MAMBO 117-element array at the IRAM 30 m, conduct square degree blank field 1.2 mm surveys to obtain statistically significant source counts of the rare, bright ($> 5mJy$) population, to study their nature, redshifts, and clustering in contiguous fields.

- With the new generation bolometers at the AST extend wide field surveys to 870 $\mu$m and 350 $\mu$m, thereby optimizing the survey sensitivity for high-redshift thermal sources, and determine the source spectral energy distributions and photometric redshifts.

- Target specific samples of objects detected at other wavelengths, such as optically selected high-redshift galaxies and quasars, radio galaxies, X-ray sources, and galaxy clusters. MAMBO is the currently most sensitive ($5\sigma$ detection limit $\approx 1.0$ mJy) instrument for pointed observations of high-redshift thermal sources.

For operation in early 2003 at the AST, a $\approx 1000$-element bolometer array at will be available for the 870 $\mu$m window, and a smaller array for the 350 $\mu$m window. The AST will surpass any other ground-based instrument in its capability to detect thermal emission at high redshift. Operating at the best (readily accessible) terrestrial site for year-round submm astronomy, the AST bolometers may even surpass the mapping capabilities of SIRTF, and in any case, will be the choice instrument for obtaining photometric redshifts of SIRFT-detected sources.

With the data obtained through our observations we will try to constrain structure and galaxy formation models which consistently account for the formation of stars and massive black holes throughout the history of the Universe. Such models are constrained mainly by the AGN and starburst source luminosity functions and redshift distributions, and the spectral energy distribution of the X-ray to radio background, which is now well determined.

### Estimate of resources expected from DFG

Two doctoral students and one postdoc. (???)

### Members of research group relevant for the project

Dr. Frank Bertoldi, Dr. Karl M. Menten, Dr. E. Kreysa

### Connections to other projects of current SFB proposal

This project is closely related to that of E. Kreysa, which proposes the development of bolometer arrays through which much of the research proposed here will be possible. It also relates to the project of P. Schneider, which investigates the large scale matter distribution in the Universe. (MORE?)

### 2.0.2 Evolution of supermassvie black holes and their connection to galaxies and dark matter halos

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**Abstract**

The ubiquitous occurrence of supermassive black holes in galactic nuclei needs to be understood, both in terms of how they grow, but also how they interact with their environment. It seems clear now that the evolution of black holes and of galactic bulges are intimately linked. Since one also supposes a connection between dark matter halos and the formation of galaxies and their bulges the evolution of galaxies seems to start and end in some form of dark mass: dark matter halos on large scales and black holes on small scales. This has also prompted speculations whether black holes could directly accrete from dark matter halos – if dark matter is even weakly dissipative.

Here we propose to study the accretion and growth of black holes in galaxies in their various life phases: during the quiescent evolution of a galaxy, during a merger with another galaxy, during a starburst, and during high accretion events in active galaxies. Necessary for this is an understanding also how black holes accrete (luminous and dark matter) and how they interact with each other, since binary black holes should be common during a certain phase of a merger. In the end we try to develop a coherent picture for black hole evolution, taking into account the constraints we obtain from black holes at various level of activity. This will have an impact not only on the importance and evolution of dark matter halos on black hole formation, but on various other questions such as: galaxy evolution, heating of gas and build-up of magnetic fields in clusters, cosmic filaments and sheets through AGN activity, which in turn can influence cosmic structure formation.

### Current status of research

Black holes are common in all galaxies, that have a bulge, a spheroidal population of stars. HST observations and spectroscopy (Faber et al., Magorrian et al., Kormendy & Richstone 1995, ARA&A 33, 581, Kormendy) have found good evidence for the presence of compact dark masses - presumed to be black holes - in the nuclei of most galaxies. Recently it was shown (Ferrarese & Merrit 2000, ApJ 539, L9; Gebhard et al. 2000, ApJ 539, L13) that there is a close connection between the velocity dispersion of stars in galactic bulges and the mass of black holes in the center. Their mass is limited from above by a ratio of about 1/300 of black hole mass to bulge mass. There are various models to explain this maximum ratio. One idea is that through accretion of gas and dust through the galaxy star formation and strong black hole accretion phases – where a galaxy appears as an active galactic nucleus – occur simultaneously or subsequently. The ratio of stars expelled into the bulge to the mass accreted onto the central black hole then approaches a constant maximum value throughout the lifetime of a galaxy (Wang & Biermann, Rees, Merritt).

Another alternative is that most of the mass accreted onto the black hole throughout a Hubble time is actually due to accretion of dark matter from dark matter halos of the galaxy. For accretion to occur this would require that dark matter is at least weakly dissipative. It can be shown that for certain parameter ranges of dissipative dark matter the bulge-black hole relation can in principle be recovered to an order of magnitude. Turned around it can constrain some of the properties of dark matter (Ostriker 2000, PRL, in press). This is a rather new idea and physics and consequences of such a dark matter accretion have not been investigated in greater detail.

In the standard model activity and evolution of black holes is thought to be via accretion of luminous matter. Over most of their life-times the activity around the central black hole is weak, but usually observable in radio-emission. In fact many of nearby galaxies show such evidence of weak activity due to low-level accretion in their nuclei (Falcke et al. 2000, ApJ, in press). This radio emission can be attributed to weak jets expelled from accretion flows. A problem is that the corresponding thermal emission from this accretion is often absent (Ho 1999, ApJ, 516, 672). Therefore one presumes that accretion of luminous matter proceeds through a rather 'invisible' hot accretion flow (Narayan et al. 1998, 492, 554) the nature of which is under strong scrutiny at present and may lead to a number of interesting elementary particle interactions near the event horizon (Markoff, Falcke, Biermann 2000, A&A) .

A perfect example for this is the central black hole in our Galaxy which provides the best evidence for a black hole and the presence of very low-level accretion. Accretion seems to be at or even below the minimum average level needed to explain the black-hole bulge ratio. The question now is whether this is due to intermittent low-level accretion events in conjunction with inferred star burst epochs, or due to some form of invisible accretion. Therefore the central black hole, Sgr A*, provides a testbed for a minimum level physics for what must happen in much more powerful activity, and is also a baseline to test the possibility of dark matter accretion, that, if the Ostriker picture were correct, should currently be the dominant form of accretion.

**Own experience**

We have studied the growth of black holes in galaxies in several papers (Wang & Biermann 1998, Wang & Biermann 2000, and Wang et al. 2000). We have studied the ejection and distribution of magnetic fields in the cosmos also in several papers (Biermann et al. 1997, Ryu et al. 1998). We have studied the influence of binary black holes on the surrounding stellar population (Zier & Biermann 1999). We have studied in many papers the production of energetic particles in the environment of black holes (Biermann, since 1987 through to today). We have also studied the central black holes and their activity and connection to their environment in many papers (Falcke et al., since 1992). All these lines of research continue actively in collaborations with researchers in Australia, Korea, China, India, Romania, Canada, the USA, and Brasil.

**Goals of the project**

This project is expected to give us a final understanding where black holes come from, how they grow, how they interact with dark matter, and how they interact with the growth of structure in the universe. We try to construct a model for the accretion onto the black hole that consistently explains the bulge-black hole relation and at the same time can be used to explain the visible signatures of accreting black holes. Through this we intend to formulate critical observational tests that constrain the amount and effects of dark matter accretion onto black holes and combines black hole and galaxy evolution.

**Estimate of resources expected from DFG**

- Visiting professor, Prof. Yiping Wang, from China, for one year.
- Later other visiting profs.
- Two PhD students for three years each.

- Support for attending conferences and workshops, especially those organized by the proposers.
- Support for short visits of other students and scientists.
- Support for page charges.

**Members of research group relevant for the project**

- Peter L. Biermann, MPIfR
- Heino Falcke, MPIfR
- Students and guests of PLB

**Connections to other projects of current SFB proposal**

Various projects in this SFB are concerned with investigating the level and nature of dark matter in galaxies and galactic halos, being important for the evolution of galaxies. Here we investigate the smallest scale in a galaxy where dark matter may be important and investigate its possible effects. In addition the energy output from black holes can have significant effects on their environment and is connected to the evolution of galaxies and galactic halos that we need to develop a coherent picture of mass distribution in galaxies and also galaxy clusters. In unpublished simulations (Ryu, Kang, Biermann) we have already been able to show, that structure formation can be influenced at small scales by the activity of galactic nuclei.

**Connection to other current research grants**

We have current programs funded with

- Univ. of Adelaide, Australia (R. Protheroe, Austral. S.E.R.C.)
- Univ. of Daejeon and Pusan, Korea (D. Ryu, H. Kang; KOSEF and DFG)
- Univ. of Bukarest, Romania (Erasmus-program, EU)
- Univ. of Cluj-Napoca, Romania (Erasmus-program, EU, application)
- Ukraina, Bjelorussia, Russia (INTAS-program, EU; in Western Europe Sweden, Germany, and Italy; PLB represents the German part here)

- Russia (INTAS-Program; in Western Europe the UK, France, and Germany; PLB represents here the German part also; application)
- Bartol Research Institute, USA (T. Stanev; NATO-grant)
- Sao Paolo, Brasil (G. Medina-Tanco; application)
- Astroparticle Physics (BMBF; application; in conjunction with many groups in Germany)

All these programs connect to this research project through the topics of Cosmic Particle Physics and Cosmic Magnetic Fields. The emphasis in these projects is usually on high energy cosmic rays and their interaction with their environment.

**Background of the proposers**

The research of the proposers can be found on their web-pages under www.mpifr-bonn.mpg.de/div/theory, which then also refers to the individual members of the group.

### 2.0.3 Dark Matter in our Galaxy and in the Local Group

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**Motivation: The nature of the problem and new possibilities**

The mass of galaxies can be determined by counting the objects of known mass or by searching for tracers of the overall gravitational field. When dealing with the Milky Way, we know the nature of the objects present, but we cannot detect them all and thus cannot 'count' them, or we look for the signature of the overall gravitational field, which is difficult since we live *within* the Milky Way. Astronomy has over time developed ingeneous ways to determine the overall mass of the Milky Way.

Counting stars, deriving the spatial distribution from those counts, and then the vertical force $K_z$ required to keep it all together, led already Oort (1932) to suspect that there is more mass in the Milky Way disk than accounted for by stars. This additional material was called **dark matter**. The detection of the interstellar material and the measurements of the HI 21-cm emission of the most abundant atom in the Universe by radioastronomers since 1953 showed, however, that the gas fraction in the Milky Way disk is about 3% only, and the mass problem remained.

Surprisingly, radioastronomical work indicated that the problem is worse still. Studying the rotation behaviour of other galaxies, Bosma (1981) showed that rotation curves are flat, do not show the expected Keplerian radial decline, and thus indicate the presence of much more directly un-detectable mass than known. What this mass is and where it might be located is entirely unclear. The material might even be present in the Milky Way halo.

New detection techniques (satellites, telescopes, detectors) now allow to collect much better data to better trace the presence of this additional "invisible" matter. Our research aims in three directions. These are:

**a) Stellar dynamics in the local part of the Milky Way**

**b) High–velocity clouds: dark dwarfs?**

### c) Micro-lensing of xxx stars to search for 'missing mass'

### a) Stellar dynamics in the local part of the Milky Way

#### Current status of research

Star counts performed by Bahcall & Soneira (1980) were, as all previous studies, based on photographic plates. These studies were very thorough, but lack the star classification precission needed to really find the spatial distribution of stars perpendicular to the Milky Way disk. ¿¿From that data is was not possible to really quantify the gravitational field and thus demonstrate the presence of dark matter.

With the HIPPARCOS satellite, very precise distances and proper motions for stars in the solar neighbourhoud could be determined. The spatial distribution of A stars appears to indicate that there is no need for dark matter in the local galactic disk (Crézé et al., 1998, Holmberg & Flynn 2000). On the other hand, an analysis of the velocity field by Bienaymé (1999) showed that the galactic potential is not extremely flat and that a dark matter component would not confined to the galactic plane. However, the stars used are nearby and their number is limited, leaving doubt about the overall validity of the results of the HIPPARCOS studies.

With the **Double Interferometer for Visual Astrometry** (DIVA) Satellite (Röser et al., 1998), which was recently approved by the DLR as the next German space project, a very homogeneous distance and spectroscopic survey will be made of the local Universe. It is expected to measure a total of 35 million stars, 350 times the number HIPPARCOS could measure. For stars out to well over a kpc precise *distances* can be determined with DIVA while for stars out to 10 kpc *proper motions* can be found. These together will be used to construct a kinematical model for the local part of the Milky Way. Using the *spectrophotometry* obtained with DIVA, precise stellar parameters can be obtained allowing the determination of distances to stars much farther out than the 'parallax' stars. In particular that data can be used to derive the true spatial distribution of stars and thus the distribution of mass well into the Milky Way halo.

#### Own experience

The Sternwarte has a long tradition in astrometry and was involved in the HIPPARCOS satellite astrometric mission (see e.g. Geffert et al., 1997). Also modern ground based measurements are carried out (Geffert & Maintz 2000).

Our studies of blue horizontal-branch (HB) stars (Moehler, Heber & de Boer 1990, ...., de Boer et al., 1997) showed kinematical peculiarities. Although the HB stars are believed to be formed from the same older parent generation of stars, very blue HB stars do not seem to exist in the Milky Way halo, whereas redder HB stars do (Altmann & de Boer 2000), while both blue and red HB stars exist in the Milky Way disk. The evolution of and dynamics in the Milky Way are not yet understood!

### Goals of the project

Using DIVA data, the spatial distribution of the stars will be determined. The spatial distribution itself must obey the gravitational pull of the disk and allows to determine the actual vertical force $K_z$ in the Milky Way, whose strength is based on the total mass available locally and elsewhere in the Milky Way. With the known properties of these very stars, however, their total mass can be calculated. This mass then will be compared with the mass as derived from $K_z$. The discrepancy between the two determinations will show us the amount of dark matter present in the Milky Way disk.

Preparatory studies will have to be performed in the phase before the launch of DIVA, foreseen for 2004, to explore the best methods of finding the luminosities of the rather numerous red stars expected to be found in large numbers in the DIVA survey. It will ultimately be the luminous red giants stars, visible over large distances, which will best trace the spatial distribution of the stars in the halo.

### Estimate of resources expected from DFG

1 postdoctoral fellow and 2 doctoral students with experience in research of galactic structure

### Members of research group relevant for the project

Bereich a):
Prof. K.S. de Boer, Prof. N.N., AOR Dr. M. Geffert, Dr. K. Reif

### Connections to other projects of current SFB proposal

### b) High-Velocity Clouds: Dark Dwarfs?

#### Current status of research

The structure of galaxies and clusters of galaxies as individuals is well known and adequate models are available. This is in marked contrast to our knowledge on groups of galaxies. Groups of galaxies are agglomerations of a few member galaxies with an un-sharp transition zone towards the high mass end, the clusters of galaxies. An important step in the understanding of cluster of galaxies was that the dominant fraction of baryonic matter is in form of X-ray emitting gas (Böhringer et al. 1999). The total mass of a cluster of galaxies is subdivided in 85% dark matter (DM), 10% gas and 5% in stars. Until the recognition of this remarkable composition, the scientific attraction of clusters of galaxies as well as on groups of galaxies of grows constantly. Of particular interest are the physical conditions of the gas, the total mass, the shape of the gravitational potential and the relative fraction of the three constituents DM, gas and stars on the total mass.

In the local group of galaxies the existence of intergalactic gas could not be established. A simple evaluation of the mass of the local group of galaxies assumes a average volume density of $n \sim 1 \cdot 10^{-4}$ cm$^{-3}$, which gives a total mass estimate of $M(gas) = 1 \cdot 10^{12}$ M$_\odot$. This mass is in the order of the total mass of the individual galaxies known to be localized within the local group. The largest uncertainty in this estimate is the average volume density. This average volume density can be derived from interaction processes between members of the local and neighbouring galaxy groups. Despite all these uncertainties, this rough estimate of the total gas mass indicates that this mass has to be considered for the understanding of the dynamics of the local group as whole. With respect to the cosmological aspects of the local group research one has to compare quantitatively the composition of total local group mass (baryonic to dark matter ratio) with that of clusters of galaxies. Information on the intergalactic gas within the local group can be derived in principle from absorption line studies against distant objects and by the analysis of broad band spectroscopy of emission lines of individual members of the local group. Observations of absorption lines in H$\alpha$, NaID and Ca against sources in M31, M81 or extragalactic sources do not indicate the existence of gas within the local group. The reason for this non-detection may be severe difficulties to separate emission and absorption lines, originating within the Milky Way and/or its halo. The radial velocities of gas clouds within the Milky Way halo and of the local group are comparable. Methods to determine the distance of local group gas clouds independently from the radial velocity are affected by systematic effects, which lead to high intrinsic uncertainties. Observations of the emission lines of local group gas clouds are faced with the same kind of problem. The recent scientific discussion focus today on the so-called high-velocity clouds (HVCs). HVCs are partly localized within the local group of galaxies (Blitz et al. 1999). The main argument for their localization within the local group of galaxies is based on mass estimates, which are quite uncertain. But assuming this working hypothesis, their masses have to be scaled to the square of the ratio between the old (Milky Way halo distance) and their new (within the local group, Mpc distance). This gives mass conversion factors of 100 to 1000, quite comparable to the mass of small dwarf galaxies.

### Own experience

Our working group at the Radioastronomisches Institut is international identified as one of the leading groups in HI observations of HVC. The discovery of head-tail structures in the position-velocity frame by our group open the opportunity to study the interaction of HVCs with their ambient medium.

### Goals of the project

Our working group at the Radioastronomisches Institut will improve the detailed knowledge on groups of galaxies by studying of their gas content. Assuming a specific interaction mechanism, these head-tail structures allow to evaluate physical parameters of the interacting gas clouds, in particular their volume densities. In addition, we anticipate to derive a rigid distance estimate for the HVCs based on these physical parameters. This will allow to identify the origin of HVCs as objects of the Milky Way halo or as objects of the local group of galaxies.

