ESI **The Erwin Schrödinger International Institute for Mathematical Physics**

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Scientific Report for 2010

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Preface

The scientific activities of the ESI in 2010 began with a two-month programme on *Quantitative Studies of Nonlinear Wave Phenomena* in January and February, organized by Peter C. Aichelburg (Vienna), Piotr Bizoń (Cracow) and Wilhelm Schlag (Chicago), which was attended by 30 of the key scientists working in this area. The programme focussed on quantitative aspects of nonlinear wave phenomena, with special emphasis on asymptotic decay of linear and nonlinear waves on flat and curved backgrounds, resonances, and the dynamics of collective variables on moduli spaces.

In March and April a two-month programme on *Quantum Field Theory on Curved Space-times and Curved Target Spaces* took place at the ESI. It was organized by Stefan Hollands (Cardiff), Matthias Gaberdiel (ETH Zürich), Volker Schomerus (DESY Hamburg) and Jakob Yngvason (ESI), and investigated the construction and the understanding of quantum field theories on curved 4-dimensional space-time manifolds. Some of the advances in this area are related to ideas that have previously been developed in the context of 2-dimensional conformal quantum field theories, in particular for curved target spaces. The programme brought together 40 experts working on these problems and culminated in a one-week workshop in late March 2010.

May 2010 started off with an intensive one-week seminar on *Number Theory*, organized by Joachim Schwermer (ESI). The aim of this seminar was to introduce young researchers at the PhD and post-doc level to recent developments of current research at the crossroads of number theory and related fields. The workshop consisted of several mini-courses and invited research lectures on a variety of topics ranging from number theory proper over automorphic forms and arithmetic quantum chaos, and was attended by a total of about 30 senior and junior participants.

In May there was also a two-day symposium at the ESI on *Diskrete Mathematik*, a joint venture of the *Fachgruppe Diskrete Mathematik der DMV* and the National Research Network *Analytic Combinatorics and Probabilistic Number Theory* of the Austrian FWF, which was organized by Christian Krattenthaler (Vienna).

The programme *Matter and radiation*, organized by Volker Bach (Mainz), Jürg Fröhlich (ETH Zürich) and Jakob Yngvason (ESI), ran from May 3 – July 30. It had almost 50 participants and was devoted to the quantum mechanical description of nonrelativistic matter (i.e., atoms, molecules, and, more macroscopically, solids or gases), collecting and comparing the diversity of results established by a variety of mathematical approaches.

From early June until August 15 the programme *Topological String Theory, Modularity and Non-Perturbative Physics*, organized by L. Katzarkov (Vienna), A. Klemm (Bonn), M. Kreuzer (Vienna) and D. Zagier (Bonn), focussed on topological properties of gauge- and string theories, which are the basis of our understanding of particle physics and quantum gravity. The programme brought together experts on the theory and application of automorphic forms, on techniques for solving the integrable structures as developed in statistical mechanics and matrix models, and on application of these techniques to the study non-perturbative contributions to the effective action of string- and gauge theory models. Almost 60 mathematicians and mathematical physicists participated in this programme, which also contained workshops on *D-branes, effective actions and homological mirror symmetry* and *topological strings, modularity and non-perturbative physics.*

The programme *Anti – de Sitter holography and the quark-gluon plasma: analytical and numerical aspects* was organized by A. Rebhan (Vienna), S. Husa (Univ. Illes Balears, Spain) and K. Landsteiner (IFT Madrid, Spain) and ran for three months from August – October 2010. This programme studied quantum chromo-dynamics (QCD), the theory of the strong nuclear interactions and focussed on the theory behind some of the expected – and some unexpected – properties of the state of matter in heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory in the USA, for example. Two workshops were part of this programme, one on *AdS holography and the quark-gluon plasma*, and one on *Hot matter*. More than 100 participants visited the ESI for various periods of time during this activity.

The last thematic programme in 2010 was *Higher structures in mathematics and physics*, organized by A. Alekseev (Geneva), H. Bursztyn (IMPA, Rio de Janeiro, Brazil) and T. Strobl (Lyon). This programme ran from the beginning of September until early November 2010 and focussed on recent geometrical developments studied by mathematicians and mathematical physicists. The three main topics were *Generalizations of symplectic and Poisson geometry*, *Higher degree graded manifolds, higher gauge theories and gauged supergravity* and *Quantum groups and quasi-Hopf algebras, Drinfeld associators and applications to low dimensional topology.* The programme hat more than 100 participants and contained a series of minicourses on topics like *Higher gauge theories*, *Supergeometry and differential graded manifolds*, and *Gauged super gravity.*

Due to financial constraints the budgets of some of these programmes had to be cut back at fairly short notice. *I would like to take this opportunity to thank the organizers for their understanding and cooperation, and to congratulate them on organizing excellent programmes in spite of the reduced budget.*

In addition to these major research programmes and their workshop there were a number of independent shorter workshops at the ESI during the second half of 2010.