### Estimate of resources expected from DFG

Project a)
1 postdoctoral fellow and 2 doctoral students with experience in research of galactic structure
Project b)
Project c)

### Members of research group relevant for the project

Project a)
Prof. K.S. de Boer, Prof. N.N., AOR Dr. M. Geffert, Dr. K. Reif

Project b)
Prof. U. Mebold
Project b)
Prof. P. Schneider

**Connections to other projects of current SFB proposal**

## Experimental Particle Physics at High Energies

Professors Brock, Hilger, Kobel, Wermes.

**Contents**

- Experimental Particle Physics at highest energies
  - Electron-Proton Collisions at HERA
  - Electron-Positron Collisions at 200 GeV
  - Proton-Proton Collisions at 14 TeV
  - Studies for Electron-Positron at a 500 GeV Linear Collider
- Development of low noise active pixel detectors for Xray-Astronomy

**Abstract**

Particle physics experiments at high energy accelerators with centre-of-mass energies above 100 GeV and up to 14 TeV study processes which were relevant in the early universe at time scales of $10^{-12}$s to $10^{-14}$s after the Big Bang. Questions governing the development of the universe between the Grand Unified Theories (GUT) epoch and the electroweak phase transition are addressed, such as fundamental symmetries and symmetry breaking mechanisms, the concept of the Higgs-Mechanism, and low energy phenomena related to new concepts in superstring related theories with extra dimensions. The experimental programme in this field in Bonn receives funding from the BMBF. Within the context of this SFB it is planned to additionally address topics specifically related to "Particles in an Evolving Universe".

### 2.0.4 Electron-Proton Collisions at HERA

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### Abstract

Electron/positron-proton collisions at energies hitherto unavailable will be investigated using data to be collected with the ZEUS detector at the HERA collider at DESY, Hamburg. The high centre-of-mass energy allows research to be carried out at and beyond the electroweak symmetry breaking scale, as well as the investigation of the colour gauge interactions in unexplored kinematic regimes. Sensitive searches for new phenomena, new particles and interactions beyond the standard model of particle physics are possible, in particular the search for new symmetries that prevailed in the early universe.

The group has been a member of the ZEUS collaboration since its inception in 1984. It has participated in the building and running of the detector, which has been operated at HERA since 1992. The group is presently involved in major upgrade work on the detector and the software in preparation for the second phase of HERA operation called HERA2000. This phase will start in mid. 2001 and will contain new features of the HERA collider that will dramatically enhance the physics potential of the programme:

- a five-fold increase in the luminosity and
- longitudinally polarised lepton beams.

### Current status of research

Lepton-proton scattering has been a prime source of our present notion of particle physics. The existence of coloured quarks as the building blocks of hadrons, as well as the dynamical role of the gluons was first observed in electron-proton scattering in the early seventies. The HERA experiments, in particular ZEUS, have made significant contributions to the understanding of the internal dynamical structure of the proton. The most important findings so far are the increasing density of gluons as their momentum fraction in the proton decreases and the rather large fraction, about 10%, of deep inelastic scattering events that contain a rapidity gap, characteristic of a diffractive process. The unification of the electromagnetic and the weak interactions is manifestly seen in the space-like exchange process, by comparing the cross-sections at 4-momentum transfers $Q^2 \approx M_Z^2$, for neutral exchanges mediated by the photon and the $Z$ boson, with those for charged exchanges, mediated by the W bosons.

HERA is unique for studying hadronic cross-sections of multi-TeV leptons and photons (in the lab. frame) and for collecting detailed information on the hadronic final state of such reactions.

### Own experience

The group has made strong contributions to the physics analyses of the ZEUS data taken so far. More than 20 of the 80 ZEUS physics papers published in refereed journals originated from this group or contain decisive contributions from its members.

The results already obtained by ZEUS at HERA are relevant for a number of current issues of astroparticle physics. Examples are the seraches for leptoquakrs, lepton flavour violation and excited fermions.

### Goals of the project

The new phase of HERA and ZEUS will require the development of a new medium-term strategy, in order to exploit the full potential of high $Q^2$ physics. One needs data taken with both electrons and positrons, polarised and unpolarised, and, ideally, with both protons and deuterons. The physics programme will complement the programme of quantum chromodynamics (QCD) physics already underway with phase I HERA data. Electroweak physics will basically start with the new HERA2000 stage, and will complement the precision measurements already made in $e^+e^-$ studies in the time-like domain at LEP. Both lines of investigation are not only interesting in their own right, but are essential if signatures for physics beyond the standard model are to be convincingly established.

In more detail the additional topics that we will address in this project are:

- search for supersymmetric particle signatures,
- search for new interactions at a very high energy scale, which then manifest themselves as effective contact interactions,

- search for substructure of leptons and quarks by searching for their excited partners,
- search for signs of large extra space-lime dimensions,
- developments to measure cosmic ray showers and interactions with the ZEUS detector and and other HERA detectors (CosmoHERA project).

**Estimate of resources expected from DFG**

Funding of the detector equipment and operation has been granted by the BMBF (Verbundforschung Hochenergiephysik) until 2003 and can be reasonably expected for some years beyond. The BMBF grant includes some funding for manpower and travel, so that the core programme of particle physics is expected to be covered by this and the university/state infrastructure and personnel. While the Bonn ZEUS group has heavy commmitments to new detector components and the HERA2000 phase, the interest in analyses relevant for the physics issues in this proposal is strong.

For the additional physics topics that will be investigated in this programme we request:

- Manpower: 1 post-doc position,
- Travel: some - mostly to SFB meetings.

**Members of research group relevant for the project**

1. Ian C. Brock (Professor C3),
2. Erwin Hilger (Professor C4),
3. James A. Crittenden (Oberassistent C2),
4. Ulrich F. Katz (Oberassistent C2).

**Connections to other projects of current SFB proposal**

1. Electron-positron collisions at 200 GeV,
2. Proton-proton collisions at 14 TeV,
3. Theory projects "Beyond the Standard Model",
4. Cosmology and High Energy Particle-Astrophysics.

### 2.0.5 Electron-Positron Collisions at 200 GeV

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**Abstract**

Electron-positron collisions are studied using data collected with the OPAL detector at the Large Electron Positron Collider LEP at CERN (Geneva). The data allow research to be carried out at the scale of electroweak symmetry breaking and questions related to the Higgs-mechanism, gauge interactions and supersymmetry to be studied. The group has participated in setting up and running the OPAL detector which has been operated at LEP from 1989 to 2000. Since 1996 data at the highest available energies (200 GeV) have been taken. In the context of the proposed SFB the group will analyse these data with a special emphasis on the above mentioned topics related to questions of "Particles in an Evolving Universe".

**Current status of research**

Electron-Positron Collisions have been prominent at the forefront of particle physics since 1974. LEP has been the largest collider of this type to date. (More text if needed).

**Own experience**

Since 1989 the OPAL detector at LEP has taken data first at c.m. energies around the mass of the $Z^0$ boson (91 GeV) until 1995 and since 1996 at the highest available energies of the LEP collider up to 208 GeV.

At 91 GeV studies on the following topics were carried out in Bonn.

- physics and properties of the tau lepton
- studies on CP violation in 2-fermion final states
- determination of the strong coupling constant and parameters of non-perturbative QCD
- production of $\Lambda$ Baryons and spin correlatons
- studies on the differences between quarks and gluon jets
- studies of Bose-Einstein Correlations

At the highest accessible energies of LEP (LEP2) the following research topics were carried out

- pair production of W and Z bosons, study of masses (W), cross sections and couplings
- search for the Higgs boson (standard model and MSSM)
- searches for beyond standard model couplings and physics
- QED precision measurements

**Goals of the project**

Within this SFB we plan to continue to study data taken with the OPAL detector until about 2004 in the following research areas

- search for the Higgs boson (until mid 2002)
- new physics from gauge couplings
- Search for low energy phenomena extending to superstring inspired models (extra dimensions, etc.)

**Estimate of resources expected from DFG**

Manpower: 1 PhD position

Travel: zero or a little bit, mainly to travel to SFB meetings

**Members of research group relevant for the project**

1. M. Kobel (Professor, C3)
2. N. Wermes (Professor, C4)
3. A. Quadt (Hochschulassistent, C1)
4. G. Martinez (Postdoc, 3.2001)

**Connections to other projects of current SFB proposal**

1. Electron-Proton collisions at HERA,
2. Proton-proton collisions at 14 TeV,
3. Theory projects "Beyond the Standard Model",
4. Cosmology and High Energy Particle-Astrophysics.

### 2.0.6 Proton-Proton Collisions at 14 TeV

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**Abstract**

With the construction of the Large-Hadron-Collider LHC at CERN, in Geneva which reaches a centre-of-mass energy of 14 TeV, the most powerful accelerator to probe the physics at time scales of $10^{-14}$s after the big bang is being built. ATLAS is one of two big all-purpose detectors to be installed in LHC in 2004. The group is involved in developing and building a 2m$^2$ pixel detector as the innermost tracking device for ATLAS located as close as possible to the interaction point. The pixel detector is vital for the detection and tagging of b-hadrons and for precision tracking close to the interaction point. With ATLAS it will be possible to study reactions related to symmetry breaking (Higgs Mechanism), supersymmetry, superstring inspired theories and other phenomena at energies well above the TeV range. The group plans to join a running experiment (D0) at the TEVATRON collider (Fermilab, Chicago) to gain experience in the physics at proton-proton colliders before the LHC turn-on.

**Current status of research**

Proton-Proton Collisions have been prominent in attaining highest collision energies at the price of a less clean evironment when compared for instance to electron-positron colliders. The LHC is as such in line with previous machines as the ISR (CERN), the SppS (CERN) and the Tevatron (Fermilab). Prominent research results at these machines are the discovery of the weak heavy vector bosons $W^{\pm}$ and $Z^0$ and the discovery of the top quark in 1995. After the successes of the LEP and SLC $e^+e^-$ colliders in precision testing the standard model of electroweak interactions, the next step probing the physics beyond the the standard model is due at the proton-proton colliders Tevatron (2 TeV) and LHC (14 TeV). Prominent examples of reasearch fields are: research of the Higgs sector, search for phenomena related to supersysmmetry and other phenomena beyond the standard model such as leptoquarks or additional vector bosons as well as tests of superstring inspired models. Detector techniques at the very forefront of current detector R&D find their realisation in ATLAS. A particular example is the ATLAS pixel detector, a high resolution tracking device consisting of about $10^8$ pixels with individual amplification electronics covering an area of 2.1 m$^2$. This detector is built in the so-called hybrid pixel technique, in which an active sensor and amplifying VLSI electronics are joined using the bump and flip-chip technique.

### Own experience

The group of Proffs. Wermes and Kobel have experience in detector building and data analysis at electron-positron colliders since 1992. Special expertise has been developed in the area of semiconductor detectors and VLSI chip electronics since 1994. The group plays a major role in the development of the ATLAS pixel detector. For this a large (250 $m^2$) silicon lab has been set up with clean room and precision measurement equipment. There is no first hand expertise in the analysis of proton-proton collisions. It is planned to join the D0 collaboration at Fermilab with a small portion of the group to obtain experience in this field before the startup of the LHC.

### Goals of the project

In the context of this SFB we plan to build the pixel detector (largely funded by BMBF) and to focus on the studies of questions related to the physics beyond the standard model and to questions related to cosmology in the one TeV and more energy range. Particular analyses we intend to look into are

- search for the higgs boson, its properties, and the understanding of the higgs mechanism
- search for supersymmetry
- search for extra dimensions, and low energy superstring phenomena
- study of symmetry breaking and CP - violation
- a precision measurement of the mass of the W-boson ??

### Estimate of resources expected from DFG

Manpower: 1 PostDoc position

Travel: 10 kDM/year

### Members of research group relevant for the project

1. N. Wermes (Professor, C4)
2. M. Kobel (Professor, C3)

3. P. Fischer (Akademischer Rat)
4. A. Quadt (Hochschulassistent, C1)
5. F. Hügging (Postdoc, 1.2001)
6. G. Martinez (Postdoc, 1.2001)
7. N.N. (Hochschulassistent C1, 10.2001)
8. G. Geich-Gimbel (Researcher)
9. T. Kokott (Researcher)

**Connections to other projects of current SFB proposal**

1. Electron-positron collisions at 200 GeV,
2. Electron-proton collisions at HERA,
3. Theory projects "Beyond the Standard Model",
4. Cosmology and High Energy Particle-Astrophysics.

### 2.0.7 Studies for Electron-Positron Collisions at a 500 GeV Linear Collider

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### Abstract

A 500 GeV linear collider is the subject of a number of studies around the world. The physics that can be done at such a machine has been studied in a series of workshops. A technical design report for a superconducting linear collider, TESLA, to be built at DESY, Hamburg is currently in preparation and should be submitted in 2001.

### Current status of research

The current status of resarch in $e^+e^-$ collisions is summarised in the section "Electron-Positron Collisions at 200 GeV". Members are participating in simulations of physics prcoesses

### Own experience

Members have been involved in many previous $e^+e-$ experiments and have a wide experience of the physics potential as well as the detector requirements for such machines.

### Goals of the project

While one can expect the agents for electroweak symmetry breaking will be discovered at the LHC before a linear collider comes into operation, an electron-positron collider can study their properties in unprecedented detail. Cross sections and branching ratios can be mneasured easily and one can use the electron beam polarisation to measure quantum numbers and important mixing angles.

### Estimate of resources expected from DFG

Manpower: 1 PhD

Travel: 10 kDM/year

### Members of research group relevant for the project

1. I. Brock (Professor C3)
2. M. Kobel (Professor C3)
3. E. Hilger (Professor C4)
4. N. Wermes (Professor C4)
5. J. Crittenden (Oberassistent C2)
6. A. Quadt (Hochschulassistent C1)
7. G. Martinez (PostDoc)
8. U. Katz (Oberassistent C2)

### Connections to other projects of current SFB proposal

1. Electron-positron collisions at 200 GeV,
2. Electron-Proton collisions at HERA,

3. Proton-proton collisions at 14 TeV,
4. Theory projects "Beyond the Standard Model",
5. Cosmology and High Energy Particle-Astrophysics.

### 2.0.8 Development of low noise active pixel detectors for Xray-Astronomy

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**Abstract**

DEPFET Pixel detectors which include an amplifying transistor in every pixel cell have been developed and shown to be very interesting as the next generation of xray detectors to be operated on xray satellite missions such as the planned XMM-Newton successor XEUS. The development and eventual imstallation of this detector in a dedicated satellite mission is proposed.

**Current status of research**

The DEPFET pixel concept is unique worldwide. The idea is to implement the first amplifying transistor directly into the silicon pixel cell and to shape the electric fiels in side the substrate material such that incident particles or radiation released charges are directly sensed by the transistor current and thereby amplified. The concept, first proposed in 1987, offers very low noise at room temperature and high sensitivity and spatial resolution for Xray detection. The DEPFET pixel development is carried out in a collaboration between the Max-Plank Institute for Extraterrestrial Physics (MPE), the Werner-Heisenberg-Institute of Physics (MPI-WHI) and Bonn University.

### Own experience

After the successful operation of DEPFET prototype pixel detectors with one pixel cell only in Munich in the early 90s, our group started to carry out dedicated research on DEPFET single pixels and large (64x64 cells) DEPFET matrices by developing dedicated switching an amplifying ASIC chips for operation and readout. In 1999 we succeeded in operating a full DEPFET system for imaging with equivalent noise charges of about 50 electrons. On single pixels we showed that the noise level can be reduced by another factor 10 or more.

### Goals of the project

The collaboration with MPE/MPI towards the development of an xray sensor for satellite missions is in place since July 2000. The goal is the development of a large area DEPFET pixel detector for the detection of distant xray sources in a dedicated satellite mission.

### Estimate of resources expected from DFG

Manpower: 1 PhD

Travel: 10 kDM/year

### Members of research group relevant for the project

1. N. Wermes (Professor, C4)
2. P. Fischer (Akademischer Rat)
3.

### Connections to other projects of current SFB proposal

1. Proton-proton collisions at 14 TeV,

2. Studies for Electron-Positron Collisions at a 500 GeV Linear Collider,
3. Cosmology and High Energy Particle-Astrophysics.
4. Kreysa ... Menten

### 2.0.9 Astrophysics and Extensions of the Standard Model

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**Abstract**

I propose to investigate the effects of extensions of the Standard Model of particle physics on the evolution of the universe. This can lead to new effects in astrophysics or to bounds on the proposed extensions. In particular, we would like to focus on the implications of weak-scale supersymmetry on dark matter, on baryogenesis and supernovae explosions. We shall also consider the implications of axions and possible explanations of the ultra-high energy cosmic rays.

**Motivation**

The Standard Model of Particle Physics (SM) has been spectacularly confirmed by the recently completed experiments at LEP [1]. It describes the physics at energies and temperatures upto $200\,GeV$. Thus in the big bang model the evolution of the universe after the first ... seconds is described by general relativity and the SM. We believe there is physics beyond the SM, which is relevant at energies and temperatures *above* $200\,GeV$. This new physics, if true, describes an even earlier epoch of the universe and which could possibly have profound effects at temperatures below 1 TeV and even observational effects as late as today. It is our purpose to study the implications of extensions of the SM on cosmology and astrophysics and also in reverse the constraints from astrophysics and cosmology on extensions of the SM. We shall focus on the the implications of "low-energy" particle physics models formulated at or below the GUT scale of about $10^{16}\,GeV$.

The SM has 12 fermions, 12 gauge bosons and 1 scalar Higgs boson. After the direct detection of the tau neutrino by the DONUT collaboration [8] only the Higgs boson remains undetected. These fields and their interactions are described by 19 parameters (gauge sector: 3 gauge couplings and one vacuum phase $\theta_{QCD}$ Higgs sector: vacuum expectation value and Higgs mass; fermion sector: 9 masses, 3 mixing angles, 1 CP-violation parameter). Most of these parameters are very well measured, in particular the lepton and heavy quark masses as well as the gauge couplings. The light quark masses are not so well known due to theoretical uncertainties. The mixing angle between the third generation and the first generation (in the PDG basis and parametrization) and the CP violating phase are experimentally poorly determined. These last two measurements will be dramatically improved by the currently running B-factories, leading to a stringent test of the SM. If a disagreement with the SM is found, in particular if the CP-violation is greater than expected then this would have immediate impact on our understanding of baryogenesis, the origin of the matter asymmetry in the universe. The Higgs mass of course remains completely unknown until discovery, hopefully at the Tevatron or otherwise at the LHC. The experimental full determination of the Higgs sector will have a similar profound impact. It is one of the main purposes of this proposal to closely follow these experimental developments and to regularly explore their implications for cosmology and astrophysics.

The SM, as presented, has at least 18 open questions, ie the number of parameters minus one. In particular the spectrum of the fermion masses, though well measured, remains in its origin a complete mystery. The Higgs sector has a severe naturalness problem and the small value of $\theta_{QCD}$ is unexplained in the SM. The proposed extensions of the SM which could explain these problems all lead to significant changes in the “prediction” for the volution of the universe. For example, the strong CP-problem can be solved by introducing an extra $U(1)$ symmetry which when broken is accompanied by an axion. This axion can significantly contribute to the dark matter in the universe and can play a crucial rôle in the explosion of a supernova. It is the purpose of this project to investigate the compatibility of extensions of the SM with the present standard model of cosmology. Here we are mainly interested in (i) supersymmetry at or below the grand unified scale of $10^{16}\,GeV$, which solves the naturalness problem of the Higgs sector, (ii) in the axion, (iii) the electroweak phase transition in extensions of the SM and (iv) in neutrinos.

### Own Experience

I have studied in some detail the effect of sphaleron transitions (at the electroweak phase transition) on GUT-scale baryogenesis in both the SM and the MSSM [4, 5]. In addition, I have worked extensively on the phenomenology of physics beyond the Standard Model, in particular on the phenomenology of supersymmetry [7] and of the search for the Higgs boson [2, 3]. Within supersymmetry, I have mainly focused on supersymmetry with broken R-parity. Combining these interests, I have determined the bounds on R-parity violating interactions from the requirement that GUT scale baryogenesis is not erased before or during the electroweak phase transition.

The SM sphaleron transitions violate baryon- and lepton-number at temperatures close to or above the electroweak phase transition, $T \geq T_{EW}$. The sphaleron transitions conserve the three quantum numbers $\frac{1}{3}\mathcal{B} - \mathcal{L}_i$, $i = 1, 2, 3$, where $\mathcal{B}$ refers to baryon-number and $\mathcal{L}_i$ to the lepton-number of the $i$-th family. If the presently observed matter asymmetry is due to GUT scale matter genesis, one would only expect non-zero contributions in the quantum numbers $\frac{1}{3}\mathcal{B} - \mathcal{L}_i$ to survive for $T < T_{EW}$. Contributions in $\frac{1}{3}\mathcal{B} + \mathcal{L}_i$ should be erased by the sphaleron transitions. In a detailed chemical potential analysis, we showed that the non-zero lepton masses below $T_{EW}$ can regenerate a matter asymmetry even if $\mathcal{B} - \mathcal{L} = 0$ at $T > T_{EW}$. In particular, even $\mathcal{B} - \mathcal{L}$ can be non-zero after the electroweak phase transition. The condition to achieve this surprising result is that at least one $\mathcal{L}_i - \mathcal{L}_j \neq 0$ at $T > T_{EW}$. Below $T_{EW}$ the leptons have mass. The number density depends on the mass. Since the masses are different at $T < T_{EW}$ the cancellation in the number densities no longer holds and non-zero matter asymmetries are generated. Next we extended this analysis to supersymmetry where (with conserved $R_p$) where the effect can be larger due to the larger scalar lepton masses.

In the case of R-parity violation no further fields are added beyond those of the MSSM. However, the superpotential is extended by the interactions

$$W = \lambda_{ijk}\epsilon_{rs}L_i^r L_j^s \overline{E}_k + \lambda'_{ijk}\epsilon_{rs}L_i^r Q_j^s \overline{D}_k + \lambda''_{ijk}\epsilon_{\ell mn}\overline{U}_i^{\ell}\overline{D}_j^m\overline{D}_k^n. \qquad (0.1)$$

Here $L, \overline{E}$ are the lepton doublet and singlet superfields. $Q, \overline{U}, \overline{D}$ are the corresponding quark superfields. $i, j, k$ are generation indices, $r, s$ are $SU(2)$ component indices and $\ell, m, n$ are $SU(3)$ component indices. The first two sets of terms in Eq.(0.1) violate lepton-number, the last set violates baryon-number.

As discussed above, any extension of the SM (or in this case the MSSM) has immediate implications for the evolution of the universe. The MSSM conserves the three quantum numbers $\frac{1}{3}\mathcal{B} - \mathcal{L}_i$ as in the SM. If we add further interactions which violate baryon- or lepton number and these interactions are in thermal equilibrium at temperatures $T \geq T_{EW}$, then possibly no conserved quantum number is left and thus no GUT scale baryogenesis may survive. In our paper we investigaed in detail the conditions under which a GUT scale baryogenesis *does* survive and determined the resulting bounds on the couplings in Eq.(0.1). If the complete set of interactions in Eq.(0.1) is in thermal equilibrium then any pre-exisiting matter asymmetry is erased at $T_{EW}$. However, if the couplings in Eq.(0.1) exhibit a similar hierarchy to the Yukawa couplings in the SM we might expect only a subset to reach thermal equilibrium. In that case the cosmological bounds on such a subset can completely vanish and low-energy phenomenology with broken R-parity is viable. The detailed flavour conditions are determined in [4, 5].

### Current status of research

In 1995 the Karmen experiment reported an anomaly in their data, which was inconsistent with the decay chain $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\nu_\mu\bar{\nu}_\mu$ as described by the SM [9]. This was at first confirmed by the improved experiment Karmen II [10]. In a recent paper [6], we investigated a potential supersymmetric solution of this anomaly: a very light neutralino ($M_{\chi_1^0} = 33.9\,MeV$) decaying via R-parity violation. Such a neutralino with this specific mass is consistent with all experiments provided the supersymmetric grand unified assumption relating the gaugino masses $M_1$ and $M_2$ is dropped.[1] As discussed above, when trying to extend the SM to explain anomalous experimental results one must always take into consideration the possible astrophysical implications. In this case, the neutralino is unstable with a cosmologically very short lifetime. It is thus irrelevant for dark matter studies. However, the neutralino mass is of the same order as the supernova core temperature and could thus possibly lead to a too rapid cooling of the core. A rough estimate [6] based on previous general studies [12] was inconclusive. A further study with a flat (and too high) core temperature distribution [11] was negative.

With the data through July 2000 included, Karmen II no longer confirms the time anomaly. Together with Peter Richardson, I am now studying the collider experimental constraints on any neutralino with mass below a few $GeV$. We will then extend this work to also study the constraints from supernovae explosions. For this we will include the proper temperature distribution in the core. This can then be used to determine the lower mass bound on a light quasi stable neutralino from supernovae.

### Goals of the project

### Estimate of resources expected from DFG

### Members of research group relevant for the project

1. Dr. Athansios Dedes (postdoc)
2. Dimitru Ghilencea (postdoc)

[1] The lower bound on the lightest neutralino from LEP $M_{\tilde{\chi}_1^0} \gtrsim 35\,GeV$ is obtained indirectly via the experimental search for charginos and the SUSY-GUT gaugino mass relation.

### Connections to other projects of current SFB proposal

can also compute relic density for very light neutralino with non-universal gaugino masses.

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### 2.0.10 Constraining the luminous and dark mass in the Local Group through high-precision proper-motion measurements of nearby galaxies with VLBI.

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**Abstract**

A key and still largely missing parameter for measuring the mass content and distribution of the Local Group is the proper motion vectors of its member galaxies. So far only the radial component of these vectors are known. Already the inclusion of a few galaxies with the full three-dimensional velocity information would start to break the ambiguity and degeneracy of current mass models for the Local Group and its galaxies. The expected proper motion of galaxies on the sky is typically expected to be between a few milli-arceconds down to some 50 micro-arcseconds per year. Such motions are well measurable by radiointerferometry techniques with very long baselines (VLBI). Ideal radio targets for such a research are stellar masers in star forming regions of galaxies such as the bright masers in M33 and IC10. Multi-epoch observations of these masers can be used to determine a geometric distance to the galaxies and their proper motion out to one Megaparsec. This will provide unique data not available through other means. The proposed project will consist of a) bi-annual monitoring of the masers in M33, IC10 b) of a systematic search for additional masers in other galaxies that can and will be included in the VLBI studies, and c) modelling of the Local Group mass distribution based on the new data. These observations will then seriously constrain dynamical models for the Local Group and the mass and dark matter halo of Andromeda and the Milky Way.

**Current status of research**

An important astrophysical question is the nature and existence of dark matter in the universe, which had been inferred originally from the flat rotation curves of galaxies (e.g. Fich & Tremaine 1991). The closest place to look for dark matter halos is the Milky Way and Andromeda in the Local Group. Various attempts have been made to weigh the galaxies in the Local Group and determine size and mass of the Milky Way and its not very prominent dark matter halo (Kulessa & Lynden Bell 1992; Kochanek 1996). Other attempts use Local Group dynamics in combination with MACHO data to constrain the universal baryonic fraction (Steigman & Tkachev 1999).

The problem when tyring to derive the gravitational potential of the Local Group is that usually only radial velocities are known and hence statistical approaches have to be used. Kulessa & Lynden-Bell (1992) introduced a maximum likelihood method which requires only the line-of-sight velocities (Hartwick & Sargent 1978), but it is also based on some assumptions (excentricities, equipartition).

Clearly, the most reliable way of deriving masses is using orbits, which requires the knowledge of three-dimensional velocity vectors obtained from measurements of proper motions. The usefulness of proper motions was impressively demonstrated for the Galactic Center where the presence of a dark mass concentration has been umambiguously demonstrated by stellar proper motion measurements (Eckart & Genzel 1996).

However, measuring proper motions of members of the Local Group to determine its mass is difficult. For the LMC Jones et al. (1994) claim a proper motion of $1.2 \pm 0.28$ mas/yr obtained from comparing photographic plates over a timespan of 14 years. Schweitzer et al. (1995) claim $0.56 \pm 0.25$ mas/yr for the Sculptor dwarf spheroidal galaxy from plates spanning 50 years in time. Kochanek (1996) shows that inclusion of these marginal proper motions can already significantly improve the estimate for the mass of the Milky Way, since it reduces the strong ambiguity caused by Leo I, which can be treated as either bound or unbound to the Milky Way. The same work also concludes that if the claimed optical proper motions are true, the models also predict a relatively large tangential velocity of the other statellites of the Galaxy.

The dynamics of nearby galaxies are also important to determine the solar motion with respect to the Local Group to help define a standard inertial reference frame (Courteu & van den Berg 1999). And again, as Courteu and van den Berg point out "interpretation errors for the solar motion may linger until we obtain a better understanding of the true orbital motion of Local Group members".

Despite the promising start, the disadvantage of the available optical work is obvious: a further improvement and confirmation of these measurements requires an additional large time span of many decades and will still be limited to only the closest companions of the Milky Way.

**Proper Motions with VLBI** On the other hand, the expected proper motions for galaxies within the Local Group, ranging from 1 mas/yr to 20 $\mu$as/yr, are relatively easy to see with VLBI using the phase-referencing technique. A good reference point is the motion of Sgr A* - the black hole in the Galactic Center - across the sky at a speed of 6 mas/yr reflecting the Sun's rotation around the Galactic Center at a speed of about 220 km/sec. This motion is well detected between epochs separated by only one month with the VLBA (Reid et al. 1999).

**Useful Local Group galaxies** The most suitable candidates for such a VLBI phase-referencing experiment are the strong $H_2O$ masers in IC 10 ($\sim$ 10 Jy peak flux in 0.5 km/sec line, the brightest known extragalactic maser; Becker et al. 1993) and IC 133 in M33 ($\sim$ 2 Jy, the first extragalactic maser discovered). Both masers have been observed successfully with VLBI (e.g. Argon et al. 1994, Greenhill et al. 1993). Additional fainter masers also exist in both galaxies that can be used to determine accurately the galactic rotation. The two galaxies belong to the brightest members of the Local Group and are thought to be associated with M31.

For a simple model of the Local Group with two dominant galaxies and a fixed mass ratio between Milky Way and Andromeda (usually assumed to be 1:1.5) our two proper motion measurements would already significantly constrain any mass model for the Local Group. In a more ellaborate approach, which takes the full data set of radial and proper motions in the Local Group into account (see Kochanek 1996), the constraints would be even stronger leading to significantly improved mass estimates and distances.

Additional information can be gained from the measurements of individual maser components. Since one knows the distance-independent radial velocity dispersion from the radio spectrum and the distance-dependent proper-motion dispersion from the VLBI-monitoring, one can simply determine the distance by matching the two. This has been demonstrated in a preliminary way already by Argon et al. (1998). A similar determination can be made from comparing the velocities of different maser regions that are found in different locations in the galaxy but are at a similar radius (as for example is the case in M33).

Besides those two galaxies there are a number of other galaxies with tentative detections of stellar maser from old surveys (Huchtmeier et al. 1978, 1980, 1988) that have not been revisited with current sensitive receivers, moreover there is no systematic survey of water masers in Local Group galaxies. Especially there are no masers found so far in the Milky Way's sister galaxy M31 - in part because it covers a large area on the sky. The 100m telescope in Effelsberg, now equipped with new sensitive HEMT receivers, is an ideal instrument to undertake a succesful survey of starforming region, e.g. those identified in CO surveys (Neininger et al. 1998), of Local Group galaxies. Masers found in companions of the Milky Way should exhibit very large proper motions of the order milliarseconds per year which could be easily measured within one year at 22 GHz with VLBI.

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## Own experience

This project will be undertaken by a collaboration between the Max-Planck-Institute and the Center for Astrophysics at Harvard, consisting of Heino Falcke (MPIfR), Christian Henkel (MPIfR), and Mark Reid (CfA). Christian Henkel has been involved in the discovery of most extragalactic masers known to date, many of which were found with the 100 m telescope in Effelsberg. Similarly, Mark Reid has been in involved in the development of the VLBI-technique for masers since its beginning and he is an expert in VLBI astrometry. He has lead many VLBI-observing campaigns on the masers in M33 and other masers so far. Heino Falcke is a theorist and an observer who has been involved in maser search and VLBI observations for the last 4 years. As a lecturer at the university of Bonn he is currently supervising a PhD project (Andreas Brunthaler) with the topic of this project.

So far observing proposals for the VLBA and the 100 m telescope in Effelsberg have been submitted that received an excellent ranking. First test experiments to find nearby calibrators and test the astromerty have been performed already which demonstrate the feasibility of the technique. Effelsberg surveys of some selected fields in M31, M33, and a few other galaxies are about to commence this winter.

### Goals of the project

The goal of the project will be to a) determine the first convincing proper motions of galaxies like M33 and IC10 with VLBI, b) find new maser sources in Local Group galaxies that can be used to trace their proper motion with VLBI, and c) construct mass models for the Local Group based on these measurements to determine reliably the mass of the Milky Way, Andromeda and the entire Local group. This will provide us with a unique estimate of the dark matter content and istribution in the Local Group.

### Estimate of resources expected from DFG

The Effelsberg surveys and the VLBI observations require one full-time position each because of the large data volume expected: one VLBI-epoch observation of one galaxy will typically have about 10 DAT tapes of data. The surveys are an ideal starting project for one or several PhD theses, while the VLBI-observations require more skills and are suitable for a PostDoc. To get reliable proper motion measurements one has to continue observing over several years - the error will decrease with the length of the project. Similarly, the Effelsberg surveys have to be performed over several years to achieve completeness. Hence, the minimum requirement for the project are one PhD student and one PostDoc over the entire duration of the SFB.

In addition we will need the computing and data storage resources for the data reduction (2 powerful work stations plus periphery and large harddisks of $\sim$ DM 25.000,- each). We also need travel funds mainly for collaboration with Harvard, scientific conferences, and the invitation of external experts of about DM 10.000,- per year.

### Members of research group relevant for the project

Dr. Heino Falcke, MPIfR Bonn (PI)
Dr. Christian Henkel, MPIfR Bonn (Effelsberg)
Prof. Mark Reid, MPIfR Bonn (VLBI)
Dipl. Phys. Andreas Brunthaler (student)

## Connections to other projects of current SFB proposal

This project will determine the presence and amount of dark matter on scales between the Galaxy and large galaxy clusters. Naturally, proper motion studies can only be done for small distances, hence the Local Group is an ideal target. At larger distances such small groups are difficult to treat observationally since techniques like X-ray observations and gravitational lensing only sufficiently work for large clusters of galaxies. On the other hand conventional stellar astrometry with optical interferometers will only works on scales of our Galaxy. Hence, in order to obtain information on the dark matter content on all scales, VLBI is the most promising technique to probe the Local Group scale.

### 2.0.11 Understanding Black Holes - Emission from Near the Event Horizon

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**Abstract**

Black holes are important as most likely candidates for the dark mass concentration at the centers of galaxies. They are intimately linked to the evolution of galaxies and their energy output can contribute a significant fraction of the energy budget of hot plasma in the universe and galaxy clusters. In addition the plasma in jets and accretion flows from black holes gives rise to a multitude of particle physics processes, high energy emission, and cosmic ray production. Emission from black holes is no longer found only in powerful quasars and radio galaxies but also in a large fraction of more or less normal galaxies, like our own Milky Way. We will further develop already successful emission models for black holes, which combine the major important concepts, like accretion disks, advection dominated accretion flows, jets, radiation processes and particle interactions. Parallel we will undertake surveys and multi-wavelength studies of black holes in the Milky Way and other galaxies. By combining theory and observations we will constrain the demographics and basic parameters of black holes, such as accretion rates and power output, and investigate the relevant physical processes near the event horizon.

**Current status of research**

Supermassive black holes mark the central region of galaxies and dominate the gravitational potential of galaxies on the smallest scales. Dynamical evidence for black holes has been found in many galaxies and most recent observations indicate that their masses scale with that of the galaxy bulges and halos, thus suggesting a common evolution (Ferrarese & Merrit 2000, ApJ 539, L9; Gebhard et al. 2000, ApJ 539, L13).