The *Senior Research Fellows Programme* of the ESI offered four lecture courses for graduate students and postdocs during 2010: *Eisenstein Series* by Neven Grbac (Rijeka), *Quantum Field Theory on Curved Spacetimes* by Stefan Hollands (Cardiff), *E_{11}-symmetry of strings and branes* by Peter West (King's College, London), and *Representations contributing to Cohomology of Arithmetic Groups* by T.N. Venkataramana (TIFR, Mumbai).

As one can see, the scientific activities of the ESI in 2010 were more than satisfactory. In other respects, however, the year 2010 had a sting in its tail:

The end of the ESI as an independent institute.

Things started harmlessly enough. On July 27, 2010, the Minister of Science, Dr. Beatrix Karl, visited the ESI and afterwards sent out a glowing press release about the work done by the Institute with frequent references to the importance of *Nachwuchsförderung*, i.e., of support and training of young scientists (postdocs and PhD students).

Since 2004 the ESI had been running a 'Junior Research Fellows' (JRF) Programme for advanced PhD students and postdocs to allow them to participate in the activities of the ESI. In 2010 this programme supported 27 Junior Research Fellows for varying periods during 2010 to work at the Institute and to participate in its scientific activities.

This enormously successful and internationally very highly respected programme was to come to an end in early 2011. We (the directors of the ESI) discussed this with Dr. Karl, who was very impressed by the JRF Programme and suggested that we discuss options for its extension with one of her section heads.

When we met the section head responsible on October 25, 2010 we were told completely out of the blue that the funding of the ESI would be terminated with the end of 2010.

Thanks largely to the overwhelming response by the international scientific community (including numerous Fields-Medal and some Nobel Prize winners) to the imminent demise of the ESI, the Ministry of Science agreed to provide basic funding to the ESI for the years 2011 – 2014, and possibly until 2015, at the same level as in 2003, and without any compensation for inflation since then. This funding will not go to the ESI directly: the Institute will have to become part of the University of Vienna, through which the funding for the ESI will be channelled.

What is unfortunate, but completely in line with the government's attitude to higher education and scientific training, is that the JRF Programme of the ESI will not be continued beyond 2010 due to lack of funding.

The 'rescue' of the ESI as part of the University of Vienna will bring a measure of financial security, and — at least in the short term — allow the institute to continue its operations (at a noticeably reduced level). In the long run, however, the seriously under-funded university may have to put pressure on the institute to become increasingly involved in graduate education and to reduce its budget for visitors. *In the first few years, the Erwin Schrödinger Institute may be seen as a gift to the university by the Ministry of Science, but in the following years it will be just another player in a zero sum game whose rules will not be conducive to the needs and priorities of a research institute operating at an international level.*

Let me put these concerns about the future aside for the time being and turn to the present. The transition of the ESI from an independent research institute to a 'Forschungsplattform' at the University of Vienna is a complicated process which could easily become a procedural and administrative nightmare. Although negotiations with the university are not yet complete, and although some serious problems are unresolved at the time of writing, I am happy to report that the university is being very helpful in every respect, and that there is justified hope that the Forschungsplattform ESI will be able — under a new directorship — to continue much of the scientific tradition the 'old' ESI has built up over the past 18 years.

Klaus Schmidt — April 2011
President

The ESI in 2010

Management of the Institute

Honorary President: Walter Thirring
President: Klaus Schmidt
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Administration: Isabella Miedl, Maria Marouschek (née Windhager), Beatrix Wolf, Alexandra Katzer
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Budget and visitors: In 2010 the support of ESI from the Austrian Federal Ministry of Science and Research was € 950.866,– (incl. € 100.000,– for the Senior Research Fellows Programme and € 160.866,– for the Junior Research Fellows Programme) and € 29.000,– from the University of Vienna (incl. € 22.000,– for the Senior Research Fellows Programme). The total spending on scientific activities in the year was € 495.911,17 and on administration and infrastructure € 428.150,90.

The number of scientists visiting the Erwin Schrödinger Institute in 2010 was 512, and the number of preprints was 84.