Fortunately, black holes are not really black. In contrast to dark matter distributed in halos and galaxy clusters, black holes are often associated with luminous thermal and non-thermal emission. Radio jets in particular have become the "smoking guns" of black holes and active galactic nuclei (AGN). Their energy output can in principle substantially contribute to the heating of gas in the universe (e.g., Enßlin et al. 1998, A&A 333, L 47) and thus be important for properly calculating the hydrostatics of hot X-ray gas in clusters.

AGN jets are also the site of many high-energy processes because particles are accelerated to ultra-relativistic energies, leading to radio through X-ray and $\gamma$-ray emission. Today we know that radio jets are relativistic, magnetized plasma flows ejected at velocities close to the speed of light, likely from the immediate vicinity of black holes (e.g. Zensus 1997, ARA&A 35). On the smallest scales, the radio emission from these jets appears as a very compact radio core with a flat and variable radio spectrum. With Very Long Baseline Interferometry (VLBI) this emission can often be resolved into a core-jet structure sometimes showing apparent superluminal motion caused by the relativistic ejection velocity. Currently, with two major X-ray satellites in orbit, hard X-ray point sources found in the nuclei of galaxies are an equally powerful tool for identifying active black holes (e.g., Mushotzky et al. 2000, HEAD 32.2101).

Compact radio cores have also been found in several other sources, including the center of the Milky Way (Sgr A*; Melia & Falcke 2001, ARA&A 39, in press), X-ray binaries (stellar mass black holes and neutron stars; Mirabel & Rodrigues 1999, ARA&A 37, 409), and many nearby galaxies (e.g. Nagar et al., ApJ 542, 186). Despite being interesting in their own right, none of these sources can compare in violence and power output with the ultra-luminous quasar class of AGN. On the other hand it is thought that the same engine – black holes – are involved in these sources, though perhaps accreting at a lower level than quasars.

Nevertheless, because of their proximity and large number, even the faint non-thermal emission in low-luminosity AGN can be of great interest. In the Galactic Center, for example, the radio and X-ray emission most likely comes from the direct vicinity of the central supermassive black hole's event horizon. General relativistic ray-tracing calculations have shown that a factor of two to three improvement in the resolution of the VLBI-technique will make it feasible to actually image the event horizon in the next few years (Falcke et al. 2000, ApJ 528, L13). Current observations already greatly constrain possible models for the emission processes on the most compact scales: a combination of synchrotron radiation, inverse Compton radiation, and perhaps also inelastic proton-proton collisions seem to be required.

Current models for active black holes – across the astrophysical spectrum – are based on combinations of standard $\alpha$-disks, where most energy liberated during the infall into the potential well is radiated, advection dominated accretion flows (ADAFs), where energy is stored and advected into the event horizon, and jet models, where a significant fraction of the energy escapes in a relativistic outflow. With the amount of new observational data pouring in, especially in the radio and X-ray regime, a major goal of research will be to understand the physical mechanisms governing the very vicinity of black holes and the associated energetic phenomena. This requires developing and improving emission models that help to constrain fundamental parameters for accretion, mass ejection and particle acceleration and identify underlying emission mechanisms. This is critical for our understanding of black hole evolution, as well as the energetics of the universe and the origin of ultra-high energy cosmic rays.

**Personal experience**

During the last couple of years, we have developed a basic model for jets and accretion flows explaining the non-thermal emission in accreting black holes (Falcke, Biermann, Markoff). Based on the idea of a "jet-disk symbiosis" the model successfully describes the emission of black holes in very different sources, like low-luminosity AGN, X-ray binaries, and quasars with the accretion rate being the main parameter. Falcke and collaborators have written numerous reviews on this topic and especially their work on the emission of Sgr A* (the Galactic Center black hole) is widely recognized. Markoff & Biermann have a strong particle physics background and thus strengthen the connection to other parts of the SFB.

In addition, Falcke, Nagar, & Wilson have been involved in a large survey of radio emission from low-luminosity AGN at various wavelengths and resolutions. This allowed them to compile a large database of (partially newly discovered) black holes with detectable emission. This extends the black hole census to low powers and provides powerful means for discerning between various models.

A strength of this collaboration will be a close connection between theory and observations of black holes.

**Goals of the project**

The goal of the project will be to develop a comprehensive emission model of black holes on all mass scales, comprising the major ideas currently discussed. We will further combine and integrate accretion flow models such as standard disk and ADAF with jet emission models and compare them with observations. As much as possible, the model will include empirical and observational constraints. Parallel to this we will expand our survey to discover more supermassive black hole candidates (mainly in low-luminosity AGN and XRBs) and constrain their emission spectra across the electromagnetic spectrum.

The final questions we hope to answer with this are: What are the demographics of black holes? What is their power output in mechanical energy through jets and relativistic particles (cosmic rays)? What is the accretion rate onto black holes in various phases of their life-cycle, given current radio and observational constraints? What physical processes can be identified as being important near the event horizon and in jets and accretion flows? We will also discuss the possible effects of accreting, dissipative dark matter on the emission spectra of black holes.

**Estimate of resources expected from DFG**

We will request two postdoc and two PhD-positions. One half will be dedicated to the observational issues and the other half to theoretical modeling. We will also require traveling funds for the students and postdocs, in order for them to attend conferences and conduct observations. Finally, we will request funds for computer equipment, and page charges for some journals.

**Members of research group relevant for the project**

Dr. Heino Falcke, MPIfR Bonn (PI)
Dr. Sera Markoff, MPIfR Bonn (PostDoc)
Dr. A. Zensus, MPIfR Bonn (Director)
Prof. Peter L. Biermann, MPIfR Bonn
Dr. Neil Nagar, Arcetri Observatory (PostDoc)
Prof. Andrew Wilson, University of Maryland & Space Telescope Science Institute

**Connections to other projects of current SFB proposal**

Black holes are at the focal point of various lines of research important for the proposed SFB. In a separate project, the common evolution and growth of black holes and galactic bulges is investigated. Our modeling of black hole emission processes, and the application of this model to data will provide crucial information about the magnitude of the central accretion rate in various phases of AGN activity. Similarly, the energy output of black holes will help to improve our understanding of the energetics of X-ray halos and thus, for example, significantly affect the estimate for baryonic and dark matter in galactic halos. Finally, the power of jets is a fundamental parameter for estimating the (ultra-high energy) cosmic ray contribution of AGN which, in turn has implications for the energy budget in the universe and astro-particle physics developed in various other projects within the SFB (e.g. the question whether dark matter is dissipative).

### 2.0.12 Gravitational field and galactic mass distribution

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**Abstract**

Current dark matter models, favoring cold dark matter (CDM), successfully describe the mass distribution on scales of clusters of galaxies and on larger scales. All models, however, fail on galactic scales. We intend to focus our attention to galactic scales and investigate the mass distribution within galaxies (radius R< 50 kpc) and their halos (R< 500 kpc).

Our approach is based on model calculations which already successfully describe the mass distribution of the Milky Way and similar spiral galaxies as a composition of isothermal disks (DM, stars, molecular-, neutral- and ionized gas) and an isothermal sphere representing the a more extended dark matter component. Our model, based on a self-consistent 3-D determination of mass and potential, is able to satisfy all known observational constraints in our Galaxy.

We aim to generalize our model and match also mass distributions of low surface brightness and dwarfs galaxies to the observational constraints. The major burden is the computational effort which is needed to determine the mass distribution, appropriate to the observations, for such systems in a self-consistent way.

**Current status of research**

CDM may be considered as the leading cosmological model which has its merits on large scales. Here we intend to focus on smaller galactic scales.

The current dark matter hypothesis fails to explain the dark matter distribution in galaxies. The severity of the mass discrepancy in spiral galaxies is strongly correlated with the central surface brightness of their disks. The lower the surface brightness, the larger the discrepancy (McGaugh & Blok 1998).

Mass models for the Milky Way (Dehnen & Binney 1998) encounter a similar problem. Minor modifications of the mass model in the center of the Galaxy cause significant changes of the dark matter distribution on large scales. Apparently the tail is wagging the dog.

In our local vicinity we find inconsistencies due to the standard halo model which has been used. If we consider $K_z$, the gravitational acceleration perpendicular to the disk, we have the problem that the general accepted $K_z$ relation (Kuijken & Gilmore 1989) implies continously rising gravitational forces with increasing distance $|z|$ from the disk, a rather unphysical assumption.

Even in the Milky Way halo and the local group on scales up to 1000 kpc, we encounter significant discrepancies between predictions based on CDM models and observations. The number of observed satellite galaxies in the local group is by far too low in comparison with model predictions (Moore et al. 2000). High velocity clouds (HVCs) have been proposed to carry the necessary amount of dark matter as members of the local group.

### Own experience

Within the last years we have made considerable efforts to observe and model the gaseous Galactic halo (e.g. Pietz et al. 1998, Kalberla et al. 1998). We describe the halo gas as a multi phase medium which is in equilibrium with magnetic fields and cosmic rays (Kalberla & Kerp 1998). Common to all these investigations is the determination of the scale height of the gaseous halo. For the solar vicinity we derive an exponential scale height of 4.4 kpc, common for HI gas, hot plasma ($T = 10^{6.2}$ K) and highly ionized gaseous phase ($T \sim 10^5$ K).

These investigations provide an important constraint for the dark matter distribution in the Milky Way which was not considered previously. The gaseous halo may be used as a tracer for the gravitational potential perpendicular to the Galactic disk. The observed HI gas allows to determine the rotation curve at high z-distances. Most important, however, is the hottest ($T = 10^{6.2}$ K) phase. Its distribution unambiguously reflects the potential outside the disk.

Based on our hydrostatic halo model (Kalberla & Kerp 1998) we developed a procedure to determine the mass distribution in the Milky Way which explicitely fits the observed vertical mass distribution in the Milky Way. We use isothermal disks to represent the density distribution of dark matter and the observed mass components and use an iterative scheme to solve the Poisson equation in 3-D. Observed mass components as well as DM distribution are constraint by observational facts such as rotation curve in $R$ and $|z|$, radial scale lengths for stars and gas, their surface densities, local gravitational acceleration $K_z$, observed and dynamical mass density (Oort limit) as well as scale heights of the stellar and gaseous mass components and their flaring with galactocentric radius R.

Our calculations result in two distinct different dark matter components. The gaseous disk is associated with an isothermal dark matter disk which has a scale height of 4 kpc. This mass component dominates the rotation curve on scales $R < 50$ kpc. In addition we find evidence for a more extended halo component which dominates the mass distribution on scales ($50 < R < 350$ kpc) and can be fitted best by an isothermal sphere.

### Goals of the project

The isothermal mass model derived by us fits the observations on galactic scales much better than previous models which were based on isothermal DM spheres only. A flattened dark matter disk implies a significant baryonic dark matter component in the Milky Way which is linked to the visible matter. Assuming that the extended (spherical) dark matter halo is non-baryonic we derive that 13% of the Galactic mass within $R < 350$ kpc is in baryonic form. We find in addition that the baryons carry 12% of the total angular momentum in the Milky Way. The baryon fraction is in good agreement with current cosmological models. The rotation characteristics of baryonic and non-baryonic matter implies that during the formation of the Galactic disk most of the angular momentum was conserved.

Our analysis implies that baryonic and non-baryonic dark matter have distinct different spatial distributions. A significant fraction of the dark matter couples directly with the visible mass in stars and gas. Our self-consistent calculations indicate that such coupling of (presumably baryonic) dark matter with the stellar distribution is strongest close to the Galactic center. This is exactly the behavior of the dark matter which is needed to solve the discrepancies between the current dark matter hypothesis and the observations as discussed in Sect. 1.2. Our self-consistent solution is stable against changes in the stellar distribution, the tail is no longer wagging the dog. Also the gravitational forces are no longer rising to infinity. Our model predicts that HVCs are born within the baryonic Galactic halo. The spatial distribution is entirely consistent with recent observational distance constraints from optical emission lines as reported by Weiner et al. (2000).

Based on the successfull application of our method to the Milky Way, we propose to extend our investigations to extragalactic systems. In particular we would like to apply the model calculations also to LSB and dwarf galaxies. Sources of interest should have well defined observational constraints which allow to model the mass distribution. Of special interest are those objects which cannot be fitted with current models (for discussion see e.g. McGaugh & Blok 1998).

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### Estimate of resources expected from DFG

The main burden of our proposal is that extremely CPU expensive calculations are needed. At present the calculations need 1-2 CPU weeks on a DEC433au workstation for a single parameter set. This is due to the iterative method which is needed to determine from an observed surface density distribution the self-consistent 3-D distributions in mass and gravitational potential which solve the Poisson equation. A fast workstation is needed for program development, testing.

Despite programming and model fitting, it is necessary to obtain useful observational constraints. Here we assume that most of the necessary data are available in literature or can be obtained in collaboration with other projects of the current SFB proposal.

We apply for a fast 667 MHz XP1000 workstation (20.000.- DM) and for a post doc position (alternatively, this work can be done by 2 Ph.D. students).

### Members of research group relevant for the project

Dr. P.M.W. Kalberla and Dr. J. Kerp, Radioastronomisches Institut der Universität Bonn

### Connections to other projects of current SFB proposal

Our proposal is closely related to the proposal "structure of dark matter halos in galaxies" which emphasizes on observational aspects.

### 2.0.13 The Soft X-ray Background: The Window to the Early Universe

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#### Motivation

The detailed study of the formation and evolution of the early Universe becomes feasible with observational facilities in the near future.

The formation of the first star–forming galaxies ($z \sim 20$) will become observable in the infrared and sub-millimetre domain with *FIRST*, *NGST* and *ALMA*. These observations will trace mainly the **cold** and the weakly ionised phase of the baryonic matter. This gaseous phases mark the first star–forming regions and the dense small–scale structures in the early Universe objects.

*XEUS* will open the X-ray window to the early Universe, while *XMM–Newton* already today allows to obtain an estimate of the physical conditions of the extremely luminous high–redshift objects. In the X-ray domain it is possible to study the **hot** phase of the baryonic matter. This hot phase settles in the potential well, hence it is **the** tracer for the large scale galactic dark matter distribution in the early Universe. Here, especially the clusters of galaxies at high–redshift and active galactic nuclei (AGN) are of interest. The goal of future X-ray missions is to perform X-ray observations of high–redshift objects which will allow to study the formation of the first gravitationally bound systems dominated by the dark matter.

**Problems :**

Because of the high–redshift, most of the diagnostic X-ray emission lines are moved into the so–called soft X-ray ($E < 1$ keV) energy range. Here, the confusion with X-ray plasma emission belonging to the Milky Way and its Halo as well as the strong photoelectric absorption by the galactic interstellar medium become a severe problem. To quantitatively study the objects of the early Universe, one has to investigate the distribution of the Milky Way X-ray emission $E < 1$ keV and the distribution of its

X-ray attenuating interstellar matter (absorption $\propto e^{-N_{\rm HI} \times \sigma}$). This work is necessary to build up a solid basis for further studies of the high–redshift Universe.

**Solutions :**

The large scale distribution of the soft X-ray emission of the Milky Way is covered in the unique *ROSAT* all-sky survey. Analysing the *ROSAT* data supplemented with *XMM–Newton* data, it is feasible to determine the temperature and emissivity of the soft galactic X-ray emission towards the high galactic latitude sky, where the next generation X-ray missions will search for early Universe objects.

Initiating and performing high angular resolution all–sky surveys in the HI 21-cm line transition is the most important step to identify 1) the most transparent windows to the early Universe and 2) to understand the soft X-ray radiation transport through the X-ray absorbing interstellar medium. If we understand the soft X-ray radiation transfer, we can observe the early Universe across the entire high galactic latitude sky. This will overcome the todays limitation to "pencil–beam" like fields of view to the early Universe objects. These data have to be supplemented by an all–sky H$\alpha$ survey (Reynolds et al. 1997), which provides the distribution of ionised atomic hydrogen. Because in the soft X-ray energy range hydrogen and helium are the dominant photo-electric absorbing atoms, the HI and H$\alpha$ data build up a complete data set.

**The project :**

Within this project, we intend to perform a high–angular resolution all–sky survey with 21-cm multi-feed detectors, using the world largest single dish radio telescopes, like those at Parkes and Effelsberg or Jodrell–Bank. We like to correlate the *ROSAT* all–sky survey and *XMM–Newton* data with the HI data to determine the distributions of the temperature and emissivity of the galactic X-ray plasma on large angular scales. The angular resolution of the HI and X-ray data match perfect to study the distribution of Milky Way X-ray emission. The available H$\alpha$ all-sky survey has a much lower angular resolution (about $1^{\rm o}$), however its distribution appears to be much smoother than of the cold dense matter traced by HI. Also its column density is an order of magnitude lower than the $N_{\rm HI}$. The combined analysis of the X-ray, HI and H$\alpha$ all-sky surveys will give unique insights into the physics of the Milky Way and its Halo, but more important, it will open the window to the high–redshift objects of the early Universe.

### Current status of research

¿¿From the *ROSAT* deep fields, we know that by far the dominant fraction of the X-ray background radiation (XRB) is produced by the superposed emission of AGNs and clusters of galaxies (Hasinger et al. 1998). The contribution of X-ray emitting individual galaxies and stars to the XRB is negligible. Only towards the tiny most transparent windows through the galactic interstellar medium (minima of X-ray absorbing galactic interstellar medium) the high–redshift X-ray sky is studied at present (*ROSAT*, *XMM–Newton*, *Chandra*). This is mainly because the redshift moves the X-ray spectrum of the high $z$ objects into the soft X-ray energy regime.

$$E(z) = \frac{1}{z+1} E(z=0) \tag{0.2}$$

For example, the important Fe$\textsc{xxv}$ line at $E(z=0) = 6.7$ keV which traces intercluster gas will be detectable at $z = 10$ at $E(z = 10) = 0.61$ keV. In this soft X-ray energy regime below $E < 1$ keV the photoelectric absorption of the galactic interstellar medium becomes one of the most severe problems, the absorption cross section of matter is $\sigma \propto E^{-3}$ (Wilms et al. 2000). The mean free path length of a 0.6 keV photon through the galactic interstellar medium is very short compared with the thickness of the galactic gas layers (Kalberla & Kerp 1998).

The X-ray emission and absorption in the soft X-ray energy window ($E < 1$ keV) is subject of a very controversial debate. Whether the soft XRB is build up by the superposition of individual supernova remnants (Snowden et al. 1998) or it is produced by the X-ray emission of the local hot bubble and the Milky Way Halo plasma (Pietz et al. 1998). If the first working–hypothesis is correct, the soft galactic X-ray emission will vary in all relevant physical parameters on arcmin scale. These variations of the soft X-ray emission will introduce large uncertainties in the analysis of high–redshift objects by disentangling their emission from that of the galactic foreground. If the second working–hypothesis is correct, the situation is much less complicated, but we need to determine the distribution of the X-ray absorbing interstellar medium as accurate as possible. Accordingly, we have now the unique opportunity to constrain and to disclose the origin of the galactic soft X-ray emission and to determine the distribution of the X-ray absorbing interstellar medium to mitigate or to overcome severe data analysis problems in future while studying the high–redshift Universe.

In addition to the photoelectric absorption, the confusion of the high–redshifted X-ray lines with those of the X-ray plasma located within the Milky Way halo and the close neighbourhood of the Sun becomes a severe problem. Both plasma have temperatures of about $T \sim 1 \cdot 10^6$ K (Pietz et al. 1998). Their X-ray spectra are expected to be dominated by a wealth of emission lines of the partly ionised heavy elements. Accordingly, one has to separate the faint X-ray lines of the high $z$ object from the bright diffuse X-ray emission of the galactic plasma.

The present research on the early Universe is focused on the X-ray energy window above $E > 1$ keV, to avoid the confusion present below $E < 1$ keV with the Milky

Way X-ray plasma and the strong photoelectric absorption. To explore really the high–redshift Universe beyond $z > 5$, one has to overcome both severe and not independent problems:

- To evaluate the distribution, the X-ray spectrum and chemical composition of the X-ray plasma in the local environment of the Sun and of that of the Milky Way halo.
- To evaluate the distribution on arcmin scale and chemical composition of the photoelectric absorbing interstellar medium.

**Own experience**

Our group is involved since more than a decade in the analysis of the soft X-ray background below $E < 1$ keV, just where the early Universe becomes visible. Based on the *ROSAT* all–sky survey data, our group developed for the first time a self consistent model of the soft X-ray background radiation (Pietz et al. 1998, Kalberla & Kerp 1998). This model is based on an empirical approach combining X-ray and neutral atomic hydrogen data in a unique way. Using this approach it is possible to model the observed soft X-ray intensity distribution of the X-ray sky down to the accuracy limits of the *ROSAT* all–sky survey. We have now a rigid first estimate of the temperatures and the emissivity distributions of both X-ray plasma as well as of the absorbing interstellar medium.

**Goals of the project**

The project aim is to determine the distribution of the soft X-ray emission of the Milky Way and the X-ray absorbing interstellar medium. The X-ray emission is available in form of the *ROSAT* all-sky survey with an angular resolution of 12 arcmin (Snowden et al. 1997). The best HI surveys offer at least a three times lower angular resolution (Hartmann & Burton 1996). The available multi-feed technology at the Parkes telescope for instance makes it possible to survey the entire sky within a few months with the world largest single dish radio telescopes. This data will match perfect to the *ROSAT* all-sky survey. HI data with even higher angular resolution will also be necessary for follow–up studies of specific objects. These data can be obtained today using the *ATCA* and *VLA* and in future ideally the *Square Kilometer Array* . However, we need to determine very accurately the total HI flux, undetectable with radio interferometers, with the highest possible angular resolution using the world largest single dish radio telescope. Accordingly, we plan to survey the southern sky with the Parkes telescope, while the northern sky will be ideally observed with the Effelsberg radio dish. The combined analysis of X-ray, HI and H$\alpha$ data give us the unique opportunity to model the soft X-ray emission of the entire Milky Way, especially towards high galactic latitudes. This work will free us from the constraint to observe the high–redshift Universe through the tiny "Lockman" or *Chandra*–window. It will be possible to evaluate the X-ray radiation transport of the high–redshifted X-ray emission through the attenuating interstellar medium. For these aims, we have to investigate the following points:

- To search for temperature gradients on small– and large–angular scales across the X-ray sky (*ROSAT*, HI and H$\alpha$ data).
- To evaluate the chemical composition of the local and Milky Way halo plasma (*XMM–Newton* data).
- To determine the distribution of the absorbing interstellar medium on angular scales of a few arcmin (multi-feed HI all–sky surveys).

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**Estimate of resources expected from DFG**

Two Ph. D. students. Financial support to build a 21–cm multi-feed system for the Effelsberg telescope.

**Members of research group relevant for the project**

Dr. Jürgen Kerp and Dr. Peter M. W. Kalberla

**Connections to other projects of current SFB proposal**

### 2.0.14 Structure of Dark Matter Halos in Galaxies

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#### Abstract

One of the key issues in astrophysical research is the unresolved problem of the nature of Dark Matter (DM). DM can be studied on various scales, from small galaxies up to superclusters. This project is to scrutinize the distribution of DM in galaxies. The final goal is to deduce the density profile of DM structures on galaxy scales.

In case of galaxies, density profiles can be obtained from precise rotation curves and optical (infrared) photometry, preferably of low–surface brightness galaxies (known to be DM–dominated). The rotation curves must utilize both, optical (H$\alpha$, central regions) and radio (HI, outer regions) techniques in order to provide the high spatial and spectral resolution that is indispensible for the anticipated accuracy.

The derived DM density profile at large radii, together with the related baryonic mass dependence, will probe the cosmological processes of galaxy formation, while at small radii, where the DM is mixed with the baryons, it will probe the subsequent galactic evolution.

#### Current status of research

Since the first evidence for the existence of DM was reported by F. Zwicky in 1933, based on his studies of the velocity dispersion in the Coma Cluster, its nature has remained totally undisclosed. Following the pioneering work by Rubin & Ford (1980; 1982) in the optical and by Bosma (1982) in the radio regime, numerous studies of galaxy rotation curves have been conducted. It became soon clear that low–mass galaxies, too, possess a significant fraction of DM (Sargent & Lo 1990), and may be even DM–dominated (Mateo 1998). Low–surface brightness galaxies (LSBGs) were shown to have rotation curves similar to those of massive spirals (Stil 1999), while their DM content may vary significantly (Swaters 1999). LSBGs are frequently DM–dominated, but there is a large spread of their DM fraction. It was the expectation that with this 'industry' of rotation curve analyses one should soon be able to deduce some properties of DM halos.

During the past decade, the importance of DM in the universe became obvious from a completely different route. It was with the successful operation of COBE that the amplitude of the anisotropy of the cosmic microwave background (CMB) was measured for the first time, with $\Delta$T/T$\sim 10^{-5}$. This rather hard number is not reconcilable with the observed density fluctuations of the evolved universe unless the bulk of its matter is non–baryonic. Models that predict hierarchical structures with Cold Dark Matter (CDM, see e.g. Jenkins et al. 1998) have been worked out in the meantime, which appear to reproduce the observed clustering properties of galaxies out to the currently accessible range of radial velocities pretty well (while Hot Dark Matter theories are faced with problems).

The so–called 'standard' $\Lambda$CDM model, which accounts for the basic set of 'modern' cosmological parameters (critical density $\Omega_0$, non–zero cosmological constant $\Lambda = 1 - \Omega_0$, Hubble constant $H_0$, baryonic mass density $\Omega_b$, mass fluctuation $\sigma$), is the currently most favoured one, but nonetheless bears some problems when juxtaposed with obsevations. Because it has its major parameters fixed, it is eminently falsifiable. In particular, its predictive power can be used to check its validity on scales different from those used to tune it. One of the major problems is that the model is at odds with the well–established Tully–Fisher relation (Navarro & Steinmetz 2000).

As far as galaxy scales are concerned, there is no reason to believe that the current quality of observed rotation curves is sufficient to allow any firm conclusions as to the distributions of various constituents in galaxies (bulge, disk, halo). As pointed out by van den Bosch et al. (2000), the whole debate that we have seen over the past years, whether or not DM halos of galaxies possess central cusps, has not come up with any convincing conclusion. They show that the spatial resolution of the data is not sufficient to put any meaningful constraints on the density profiles of dark halo, or on cosmological parameters, in contrast to such claims in the literature. In order to overcome the degeneracy inherent to the interpretation, high–resolution rotation curves have to be obtained, the best targets being LSBGs or dwarf galaxies that lack bulges and in which the contribution of the stellar disks to the total mass is less important.

### Own experience

The study of the structure and kinematics of galaxies has long tradition at our institute. Investigations of halos in different types of galaxies have been carried out in various spectral regimes (radio continuum: Beck et al. 1994, Dumke et al. 1995, Klein et al. 1996; HI: Bajaja et al. 1994; Koribalski et al. 1993; cold dust and CO: Thuma et al. 2000; X–rays: Pietsch et al. 1994, 2000).

The kinematics of galaxies, in particular of low–mass ones, has been one of the subjects of galaxy research at Bonn (Brinks & Klein 1986; 1988; 1989; Bajaja et al. 1994; Walter et al. 1997), in the course of which important contributions to the question of DM in such systems were made. This is still one of the major topics of our on–going Graduiertenkolleg *The Magellanic System, Galaxy Interaction, and the Evolution of Dwarf Galaxies*, jointly run by the Astronomical Institutes of the Universities of Bonn and Bochum. In the framework of this, several dissertation and postdoc projects are and have been devoted to the study of the properties of the ISM, with the special aspect of widely different environments. These studies, which utilize both, the HI and the CO lines, cover both, small and large scales. On small scales, the mutual relation interaction star formation and the ISM are studied, with enormous progress concerning the relevant input parameters for numerical models (Barone et al. 2000; Walter et al. 1998; Walter 1999; Weiß et al. 1999; Weiß 2000; Taylor et al. 1999).

On galaxy scales, the gas kinematics is used to disclose the overall mass distribution, with special emphasis on the galaxies' structures and environments. Following thorough studies of the influence of gravitational interactions on bulge Lütticke 1999) and disk (Schwarzkopf 1999) structures, the recently proposed scenario of the formation of boxy bulges via soft merging is being investigated in a large sample of edge–on galaxies with boxy bulges using the HI for the kinematic diganostics, but also photometry to scrutinize the distribution oft he stellar light (Vergani, Ph.D. thesis, in prep.). Finally, a collaboration with P. Salucci (Triest/SISSA) commenced this year, in which the density profiles of DM halos will be subject to scrutiny, in the way described in more detail in the next section (also Ph.D. thesis to start this fall). The kinematics of low–mass galaxies is more difficult to study, since their rotation velocities are naturally low. As a result, one has a hard time to derive their mass distributions, let alone that of DM (e.g. Kohle, 1999; 2000). In the extreme case, at the low–mass end of the mass spectrum, the problem of rotational support of dwarf galaxies is being investigated (Ott et al. 2000; also on–going Ph.D.).

**Goals of the project**

In the framework of this project, we plan to explore the distribution of DM on the scale of galaxies. This will be achieved by combining high–precision optical (H$\alpha$) and radio (HI) rotation curves.

In order to obtain 'clean' rotation curves, our galaxy sample will be selected according to the following prerequisits: Their mass distributions should not be governed by bulges, neither by disks. It is usually a big obstacle in such investigations if there are dominating stellar components. We shall thus cull a statistically significant sample from catalogues of intermediate–mass galaxies. Genuine dwarf galaxies are not suitable either since their kinematics is strongly influenced by turbulence of the ISM (see Sect. x.1.3). The best targets are therefore LSBGs as well as targets with masses like the LMC. All of them must be carefully selected against any external influences (tidal interaction, ram pressure in clusters).

The radio observations will have to be performed with the ATCA (southern galaxies) and the VLA (northern ones). The WSRT will not be considered in this project because of its lower angular resolution. In the framework of the WHISP programme (Westerbork observations of neutral Hydrogen in Irregular and SPiral galaxies) Swaters (1999) studied a sample of about 80 dwarf galaxies. He showed that the spatial resolution obtained with the WSRT at $\lambda$21 cm is insufficient for galaxies that small. Optical (I–band) photometry of the target galaxies will serve to derive the mass distribution of the stellar constituent. Slit spectroscopy in the H$\alpha$ line will complement the HI data. This complementary approach also ensures that in (the frequent) case of a central HI deficiency the kinematic information is still gained (via H$\alpha$). We shall thus obtain high–precision rotation curves over the whole body of each galaxy. The derived DM density profile at large radii, together with the related baryonic mass dependence, will probe the cosmological processes of galaxy formation, while at small radii, where the DM is mixed with the baryons, it will probe the subsequent galactic evolution. Optical rotation curves alone are not sufficient, since there is evidence for large DM core radii that even exceed the radius of the optical disk (Salucci & Burkert 2000).

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**Estimate of resources expected from DFG**

We have already embarked on a first project to investigate the rotation curves of a fair sample of LSBGs. This project is embedded in our Graduiertenkolleg, as it requires a Ph.D. student for successful completion. It is, however, foreseeable that a thorough and systematic investigation in this research topic requires more efforts, both, in terms of man power and as far as resources are concerned. In order to plan and carry out the observations, reduce the data, interprete and publish them, we require an experienced postdoctoral fellow, i.e. a full position (BATIIa). The postdoctoral fellow is expected to plan and carry out the relevant observations. He is to publish them in refereed journals, and at the same time present results on pertinent conferences. He is furthermore required to organize the collaboration with other groups (with P. Salucci in Triest). This necessitates travel funds to attend two conferences per year, and two visits to the collaborating insitutes. The HI data cubes obtained in the course of this project requires a dedicated state–of–the–art computer with periphery. This foreseeably requires about 5 kDM in the first year, and about 2 kDM in the subsequent ones.

### Members of research group relevant for the project

Priv. Doz. Dr. A. Heithausen (staff member); Dr. P. Kalberla (staff member); Prof. Dr. U. Klein (project leader); Prof. Dr. U. Mebold (managing director).

### Connections to other projects of current SFB proposal

This project is intimately related to x.x.x. In particular, our proposed search for dwarf satellites around massive galaxies perfectly complements the search for, and study of, HVCs in the Milky Way and the Andromeda galaxy. The proposed scrutiny of galaxy rotation curves provides the obvious link to project x.x.x that investigates the nature of DM.

### 2.0.15 Structure formation in the local universe

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#### Abstract

Currently favoured models of Cold Dark matter (DM) are tuned to be in accord with an array of observationally supported cosmological parameters. Because of their predictive power they have to be tested by confronting them with observations of DM on all scales. This project is to investigate the distribution of DM on the scale of groups and clusters of galaxies.

The distribution of DM in groups and clusters of galaxies will be studied using the X–ray emission of the hot gaseous cluster halos. Both, the spatial and spectral resolution of modern X–ray telescopes such as XMM and CHANDRA meanwhile allow to also study the kinematics of this gas, thus allowing to disclose the dynamics of ongoing structure formation in the local ($z \leq 0.1$) universe. Radio continuum measurements disclose the shocked interface regions in which pools of cooled particles are re–accelerated to highly relativistic energies. Their synchrotron radiation exhibits characteristic properties of the particle spectrum and the magnetic field morphology.

#### Current status of research

With the successful operation of COBE in 1992, a long–standing problem has been solved, viz. the true amplitude of the anisotropy of the cosmic microwave background (CMB), for which prior to COBE only upper limits were available. One of the immediate consequences of this imprint of commencing fluctuations onto the CMB (at the last scattering surface) is that some unknown form of DM must dominate the universe that interacts solely by gravitation. Otherwise, the observed level of unisotropy $\Delta T/T \sim 10^{-5}$ would be in flat contradiction to the density fluctuation seen in the evolved universe (of order $10^6$ for galaxies, $10^3$ for clusters, $> 10^1$ for superclusters), accounting for their evolution out of the initial fluctuation spectrum.

Models of structure formation aim at producing the observed large–scale structure as realistically as possible, but should ideally also reproduce the hierarchy of structures, from galaxies to superclusters. Such models that are based on Cold Dark Matter (CDM, see e.g. Jenkins et al. 1998) have been worked out in the meantime. They appear to reproduce the observed clustering properties of galaxies out to the currently accessible range of radial velocities pretty well, thereby predicting the total dark mass of (e.g.) clusters and, at the same time, the mass spectrum of galaxies within a larger structure.

It turns out that the models are faced with some severe problems when compared with observations. In particular, a clear mismatch was found by Moore et al. (1999) when confronting these hierarchical, scale–invariant model structures with observations. While on the cluster scale (the Virgo Cluster in that case) the model reproduces the observed mass spectrum of member galaxies pretty well, it overpredicts the number of satellites around the Milky Way by factor of $\sim$50! No one really knows what 'went wrong' with the Milky Way, given that the models are correct. On the other hand, it is difficult to make/leave (dwarf) galaxies 'dark', or make them disappear by soft merging with the main galaxy. In the case of the Milky Way, a large number of merged satellites would have heated its disk very strongly, which is not observed (Moore et al. 1999). If such a scenario is suggested by observations, it seems that this process produces a giant elliptical, leaving behind a poor group (e.g. Barnes 1989; Athanassoula et al. 1997), a nice example being NGC 1132 (see Mulchaey & Zabludoff 1999). Given the scarce results of recent deep HI surveys aiming at the discovery of dwarf satellites in galaxies and groups of galaxies (Sorar 1994; Zwaan et al. 1997), or to disclose intergalactic HI clouds (e.g. Disney et al. 1999), it is clear that a really huge effort is to be made in order to derive the HI mass function at the low–mass end of galaxies. On the other hand, even though the models may require uncomfortable changes in their parameters in order to be reconcilable with observations, there may still be some room left for such changes (Navarro & Steinmetz 2000). For instance, a tilted primordial power spectrum could do the job, i.e. suppress power on galactic and sub–galactic scales. And finally, owing to the numerical resolution of the models, deviations from observations are most compromised on small scales.

This certainly does not hold on scales of galaxy clusters, where the modelled large–scale structure reproduces the observations pretty well. An interesting aspect of studying clusters of galaxies is to explore their substructure, where X–ray measurements can be utilized as very sensitive tools (in more distant clusters this can be accomplished via gravitational lensing). Harris et al. (1980) early on deemed the radio halos in galaxy cliusters to represent shock zones between merging subclusters. This picture has in the meantime matured, owing to theoretical and observational progress. Multi–frequency measurements allow to deduce important physical properties such as the morphology and strength of the magnetic field in such regions, and the continuum spectrum of the synchrotron radiation. One of the most spectacular examples is witnessed in A 2256 (Röttgering 1993; Thierbach 2000). As shown by Enßlin (1999; see also et Enßlin al. 1998) this yields a picture of the 3–D structure of the shock region, from which one gains knowledge about the structure formation in the local universe.

### Own experience

The study of galaxy clusters has a long tradition in Bonn (RAIUB/MPIfR). The emphasis of these investigations has been on the statistics and evolution of radio sources early on, starting with the early low–frequency work by Waldthausen (1980), and pushed towards higher frequencies (Andernach 1981), the focus turning to the nature of radio halos by Sievers (1988) and Thierbach (2000). The properties of the IGM and ICM have been investigated via multi–frequency observations of tailed and giant radio sources (Mack 1992, Ballarati et al. 1993, Feretti et al. 1998, 1999, Zech 1995, Rottmann 1996, Rottmann et al. 1996, Mack 1996, Fuhrmann 1999). The Sunyayev–Zeldovich effect has been investigated by Schallwich (1980), Klein et al. (1991), and by Thierbach (1996). Effects of the cluster environment on the properties of spiral galaxies in clusters have been studied by Niklas et al. (1995, Virgo Cluster) and by Fritz (2000, Centaurus Group).

A very important astrophysical aspect emerging from those investigations and relevant to the here proposed project is the interpretation of cluster radio halos in terms of shock–induced acceleration of pools of cooled particles (Enßlin et al. 1998, Enßlin 1999, Thierbach 2000, Enßlin et al. 2000). What we are witnessing here is the effect of ongoing cluster or subcluster merging, i.e. large–scale structure formation in the local universe. It could be shown here that this interpretation, which had been the subject of many controversary discussions in the literature, nicely explains the spectral and polarization properties of 'radio halos' (coined 'radio ghosts' by Enßlin).

In order to conduct X–ray studies of galaxy clusters we shall utilize the new generations of excellent X–ray telescopes. X–ray studies of various kinds of objects have been carried out at our institute in the past, and still are (HVCs: Kerp et al. 1999; dwarf galaxies: Blondiau 1996, Blondiau et al. 1997; Walter et al. 1998; spiral galaxies: Pietsch et al. 1994, 2000; radio galaxies: Mack et al. 1997).

### Goals of the project

The amount of DM in clusters of galaxies can be deduced in three ways: from the velocity dispersion of the galaxies, from the variation of density and temperature of the hot coronal plasma (assumed to be in hydrostatic equilibrium), and – in case of distant clusters – from gravitational lensing of background objects by the cluster. The above mentioned problems of ΛCDM models obviously necessitate further observational tests. This requires both, the search for satellites around external galaxies as well as a scrutiny of galaxy groups and clusters, with the aim to derive their mass spectrum. The existing data impressively demonstrate the power of X–ray observations (see e.g. Böhringer 1995, for a review). New–generation X–ray telescopes will allow much more detailed studies of the hot cluster gas than hitherto possible.

In the framework of this project, we plan to observationally explore the structures of visible matter and DM on scales of groups and clusters of galaxies, with emphasis on their (still forming) substructures. The primary tool to accomplish this is provided by X–ray measurements of the pervasive hot plasma surrounding the central galaxies. Numerous examples for this possibility have been delivered by the ROSAT mission, and Schuecker & Böhringer (1999) have identified a substantial fraction of clusters possessing radio halos or relics out of the ROSAT cluster sample. X–ray observations probe both, the temperature and density of the ionized gas. Imprints of the collision zone are particularly distinctly visible in the temperature profiles across such regions, a first prominent example reported by (Kikuchi et al. 2000).

While it is mandatory to use modern X–ray telescopes at their best, much can be gained by 'data mining'. The ROSAT archive still contains a host of individual pointed observations - as yet unreduced. Likewise, the All Sky Survey can be regarded as a treasure box. These data will serve as an important tool for our candidate search and sample definition as far as galaxy clusters are concerned. For the derivation of detailed properties of the hot gas (distribution of density and temperature) it is mandatory to utilize modern X–ray telescopes in the framework of this project. Besides their greatly improved sensitivity and their much improved angular resolution, one important advantage is that their spectral resolution allows to even investigate relative motions of the hot gas via spectroscopy of (mainly) the iron line (several 100 km $s^{-1}$.

Once the interface zones of merging (sub)clusters have been identified, these have to be observed in the radio continuum. Multi–frequency radio continuum observations will be used to derive properties such as the morphology and strength of the magnetic field within these radio halos, and the continuum spectrum of the synchrotron radiation. This requires both, interferometers (at low frequencies) as well as the Effelsberg

100–m telescope (at high frequencies), in order to fix the break in the spectrum, hence the time elapsed since the particles were (re–)accelerated.

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**Estimate of resources expected from DFG**

Manpower: The programme outlined above obviously requires experts who are familar with observational techniques in two rather different spectral regimes. The load of work makes a full position (BATIIa) for each spectral domain indispensible. The postdoctoral fellows are expected to plan and carry out the relevant observations. They are to publish them in refereed journals, and at the same time present results on pertinent conferences. They are also required to organize the collaboration with other groups (with L. Feretti at CNR in Bologna and H. Böhringer at the MPIE in Garching). This necessitates travel funds to attend two conferences per year, and two visits to the collaborating insitutes. In order for the postdocs to efficiently cope with the data analysis they have to be provided with powerful state–of–the–art computers and some periphery. This foreseeably requires some 10 kDM in the first year, and about 2 kDM in the subsequent ones.

**Members of research group relevant for the project**

Dr. J. Kerp (staff member); Prof. Dr. U. Klein (project leader); Prof. Dr. U. Mebold (managing director).

**Connections to other projects of current SFB proposal**

This project is intimately related to project x.x.x. The proposed scrutiny of DM in groups and clusters is linked to project x.x.x that investigates the structure of DM on galaxy scales, as well as to project x.x.x that aims at disclosing the nature of DM.

### 2.0.16 Bolometer Arrays for Submillimeter Cosmology

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#### Abstract

Large bolometer arrays of ever increasing size and sensitivity are the detectors of choice for observations of redshifted thermal emission from young galaxies and fluctuations of the cosmic microwave background temperature at millimeter- and submillimeter wavelengths. Based on extensive experience in the development and construction of bolometer arrays, we propose to push research and development toward a next generation of these arrays.

#### Current status of research

Presently, several developments are taking place that will allow the manufacture of very large arrays of bolometers. Foremost among these is the microlithographic fabrication of electronic and mechanical components. It is not the shrinking of the device size that is of interest here, because the dimension of the absorbing structure in a bolometer is tied to the operating wavelength. It is rather the reliability combined with the ease of increasing the array size at a small incremental cost that make microlithographic techniques attractive for bolometer technology. If one compares the mapping speed of two bolometer arrays of different size (i.e., number of elements $n$), the mapping speed – defined as the time to reach a given signal-to-noise ratio for a given area – scales with $n$, provided the individual bolometers have the same sensitivity. This is strictly true only for the case when the area of sky to be mapped is much larger than the array, which applies for much of the current front-line research, e.g., the search for cosmological point sources.

At the extremes, bolometer arrays can be classified as fully efficient (sparsely sampled, with channel separations of 2 beams) or as fully sampled (half beam separation). A recent study for SPIRE (the bolometer camera of FIRST) indicates that the speed advantage of a fully sampled array over a fully efficient one is less than a factor of two. However, the fully sampled array has 16 times as many elements, which implies a large increase in system and data complexity. For the same number of elements (and wires) the fully efficient array is much more sensitive for large scale mapping. For both array types, Nyquist sampling will be achieved naturally during a continuous scan.

The sensitivity of (sub)mm bolometers can be limited by two effects. The first is the fundamental photon background noise, i.e., the statistical fluctuations of the thermal photon field. The second is the time variation of large-scale inhomogeneous emission in the atmosphere, mostly from water vapour. Current semiconducting bolometers are already close to being limited by photon noise. If the sensitivity cannot be improved significantly, it is more sensible to push the limits of array size instead. The skynoise is generally much higher than the photon noise, and it is of non-Gaussian character, so that the sensitivity does not integrate down with the square root of integration time. Highest sensitivities can only be achieved with low, stable backgrounds, i.e., by moving to the best possible site.

There have been various recent proposals for new detector devices. Of those, we consider superconducting transition edge bolometers to be the most likely to reach technical maturity in the near future.

Existing state-of-the art instrumentation on ground-based facilities include

- a series of Max-Planck Millimeter Bolometer (MAMBO) arrays built at the MPIfR and installed at the IRAM 30 m telescope on Pico Veleta, Spain for the 1-mm window – a 117-element array has just replaced the previous 37-element array;
- a 19-element MPIfR array for the 870 $\mu$m window at the 10 m Heinrich-Herz-Telescope (HHT) on Mount Graham, Arizona;
- a new 37-element array (SIMBA) for the 1-mm window at the Swedish-ESO Submillimetre Telescope (SEST) on La Silla, Chile, that the MPIfR is currently deploying;
- the SCUBA arrays for the 870 $\mu$m and 450 $\mu$m windows at the 15 m James-Clerk-Maxwell Telescope on Mauna Kea, Hawaii;
- BOLOCAM for the 1-mm window at the 10.4 m Caltech Submillimeter Telescope, on Mauna Kea.

### Own experience

The proposer has extensive experience in the theory, design, and building of detectors for millimeter- and submillimeter-wavelength astronomy. Since the 1970s, he has concentrated on bolometer systems, which have been very successfully used at various facilities. His group has built all of the MPIfR bolometers, namely several generations of MAMBO, the facility bolometer instruments for the SEST and its next generation instrument SIMBA, a multi-color bolometer and a bolometer array for the HHT, and various other systems.

Dr. Kreysa is very much interested in the astronomical questions that can be addressed by his bolometer arrays, in particular research on dust emission from the high redshift universe and studies of the cosmic microwave background radiation.

The present generation of bolometers built at the MPIfR are based on the very reliable Neutron-Transmutation-Doped Germanium (NTD-GE) thermistors. We were involved in the development of these thermistors by the group of E.E. Haller at LBNL in Berkeley. Unfortunately the production of NTD-Ge chips is not very compatible with microfabricaton of bolometers. The chips have to be attached manually to the bolometer structures.

Bolometers require a weak thermal link between the absorber of the radiation and the cold surface. In our case this a free-standing membrane of Silicon-Nitride deposited by chemical vapor deposition. The complete array structures, including wiring and absorber, are micromachined on a Silicon wafer in the microlab of UC Berkeley. The wafer is then matched to an electroformed array of horn antennas. This proven design can be refined and scaled to 1000 elements. At the wafer level, a transition to Indium bump bonding will required in order to increase the reliability of thermistor attachment.

### Goals of the project

The goal of the project is to design, develop, and operate state-of-the-art continuum detector arrays for unique frontline telescopes like the AST and the IRAM 30m telescope.

The first major project will be the development of a 1000-element bolometer array for the AST, operating in the 870 $\mu$m band with a total field of view of $\approx 20$ arcminutes. To search for high-redshift dust emission, the 870 $\mu$m window is best because of a high source flux and good atmosheric transparency. In addition, a 37-element bolometer array covering the 350 $\mu$m window will be built for the beginning of the AST operation.

It will be essential for determining the spectral index of sources found, e.g., through 870$\mu$m surveys.

In the later phases of the project, the unique quality of the AST site should allow us to take advantage of the extreme submm windows at 450 $\mu$m and 350 $\mu$m with very large arrays, of the order of several thousand elements. This will require new technology. At present superconducting bolometers with multiplexed SQUID readout look promising, but detector development is a rapidly evolving field which must be monitored carefully.

Because of the short time left until the begin of the AST operation (early 2003) we will initially rely mostly on proven technology. Still, significant research is necessary on the several issues which are critical for the success of our new developments:

- silicon micromachining of the bolometer structure,
- bump bonding of the thermistors,
- cold multiplexers,
- highly effective thermal rejection filters,
- closed-cycle cryogenics,
- powerful, low interference, data acquisition.

The size of arrays might eventually be limited by the number of wires and/or the electrical dissipation of the pre-amplifiers. There are several promising multiplexing technologies under development which would reduce the problem considerably, most of which are being developed for superconducting devices. In a relatively high background environment, the multiplexing capability, and not the sensitivity advantage, is the major attraction of the new superconducting bolometer technology. For Arrays with NTD-Ge thermistors the multiplexing problem remains to be solved, but some of promising ideas are already being investigated.

In a ground-based environment, bolometers are working under a high thermal background. Filters must be employed on all intermediate temperature shields to restrict the background to a passband in the Rayleigh-Jeans tail of the 300 K peak. It does not help to increase the cooling power of the cryogenic system, because any out-of-band power would overwhelm the bolometers. Scaling the filter size with array dimensions is problematic too. Given the limited thermal conductivity of some filter components, the out-of-band power they absorb could heat them and thus increase the thermal load on the bolometers. It is likely that filter technology will limit the maximum array size.

At an altitude of 5000m, all observations must be performed with a minimum of physical intervention and effort by the staff. Even at this exeptional site excellent submm condition can arrive with little warning, and the equipment has to be on standby for long periods. Cryogenics are a particular challenge in that respect. For the arrays we have to provide temperatures of 100mK, ideally without the need for liquid helium. Pulse tube coolers reach 4K with low vibration levels and can be combined with adiabatic demagnetisation refridgerators for 100mK. Both need further development for our purposes.

Also needed is a substantial effort in data acquistion hard- and software. The cold multiplexers need special backends which have to take into account the intrinsic sensitivity of bolometers to interference of any kind. Mapping wide areas with large arrays will involve high data rates and the data acquisition has to be optimized for that observing mode.

#### Estimate of resources expected from DFG

To be discussed.

#### Members of research group relevant for the project

Dr. Ernst Kreysa, Dr. Hans-Peter Gemünd, Dr. Lothar Reichertz, Andrea Raccanelli, Giorgio Siringo

#### Connections to other projects of current SFB proposal

The project is closely related to the project lead by Dr. F. Bertoldi, which utilizes new bolometer technology for cosmological studies.

### 2.0.17 Cosmology of brane world systems

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**Abstract**

In the last years, the concept of extra space dimensions has become one of the central research subjects in elementary particle physics. Guided by the properties of string theories one is led to the so-called brane worlds, where our universe might be a multi-dimenional brane embedded in a higher dimensional universe. Many particle physics phenomena have been investigated in this framework, and only recently the comological properties of such a scheme have been addressed. We would like to study the evolution of the universe in this picture with special emphasis on the questions of the cosmological constant, the mechanism of inflation and the asymmetric expansion of spatial dimensions.

**Current status of research**

Since the work of Horava and Witten on the heterotic M-theory [1] the picture of an d=11 dimensional universe suspended between two d=10 dimensional walls has attracted much attention. With the concept of D-branes [2] this picture can be generalized and applied to many higher dimensional systems, and gives new insights in the process of compactifaction of extra dimensions traditionally discussed in the framework of string theories. Consequences of this new picture have been worked out mainly with focus on elementary particle physics. Possible implications for cosmology have recently been discussed as well but are still in a very preliminary stage: for a review see ref. [3]. The observational evidence for a possibly nonvanishing cosmological constant from supernovae studies enter the discussion with various schemes of so called quintessence. Also here we are just witnessing a first step in a direction that will be important for any discussion of cosmological questions in the not so distant future.

### Own experience

Using our expertise in string theory and compactification of extra dimensions the group in Bonn has started a program to work out possible cosmological consequences of the new schemes appearing in the so-alled brane world picture.

A first application has been the discussion of the cosmological constant [4], where we could clarify some aspects of higher dimenisional dynamics on the vacuum energy. The subject has not been clarified yet, as up to now, only a static model has been given [5]. The generalization of this picture to an evolving universe should be discussed, but would need the inclusion of matter on the various branes. This would then raise the questions of a generalization of the Friedmann universe to extra dimensions, the (critical) matter density. As these investigations are still in a quite early stage, the further development of the field will strongly depend on the results obtained in the next year.

This would hopefully shed some light on the question of a possible successful incorporation of quintessence in these extra dimensional schemes. First attempts look promising, as broken supersymmetry in the bulk might leave traces as a small cosmological constant on the wall a possibility that is right now analyzed by our group.

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### Goals of the project

Text needs to be written.

### Estimate of resources expected from DFG

- 1 postdoc position
- 1 PhD student?
- travel money
- money for invitation

### Members of research group relevant for the project

- Prof. W. Nahm

- Dr. s. Foerste
- Dr. A. Wisskirchen
- Dr. S. Groot Nibbelink
- H. Klemm

International collaborations with S. Sarkar (Oxford), P. Binetruy (Paris), M. Quiros (Madrid) and A. Masiero (Trieste).....

**Connections to other projects of current SFB proposal**

Connections to work that ...

### 2.0.18 Supersymmetry and the early universe

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#### Abstract

We investigate the supersymmetric extension of the $SU(3) \times SU(2) \times U(1)$ standard model of strong, weak and electromagnetic interactions. This generalization predicts various new particles (like neutralinos, axinos, gravitinos among others) that might be relevant for cosmological and astrophysical applications. One aspect of the research concentrates on the possibility that these particles could be realistic candidates for cold dark matter observed in the universe. We would like to explore the various theoretical schemes and their implications for the properties of dark matter, also in view of the experimental efforts to detect these particles directly. A second aspect concerns the question of new symmetries and their relevance for rare processes as e.g. proton decay and related cosmological consequences like the creation of a baryon asymmetry in the early universe.

#### Current status of research

The $SU(3) \times SU(2) \times U(1)$ standard model of particle physics describes practically all known microphysical phenomena. Its predictions have been successfully tested within the last two decades. Nonetheless there are various theoretical questions that could not been answered in this framework and that led to the study of extensions, the most popular of which is the one based on supersymmetry. This theory has attracted much attention in the last ten years not only in the field of particle physics but also in view of its possible relevance for cosmology and astrophysics. A central prediction is the existence of a stable, neutral, massive and weakly interacting particle, now believed to be a neutralino: a supersymmetric partner of one of the neutral gauge bosons that mediate the weak and electromagnetic interactions. Mass and interactions of this particle could be in a range that leads to a relevant cosmological abundance and make this particle a candidate for cold dark matter in the universe. By now various classes of models are well understood and the cosmic relic abundance can be computed. What is less well understood are theoretical arguments in favour of one or the other model. It is believed that the mechanism of spontaneous supersymmetry breakdown is relevant for the specific properties of these models, but more work is needed to draw a final conclusion.

The investigation of properties of could dark matter has concentrated mainly on the size of the relic abundance. More detailed questions concerning the spatial distribution of dark matter still have to be answered.

One of the arguments for a generalization of the standard model of electroweak interactions is the fact that it does not lead to a satisfactory explanation of the baryon asymmetry of the early universe. Here as well the supersymmetric generalization of the models offers various alternatives that have to be explored in detail.

### Own experience

Members of this group have been among the pioneers of the supersymmetric extension of the standard model [1] and have experience in the particle physics as well as cosmological appication of this scheme. Specifically we have an expertise in the study of the mechanism of supersymmetry breakdown and the determination of the resulting soft breaking parameters. Theoretical concepts like the embedding of the models in string theory have been studied recently [2]. This resulted in a specific pattern of masses for neutralinos that have consequences for their relic abundance [3]. We are currently trying to examine this question in connection with a possible existnce of a nonvanishing value of the cosmological constant along the lines of earlier work [4].

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**Goals of the project**

We would like to clarify detailed properties of dark matter candidates that appear in the supersymmetric extension of the standard model. This does not just concern the value of the relic abundance and the fact that these relics are cold, but also more specific questions of e.g. self interactions that might be relevant for the distribution of dark matter in the universe. One such question aims at the abundance of dark matter at the center of our galaxy and its possible influence on the central black hole.

Moreover, present experimental searches, like the ones at accelerators as LEP and the Tevatron restrict the possible candidates for dark matter. Direct searches for WIMPs in our galaxy (e.g. DAMA) seem to give positive evidence at a quite unexpected range, but this result is not confirmed and even questioned (CDMS experiment).

The nature and the properties of dark matter candidates depend crucially on the mechanism of supersyemmtry breakdown and this is one of the central research efforts in our group. It is here that more formal questions having to do with supergravity, unification of coupling constants, string theory and extra dimensions come into play. Current data on (lower) limits on the mass of the supersymmetric partners (not just the dark matter candidate LSP) contrain these models more and more, and give therefore useful indirect information on the LSP.

The models are matured in the meantime in such a way that one can begin to simulate the distribution of dark matter candidates in collaboration with astronomers that have prepared the calculational tools.

Meanwhile we have learned, that the contribution of dark matter $\Omega_M$ to the critical density is not 1 but more between 0.3 and 0.5 while $\Omega_M + \Omega_\Lambda$ is of order unity, with $\Omega_\Lambda$ a contribution that might correspond to a constant vacuum energy (a cosmological constant). Central questions, why this gives critical density and what is the size of the individual contributions have to be addressed from the theoretical point a view. Up to now we have treated these numbers as parameters that have to be determined by experimental observations and it seems now the time to look at this from the viewpoint of the underlying theory and its consistency. In fact, we have to see how the relic abundance of the dark matter in its dependence on the soft supersymmetry breaking parameters might be influenced by the presence of a cosmological constant or the vacuum energy of a slowly varying field (quintessence), which in turn might be connected to the mechanism of inflation in the early universe.

Supersymmetry leads to models of unification of strong, weak and electromagnetic interactions in so-called grand unified theories (GUTs) at a high scale, where bryon number is violated, a mechanism necessary for the generation of a net baryon asymmetry in the universe. The interrelation of this mechanism with the rate of proton decay in GUT theories has to be studied also in view of upcoming experiments that probe the predictions of the simplest model.

**Estimate of resources expected from DFG**

- 1 postdoc position
- 1 PhD student?
- travel money
- money for invitations

**Members of research group relevant for the project**

- Prof. H. P. Nilles
- Dr. D. Ghilencea

- R. Schreyer
- M. Hillenbach

International collaborations with Ibanez(Madrid), Masiero(Triete), Antonadis(Paris), Ross(Oxford) and Barbieri(Pisa).

**Connections to other projects of current SFB proposal**

Connections to High enery experiments, Brock, Hilger, Kobel, Wermes: related theory Dreiner, Nahm and astronomers, Biermann, Falcke, Schneider.

### 2.0.19 Inflation and nonthermal production of gravitini

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#### Abstract

The mechanism of inflation in the early universe solves some cosmological puzzles as the horizon and flatness problems. Simple toy models exhibit the basic properties of inflation, but many detailed questions remain unanswered. One of these questions is the production of particles at the end of inflation. In the framework of broken supersymmetry, the gravitino could be overproduced thermally as well as nonthermally. While the former is not a major obstacle to realistic model building the latter has been argued to be a severe problem. We try to answer this question through direct calculations in a variety of models. We hope that these restrictions will narrow down the number of models for a succesfull inflationary mechanism, and lead to more refined predictions that have to be worked out and confronted with observations.

#### Current status of research

There exist many schemes of inflation, like old, new, chaotic, extended inflation (just to name a few) that try to provide a particle physics description of this mechanism. Usually a given model concentrates on a specific question, but a full satisfactory scheme has not yet been found. Especially the mechanism of supersymmetry breakdown is usually ignored within this discussion. If one tries to calculate the abundance of various field after the inflationary epoch, one is often faced with severe problems. One of them is the possible overproduction of the gravitino. This question has been addressed in the literature up to now only in one-field models with unbroken supersymmetry [1, 2]. It is not clear to us (nor to anybody else) what these observations really imply.

### Own experience

We came across this problem at the COSMO99 meeting in Trieste in discussions with Kallosh, Kofman and Linde, who claimed that there is a severe problem with the nonthermal overproduction of gravitini at the end of inflation. We pointed out to them that their conclusion was premature and that a more complete model was needed to address this question. Meanwhile M. Peloso [3] has worked out a code to compute the nonthermal production of particles in inflationary models with several scalar fields and broken supersymmetry. Specifically we also want to analyze models based on D-term inflation discussed in earlier work of ours [4]

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### Goals of the project

We would like to clarify the question of gravitino production (as well as production of string moduli) in the process of preheating and reheating after inflation. At the moment this appears to be a serious problem, since all existing models point at an overproduction of these relics. However, in many of these models the question of supersymmetry breakdown has not been addressed in a satisfactory way. We will set up various representative classes of models with exhibit inflation in the presence of supersymmetry breakdown. One of them incorporates the Polonyi superpotential, while others are derived from more abstract supergravity models making use of Fayet-Iliopoulos terms. We then intend to compute the production of inflatinos and gravitinos numerically using methods developed by Peloso and coworkers.

These calculations will shed light on some basic questions concerning the coupling (decoupling) of the goldstone fermion in local (global) supersymmetry in the early universe. During the period of inflation, supersymmetry is broken even if the groundstate of the theory at zero temperature is supersymmetric. Thus the nature of the candidate goldstino is time dependent and the "real" goldstino (that is the longitudinal component of the gravitino at zero temperature) might not be produced during reheating. One attempt to avoid an overproduction of gravitini could therefore be a decoupling of the “real” goldstino from the inflaton multiplet at the level of global supersymmetry. The coupling would then be purely gravitational, possibly avoiding a dangerous relic density.

String moduli, i.e. light scalar fields that parametrize the vacuum degeneracy of superstring theories might suffer from the same problem as gravitini. Here as well, one has to discuus possible solutions to this problem.

Given these calculations, it has to be expected that a solution of the problem of overproduction of dangerous relics will only be possible within a very restrictive class of models of inflation, and therefore pose severe restrictions on the mechanism of inflation itself. In fact, a successful mechanism of inflation will necessarily be linked with a satisfactory mechanism of supersymmetry breakdown. With the results expected from the considerations above, we would then be led to a quite restrictive set of multi-field models with a chance to realistically describe exponential expansion in the early universe.

This restricted set of models would then have to be investigated in detail with respect to generic predictions of the mechanism of inflation, that would be linked to phenomena in particle physics through the mechanism of supersymmetry breakdown. This would then allow us to see whether some of the theoretically favoured models, like chaotic inflation or D-term inflation are surviving the test of consistency from other cosmological considerations like the relic density of gravitini and string moduli.

**Estimate of resources expected from DFG**

- 1 postdoc position
- 1 PhD student?
- travel money
- money for invitation

**Members of research group relevant for the project**

- Prof. H, P. Nilles
- Dr. M. Peloso
- Dr. S. Groot Nibbelink
- J. Conrad

- G. Honecker

International collaborations with Quiros(Madrid), Masiero(Triete), Binetruy(Paris), Sarkar(Oxford) and Giudice(CERN).

**Connections to other projects of current SFB proposal**

Connections to work that deals with cosmic background radiation....

### 2.0.20 The dark matter distribution in the Universe on large scales as seen with weak gravitational lensing

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#### Abstract

The nature and spatial distribution of dark matter in the Universe is the central issue of modern cosmology. Weak gravitational lensing, the distortion of distant faint galaxy images by the tidal gravitational effect of intervening matter, provides an ideal tool to study the dark matter distribution, as the light deflection depends on the total (dark + luminous) mass distribution. The statistical properties of the distortion field, that can be obtained from the image ellipticities, immediately translates to the statistical properties of the dark matter distribution, the large-scale structure (LSS). Aim of this project is to exploit this novel technique to constrain the properties of the LSS.

#### Current status of research

Weak gravitational lensing (see Mellier 1999; Bartelmann & Schneider 2001 for recent reviews) employs the fact that light bundles are distorted when propagating through an inhomogeneous matter distribution; the corresponding tidal fields change the observable image ellipticity of distant sources in a predictable way. Since the extragalactic sky is densely filled with faint galaxies, the statistical investigation of their image shapes directly yields information about the (statistical properties of the) matter distribution in the Universe. For example, any two-point statistics of the corresponding distortion field – also called shear – yields a weighted average over the power spectrum of the LSS, which by itself is one of the central quantities to describe the Universe and structure formation. Although this connection had been known for quite some time (e.g., Blandford et al. 1991; Kaiser 1992), only in 2000 was this effect discovered, by four independent teams (Bacon et al. 2000; Kaiser et al. 2000; van Waerbeke et al.

2000a; Wittman et al. 2000). Progress became possible through the great advances in optical detector arrays and in image analysis procedures. A further detection of cosmic shear has been reported very recently (van Waerbeke et al. 2000b), based on observations carried out with the new Very Large Telescope. In this paper, the measured results on cosmic shear were used to derive a relation between the normalization of the power spetrum $\sigma_8$ and the density parameter $\Omega_0$ of the Universe. It turned out that the derived relation is in very good agreement with the normalization based on the local abundance of massive galaxy clusters. Since the latter depends not only on the power spectrum, but also on the statistical nature of the density field – usually assumed to be gaussian – this close agreement is a very strong hint for the Gaussianity of the primordial density fluctuations.

Beside the two-point statistics, the cosmic shear data carry substantially more information about the properties of the LSS. As has been pointed out by Bernardeau et al. (1997), Schneider et al. (1998), van Waerbeke et al. (1999), Kruse & Schneider (1999, 2000), Jain et al. (2000), and others, higher-order statistics, such as the skewness or the peak probability distribution, can be used to test the standard gravitational instability theory for structure growth, the redshift dependence of the power spectrum, and therefore the cosmological parameters $\Omega_0$ and $\Lambda$.

### Own experience

The proposer has been leading a group on gravitational lensing research for about 10 years in which more than 100 refereed publications were written. He first-authored the monograph on the topic (Schneider, Ehlers & Falco 1992). The group played a leading role in the development of weak gravitational lensing, both in theory (see Bartelmann & Schneider 2001 and references therein) and from an observational point-of-view (e.g., Seitz et al. 1997; Erben et al. 2000; Clowe et al. 2000). Our group has also deeply been involved in the development of cosmic shear analysis (Schneider et al. 1998; Schneider 1998; van Waerbeke 1998, Kruse & Schneider 1999, 2000; Reblinsky et al. 1999), and participated in the first detections of the cosmic shear signal (van Waerbeke et al 2000a,b). Furthermore, our group leads a major observational effort to observe cosmic shear with the Hubble Space Telescope, for which 1200 parallel orbits have been assigned.

### Goals of the project

The goal of this project is to exploit cosmic shear in order to obtain the strongest constraints on the LSS and therefore to provide invaluable input to cosmology. Taking into account the near-term perspectives in observational astronomy (e.g., the newly-built wide-field imaging telescopes VST and VISTA, the MEGACAM project at the CFHT etc.) we shall have in the near future a greatly increased amount of data usable for this goal. Therefore the following steps shall be taken:

- Continued participation in the observational programs and the data analysis. This part of the project will be carried out in very close collaboration with the group in Paris, led by Y. Mellier (IAP), and partly with a group at the ST/ECF at ESO, led by W. Freudling. Members of our group (D. Clowe, T. Erben, M. Schirmer) have extensive experience in these aspects. Preparation for, and analysis of the VST photometric data will be the focus of this aspect.

- Theoretical predictions and statistical analysis. Given that the density field in the Universe is highly non-Gaussian at later times, there is no unique prescription for the optimal extraction of cosmological information from the cosmic shear data. Several statistical measures have been suggested, each of them providing one particular view of the picture. The data material will soon become sufficiently large that such optimal extraction methods need to be developed. The fact that we have been able to obtain a first cosmological constraint from cosmic shear measurements (van Waerbeke et al. 2000b) shows that this new cosmological tool has matured. The future possibilities to take photometric redshift information into account when analyzing cosmic shear data need to be explored; a preliminary analysis (Hu 1999) shows that the power-spectrum estimate can be improved by a significant amount when this redshift information is accounted for.

- Refinement of cosmic shear extraction from observations. Whereas detailed investigations have shown that shear signals of the order of 1% can certainly be extracted from deep images of a quality now routinely achieved at the best astronomical sites, it is still unclear whether shears below 1% can be detected, i.e., separated from systematics coming from PSF anisotropies, distorting telescope optics etc. Such small values of the shear are expected on angular scales above $\sim 20'$ which probe the linear regime of structure formation at late times. These scales are of particular importance as they permit a direct comparison with CMB data; together, these two methods will be able to *directly prove* the gravitational instability picture of structure growth and significantly increase the precision of cosmological parameter estimates from CMB measurements alone (Hu & Tegmark 1999).

### Estimate of resources expected from DFG

The long time-span between the realization of the potential of cosmic shear and its first detection indicates the complexity of the technical aspects of this research area. In order to make proper use of the upcoming wide-field imaging data, an experienced researcher is needed who is able to carry out the data analysis using state-of-the-art methods. This can only be done by an experienced post-doctoral researcher who shall also take part of the responsibilities of maintaining the computer system for this project. Given the current sophistication of power-spectrum extraction from noisy data, as has been pioneered for the purpose of the analysis of future CMB data, a significant improvement in the quantitative analysis of cosmic shear data requires the involvement of a post-doc with considerable experience in statistical methods – preferably someone who has been involved with one of the CMB teams. The investigation of the limitations of cosmic shear measurements via simulations and analytical estimates provides an ideal dissertation project which shall be supervised jointly by the proposer and the post-doctoral researcher working on the wide-field imaging data.

### Members of research group relevant for the project

Prof. Peter Schneider, Dr. Douglas Clowe, Dr. Marco Lombardi, Dipl. Phys. Thomas Erben, Dipl. Phys. Hannelore Hämmerle, Dipl. Phys. Michael Schirmer

### Connections to other projects of current SFB proposal

Schau mer mal

### 2.0.21 The mass profiles of galaxies and clusters

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**Abstract**

The nature and spatial distribution of dark matter in the Universe is the central issue of modern cosmology. Weak gravitational lensing, the distortion of distant faint galaxy images by the tidal gravitational effect of intervening matter, provides an ideal tool to study the dark matter distribution, as the light deflection depends on the total (dark + luminous) mass distribution. Measuring the distortion field from the image ellipticities of background galaxies, the tidal gravitational field of the deflector, and thus its (projected) mass distribution can be derived. One can therefore derive the density distribution of these deflectors, either individually (which is possible for clusters of galaxies) or as an ensemble. The current project aims at exploiting these possibilities to test fundamental properties of the dark matter distribution in virialized halos.

#### Current status of research

Weak gravitational lensing (see Mellier 1999; Bartelmann & Schneider 2001 for recent reviews) employs the fact that light bundles are distorted when passing a matter inhomogeneity; the corresponding tidal gravitational field changes the observable image ellipticity of background sources in a predictable way. Since the extragalactic sky is densely filled with faint galaxies, the statistical investigation of their image shapes directly yields information about the matter distribution of the deflectors.

As was first shown by Kaiser & Squires (1993), from the observable tidal field (or gravitational shear) the projected mass distribution of clusters of galaxies can be reconstructed in a parameter-free way. Several modifications have improved the original method and made it more versatile (Schneider 1995; Kaiser 1995; Schneider & Seitz

1995; Seitz & Schneider 1995, 1996, 1997, 1998; Bartelmann et al. 1996; Seitz et al. 1998; Lombardi & Bertin 1998a,b, 1999a,b). These methods have been applied to quite a number of clusters hitherto (e.g., Fahlman et al. 1994; Smail et al. 1995; Squires et al. 1996a,b; Seitz et al. 1996; Kaiser et al. 1998; Hoekstra et al. 1998, 1999; Fischer et al. 1999; Clowe et al. 1998, 2000, Athreya et al. 2000; Lombardi et al. 2000). The results of these studies show a variety of mass-to-light ratios, amounts of substructure, and radial mass profiles; in many cases, cluster galaxies follow the dark matter distribution, whereas in others this is not the case.

The mass properties of individual galaxies cannot be probed with weak lensing as they are not massive enough. However, the lensing properties of galaxies can be statistically superposed, a technique called galaxy-galaxy lensing. It has been successfully applied to a few sets of data (Brainerd et al. 1996; Griffiths et al. 1996; Hudson et al. 1998; Fischer et al. 2000); the main result from these studies is that the dark matter halo of galaxies is very extended, and only lower limit to the tidal cut-off radius have been derived.

### Own experience

The proposer has been leading a group on gravitational lensing research for about 10 years in which more than 100 refereed publications were written. He first-authored the monograph on the topic (Schneider, Ehlers & Falco 1992). The group played a leading role in the development of weak gravitational lensing, both in theory (see Bartelmann & Schneider 2001 and references therein) and from an observational point-of-view (e.g., Seitz et al. 1996; Erben et al. 2000; Clowe et al. 2000). In particular, our group has been at the forefront of cluster mass reconstruction techniques (Schneider 1995; Kaiser 1995; Schneider & Seitz 1995; Seitz & Schneider 1995, 1996, 1997, 1998; Bartelmann et al. 1996; Seitz et al. 1998), and developed the state-of-the-art technique for the analysis of galaxy-galaxy lensing (Schneider & Rix 1997).

### Goals of the project

- The selection of clusters for which mass distributions have been reconstruted up to now was mainly done on the basis of cluster peculiarities: eiher the most massive clusters, the highest redshift clusters, or those which show strong lensing effects in the form of giant arcs. It is therefore unclear how characteristic the results derived from these individual clusters are. The goal of this project is to study the mass distributions of a well-defined cluster sample (e.g., selected by their X-ray flux), and to obtain statistically significant results on their radial mass profile, their elongations, their amount of substructure, and their mass-to-light ratio. In particular, appplying a newly developed method for determining mass profiles (Schneider et al. 2000; King & Schneider 2000), the applicability of the 'universal' dark matter halo mass profile (Navarro et al. 1996, 1997) shall be tested. Several data sets have already been obtained and can be used for this purpose. Furthermore, most of the cluster investigations up to now have been restricted to the inner $\sim 500$ kpc, whereas it would be of utmost interest to follow the profile up to the tidal radius, about a factor of 3 further out in radius; the new wide-field imaging cameras allow us to do so, and one very high quality data set has already been obtained – the shear can be followed right up to the tidal radius in this cluster. It should be stressed that the mass profile in the inner part of the cluster provides a sensitive test for the hypothesis that dark matter particles are weakly dissipative, as that will affect the central density profile; hence, the results of this study has direct implications for the nature of the dark matter particles.

Given the expertise of some Bonn astronomers in X-ray astronomy, these lensing studies shall be complemented with X-ray studies of clusters, making use of the new European X-ray satellite XMM-Newton. Already the first results from this observatory show its great capabilities in studying the mass distribution in clusters. A further constraint on the (baryonic) mass distribution comes from observations of the Sunyaev-Zeldovich effect in clusters, the Compton upscattering of CMB photons. Current instrumental developments at the MPIfR bear the promise that these studies can soon been carried out in Bonn, in which case all three observational techniques shall be combined into a coherent study of cluster mass profiles.

- The results from galaxy-galaxy have been rather sparse up to now, mainly because the data sets used for the analyses have been moderate. The currently available wide-field imaging cameras allow us to use a much larger data set of galaxies, which when supported by photometric redshift estimates can greatly improve the parameter estimates for the dark matter halos of galaxies. The techniques for this are available, e.g., to obtain a much more sensitive probe for the spatial extent of the halo (Schneider & Rix 1997; see also Geiger & Schneider 1999), or to study the flattening of dark matter halos (Natarajan & Refregier 2000). Whereas the previous studies obtained the dark halo properties of the average galaxy population, multi-color photometry can split the lens galaxy sample into various subclasses and investigate the dependence of the halo mass on the classification (early vs. late-type galaxies; high vs. low-redshift galaxies; galaxies in clusters vs. field galaxies). In particular, if cluster galaxies are found to have a different halo size than field galaxies, this would yield invaluable constraints on the formation of clusters and the evolution of their substructure, including the question of how the metal-enriched X-ray gas in clusters was formed. In addition, the detection of a flattening of galaxy halos would yield insight into the formation of galaxies and the relation between the dark and baryonic matter in them. The goal of this project is therefore to exploit the potential of galaxy-galaxy lensing, by applying state-of-the-art analysis methods with high-quality wide-field imaging data that our group has access to.

- Although still quite some time in the future, the Next Generation Space Telescope will provide astronomers with unprecedented observational opportunities. These will revolutionarize the field of dark matter investigations with weak lensing. The proposer has been involved in devising the weak-lensing proposal within the Design Reference Mission for NGST (see also Schneider & Kneib 1998). The experience gained by a young generation of astronomers from the currently proposed project will be of great value when the opportunity arises to use NGST. In addition, owing to the unprecedented depth and angular resolution of NGST, analysis techniques need to be modified substantially; for example, the characteristic redshift of a galaxy observed with NGST is so high that the assmption of having only a single deflector along a line-of-sight certainly breaks down, and new methods for 'redshift tomography' in gravitational lensing need to be developed. This preparation for NGST shall be done to some degree within this project in order 'to be ready', and thus to profit maximally once it flies.

**Estimate of resources expected from DFG**

**Members of research group relevant for the project**

Prof. Peter Schneider, Dr. Douglas Clowe, Dr. Lindsay King, Dr. Marco Lombardi, Dipl. Phys. Thomas Erben, Dipl. Phys. Hannelore Hämmerle, Dipl. Phys. Martina Kleinheinrich, Dipl. Phys. Michael Schirmer

**Connections to other projects of current SFB proposal**

Schau mer mal

### 2.0.22 (Dark) matter distribution in galaxies

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**Abstract**

High-redshift sources, gravitationally lensed and multiply imaged by foreground galaxies, provide one of the most precise measurements of the mass distribution in galaxies; in some cases, mass estimates with accuracies of a few percent have been obtained. In addition to these mass estimates, such multiple image systems allows the study of substructure in the (dark) mass distribution of lensing galaxies. Based on very high precision measurements of such strong lensing systems, we intend to explore the properties of galaxy mass distributions, and in particular their small-scale structure.

**Current status of research**

The bending of light by a gravitational field can be used to measure the distribution of matter causing this gravitational field. The image of the background object, e.g. a distant quasar, can be split into two or more images when the light passes close to a massive object such as a galaxy. One can estimate the total mass of the galaxy as well as its spatial distribution by studying the properties of these gravitationally lensed images of the quasar.

One can also determine the Hubble constant from the study of gravitational lens systems. The light paths of the multiple images are not equal. If the background quasar is variable, the signature of this variability will reach the observer at different epochs from different images. By measuring the 'time-delay' between the images, one can estimate the Hubble constant, provided the mass distribution of the lens is sufficiently well known.

Currently, there are six gravitational lens systems for which this time delay has been measured. The uncertainty in the measurement is less than 10%, and in one case it is 1%. However, it is difficult to get a unique mass model for the lens which dilutes the significance of the Hubble constant determinations. Therefore, it is very important to determine the mass distribution of the lens to much better accuracy than has yet been possible.

For most of the known lens systems, the image positions can be well fit with relatively simple mass models. However, in some cases the flux ratios are extremely difficult to understand, the best example being the quadruple QSO 1422+231; here, no smooth mass distribution has been found which can account for the image positions and flux ratios. Mao & Schneider (1998) have argued that this deficit of the lens models can be remedied with just a small amount of substructure in the lens. Such small amounts of substructure affects the flux ratios, but leaves the time delays basically untouched.

There are now several lens systems for which the presence of substructure provides a natural explanations for their flux ratios which cannot be reproduced with smooth mass profiles. In addition, the accuracy of image position measurements is becoming so impressively good (e.g., Patnaik, Kemball, Porcas & Garrett 1999) that even image position are not easily fitted with simple smooth mass models. These new observations thus open up a new sensitive probe for the substructure in (and around) lensing galaxies.

In fact, the existence of this substructure is expected from theoretical studies of the formation of galaxies. N-body simulations of the large-scale structure in the Universe predict that every massive galaxy shall be surrounded by several hundred of much less massive satellite 'galaxies'. Whereas the Milky Way has a number of satellites, most prominently the Magellanic Clouds, their number is far less than theoretically expected. The low-mass satellites may have had a completely different history of star formation, perhaps blowing out their gas shortly after a first brief period of star-bursting, and since then remain basically dark. These dark satellites would be difficult to detect with any other means than gravitational lensing. Demonstrating their existence, or otherwise, provides one of the most important tests of cold dark matter-dominated structure formation in the Universe.

In addition to the above aspects, we can study the source of background light as a probe of the interstellar medium of the lensing galaxy. The molecules in the ISM can absorb the background light, and one can determine the abundances of various species of molecules and compare them to those in our Galaxy, thereby studying the physical condition and the composition of the ISM of a distant galaxy. As an important spin-off of these absorption line measurements, one can also determine the cosmic microwave temperature at the redshift of the lensing galaxy, thus probing directly the $T \propto (1+z)$-dependence.

### Own experience

Our team has extensive experience in the observations of gravitational lens systems, in particular in radio observations with interferometers and with Very Long Baseline Interferometry (VLBI). The PI has been the discoverer of some of the best studied lens systems (Patnaik et al. 1992, 1993, Winn et al. 2000a, b), and has carried out extensive follow-up studies of many of the known radio lenses (e.g., Patnaik et al. 1995, 1996, 1999, Patnaik & Porcas 1996, Porcas & Patnaik 1996), including the very high precision measurements of image positions with VLBI measurements (Patnaik et al. 1999). Our team was strongly involved in the study of lens systems in the JVAS survey, the first complete lens survey (e.g., King et al. 1998a, b, 1999) and its statistical analysis (King & Browne 1996). Furthermore, our team is experienced in detailed modelling of lens systems (e.g., Kormann, Schneider & Bartelmann 1994a, b), and initiated the research for substructure in lens systems (Mao & Schneider 1998). Schneider (1998) has shown that the lensing effects of the large-scale matter distribution in the Universe on the lensing property of a galaxy can be described by a simple shear term, so that this does not provide an increased level of difficulty. We also have wide experience with molecular spectroscopy of lens systems, that led to the discovery of rather complex molecules at very high redshifts (Menten & Reid 1996, Gerin et al. 1997, Menten, Carilli & Reid 1999).

### Goals of the project

As mentioned above, we aim to study the distribution of matter in distant galaxies through gravitational lensing. We will continue in obtaining very high angular resolution radio observations using VLBI to measure the image positions, brightness distributions and polarisation distributions of lens systems, thereby providing very stringent constraints to lens models. In order to make the best use of the imaging data, a new mapping algorithm shall be developed which accounts simultaneously for the visibility data and the relative image transformation matrices of the individual lensed images. In this way, the most stringent relative magnification constraints will be derived, using both total flux and polarized flux measurements which complement each other.

On the theoretical side, these new constraints will be used to construct mass models for the lenses. As a first step, the best-fitting smooth mass model will be obtained, and checked whether the modeled image positions and flux ratios are compatible with the observed ones. Secondly, we shall allow for the presence of substructure and determine the minimum amount of substructure with which an acceptable fit to the data can be obtained. In principle, we can determine structures in the lens at mass scales of $10^6$ to $10^7$ solar masses. Currently, there are about 6 lens systems which can be used to obtain such stringent constraints on the amount of substructure; with the upcoming Sloan Digital Sky Survey, several hundred new lens systems will be detected, of which a fraction of $\sim 10\%$ can be used for detailed radio follow-up studies including VLBI. Hence, over the course of the next $\sim 5$ years there will be more than 20 galaxies for which we can test for the presence of substructure, and therefore the presence of satellite galaxies which are predicted from cosmological CDM models. The influence of the substructure on time delays, and thus on the determination of the Hubble constant will be derived.

Molecular spectroscopy of the lenses will be carried out to study their interstellar medium, thereby obtaining the chemical evolution and its relation to the star-formation efficiency. Combined with optical studies of these lens systems, the relation between molecular contents and dust obscuration can be derived (note: since a lens allows the observation of the *same* sources through different sightlines through a galaxy, the reddening of images can be obtained directly without any assumptions on the unreddened source spectrum). The current uncertainties of the amount of obscuration, in particular in star-forming systems, provides the major obstacle in understanding the global star formation history in the Universe.

Bonn is an ideal place for carrying out this research, combining the expertise in observations and modelling of lens systems with the presence of hardware, like the Effelsberg 100m radio-telescope, one of the cornerstones for high-sensitivity VLBI experiments, the VLBI correlator, one of only a few in the world and our group has a strong presence at the telescopes such as 30m at Pico Valeta, the 10m HHT at Arizona for molecular spectroscopy research as well as a contributor to the ALMA project.

#### Estimate of resources expected from DFG

The research project outlined above requires the participation of three PhD students. One of them shall be involved in the VLBI observation of radio lens systems, but the main task will be to develop an efficient procedure for the reconstructions of the multiple radio source images using the fact that they are basically linear mappings of each other. This will reduce significantly the noise of the resulting images, and at the same time yield the best estimates for the relative magnification matrices, i.e., that quantity that will be used in the detailed lens modelling. A second PhD student will work on the theoretical aspects of this project, developing modelling tools which yield the constraints on the presence, amounts, and characteristic scales of substructure present in lenses. The substructure studies currently available have been very rudimentary, which is good enough for individual lens systems, but falls short of a systematic study of a sample of well-studied lenses. The third PhD student shall combine molecular spectroscopy data of lens systems with optical observations from the HST, which are publicly available from the CASTLE survey, and study the relation between molecular contents, reddening and obscuration. This project will be a healthy mixture of observational research and theoretical modelling for which Bonn provides a unique location.

### Members of research group relevant for the project

Dr. Alok Patnaik (MPIfR), Dr. Karl Menten (MPIfR), Dr. Richard Porcas (MPIfR), Prof. Peter Schneider (Uni Bonn), Dr. Lindsay King (Uni Bonn).

### Connections to other projects of current SFB proposal

To be filled in later ...

### 2.0.23 Ultra-high energy events in cosmic rays

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#### Abstract

#### Current status of research

Ever since the 1960ies cosmic ray events have been observed with an estimated energy per event of near or above $10^{20}$ eV. After many tests and using many new arrays to measure these events in air fluorescence, in electron/positron airshowres, in muon data underground, the consensus is indeed that these events are particles coming into the atmosphere with an energy up to $3\,10^{20}$ eV. With reasonable values of the galactic magnetic fields, these particles cannot be contained inside our Galaxy, and so must come from outside. The best fit to the data is found with the assumption that these events are protons or Helium nuclei. However, in the ubiquitous radiation field of the big bang, the microwave background, these particles cannot come from farther than about 50 Mpc real travel distance - since in cosmic magnetic fields they may be scattered, the real distance of their site of origin may much closer than this. Assuming a cosmological distribution of sources, the resulting spectrum should show a cutoff near $5\,10^{19}$ eV, and this cutoff is absent in the data; however, if the source distribution is patterned after the galaxy distribution, the discrepancy is much less, although still there.

There are three classes of proposals how to explain these events:

First, they may be the decay products of more massive particles created in the big bang, like topological defects, monopoles or the like. This proposal has the advantage, that the protons start with $10^{24}$ eV and so can come from some distance. However, it follows, that there should be a strong gamma-ray and neutrino background, a test which will be possible in the near future. If there were any correlation with the dark matter distribution, directional signatures should be there.

Second, it may be due to particles that masquerade as protons, but are actually something else, like special low mass monopoles or supersymmetric particles. This may work if these new hypothetical particles do not interact with the microwave background, but interact with the atmosphere hadronically. Low mass monopoles are a natural choice since the cosmological magnetic fields easily accelerate monopoles to energies near and above $10^{21}$ eV. We will be able to test such ideas if we get much better statistics and so pointing, because the statistics of arrival directions, and possible correlations either with the cosmologically local magnetic field, or with distant quasars should be a tell-tale signature. The detailed shower development may also be quite different between particles such as low mass monopoles, supersymmetric particles and protons.

Third, these events at the highest energy may due to a single nearby acceleration site, and then the question is which one: Radio galaxies have been suggested, such as Cen A or M87. For Cen A it is clear that the source does not have today such an acceleration site, and so this proposal requires that Cen A was much more powerful at the time the particles were emitted. The directional scattering, so as to achieve near isotropy in arrival directions, is done in the local sheet of the galaxy distribution in this proposal. For M87 it has been demonstrated some time ago, that the source can accelerate protons and Helium nuclei to the required energy, but then the directional scattering has to be happen in a Galactic halo wind, quite analogous to the Solar wind.

In all these proposals neutrinos at high energy are produced, which may be measureable soon as horizontal airshowers.

### Own experience

Currently Peter L. Biermann is involved in theroetical work with the various groups which operate air shower arrays, such as AGASA in Japan, and HIRES in the US, and AUGER (from Germany Karlsruhe is participating in the construction).

In NRW there is a proposal to build an airshower array across the country using public buildings such as schools as sites. Such an array would not only contribute to public comprehension of basic physics, but also help to complement the AUGER array, which is in the Southern hemisphere. This, however, does require a broad suppoirt in the community.

Peter L. Biermann is one of the co-proposers (for Germany) of the EUSO project, an attempt to observe airshowers from space. This proposal was accepted for study by both the Astronomy Working Group as well as the Fundamental Physics Working Group of the European Space Agency, and has been slated for an accomodation study on the International Space Station.

It would be very useful to work out tests of what EUSO might observe at the highest energy end, in several PhD theses. In this work it may be possible to then determine what happens inside radio galaxies which have a beam dump site, since there we have particles at $10^{21}$ eV crashing into a beam dump with a power near to $10^{46}$ erg/s, and a spectrum which is energetically flat, i.e. $E^{-2}$. This may lead to new tests for various newly proposed particles in extensions of particle theory.

The most recent review by Peter L. Biermann was published at the Puebla (Mexico) meeting, August 2000.

**Goals of the project**

**Estimate of resources expected from DFG**

**Members of research group relevant for the project**

**Connections to other projects of current SFB proposal**

**Connection to other current research grants**