Scientific Reports

Main Research Programmes

Quantitative Studies of Wave Phenomena

Organizers: P.C. Aichelburg (Vienna), Piotr Bizoń (Krakow), Wilhelm Schlag (Chicago)

Dates: January 7 - February 28, 2010

Budget: ESI € 30.827,32

Preprints contributed: [2242], [2243], [2246], [2256], [2268]

Report on the programme

The program "Quantitative studies of wave phenomena" was devoted to linear and nonlinear wave equations, focusing on geometric equations such as wave maps, Yang-Mills equations and Einstein's equations.

The program was attended by 30 participants, distributed more or less uniformly in time during the period of 7 weeks. 25 talks were given. Below we describe briefly some highlights of the workshop (organizers' favourites):

1. *Critical wave maps and Yang-Mills equations:* This has been one of the most intensively studied topics in hyperbolic PDEs during the past 10 years. The top researchers involved in these studies (Joachim Krieger, Pierre Raphael, Wilhelm Schlag, Michael I. Sigal, Michael Struwe) presented the state of art in the field. Krieger discussed the methods of concentration compactness which he used together with Schlag to prove global regularity of wave maps for negatively curved targets. Raphael and Sigal described very recent results on the detailed asymptotics of blow-up for equivariant wave maps into the two-sphere. These results provide a remarkably satisfactory confirmation of conjectures made by Piotr Bizoń and collaborators on the basis of numerical and heuristic considerations. Struwe showed one of the first new results on a supercritical wave equation in two spatial dimensions.

2. *Linear waves on curved backgrounds:* This is a hot subject in geometric analysis. The goal is to obtain local decay estimates for waves in the presence of trapping. Such estimates are a necessary first step in proving nonlinear stability of the Kerr black hole. Roland Donninger and Wilhelm Schlag discussed their recent results on almost optimal decay estimates for wave tails on the Schwarzschild black hole which they obtained (together with Avy Soffer) using an integral representation of solutions of linearized equations. Lars Andersson presented his recent work with Pieter Blue in which they make use of the hidden symmetry of the Kerr solution to circumvent the problem of trapping.

3. *Dissipation by dispersion:* This was a leitmotive of the workshop. Avy Soffer gave a pedagogical review of the problem which served as a background for further discussions. Maciej Zworski gave

two talks on the role of resonances (quasinormal modes) in the process of dispersion of waves on unbounded domains.

4. *Numerical simulations of nonlinear waves:* In a very lively presentation Matt Choptuik showed his recent work with Frans Pretorius on formation of black holes in head-on ultrarelativistic collisions of two gravitating solitons. Istvan Racz described a new framework which allows to resolve the singularity forming inside a black hole in gravitational collapse. Andras Laszlo presented GridRipper, a new spectral code for 3d simulations of Einstein's equations. Vincent Moncrief introduced a new formulation of conformally compactified Einstein's equations which is regular at future null infinity andOliver Rinne showed how to implement this formulation numerically in axial symmetry.

The program was extremely stimulating. We received a very positive feedback from the partipants concerning the impact of the program on their research. During the workshop several new collaborations were initiated and many old ones were continued. In near future a number of publications is expected to appear as a direct result of the research during the workshop. Besides senior participants, we also invited several promising young scientists (from Cracow, Golm, and Budapest) to provide them an opportunity to meet leading researchers in the field.

Here is a list of specific collaborations during the programme:

1. *Weak solutions of the Einstein-Euler system (Alan Rendall, Philippe LeFloch).* Under the assumption of Gowdy symmetry on T3, low regularity matter spacetimes were constructed. These spacetimes admit impulsive gravitational waves in the metric and shock waves in the fluid. Using a distributional formulation of the Einstein-Euler equations, the existence of a maximal future development was established. So far, 3 new papers were submitted to the ESI preprint series.

2. *Gravitational collapse for the Einstein-Vlasov system (Alan Rendall, Juan Velazquez).*

3. *3d simulations of the Einstein equations (J.M. Martin-Garcia, Vince Moncrief, Istvan Racz, Oliver Rinne).* During the workshop J.M. Martin-Garcia gave an informal presentation of his xAct tools for tensor computer algebra in Mathematica. This presentation was a starting point for intensive discussions on the possibility of constructing a spectral code for numerical simulations of Einstein's equations based on the decomposition of the metric into spherical tensor harmonics.

4. *Long-time simulations of black hole spacetimes (Peter Aichelburg, Andras Laszlo, Istvan Racz, Andrzej Rostworowski)* It has been shown recently by Bizoń and Rostworowski that the late-time tails in relaxation-to-equilibrium processes have a nonlinear origin. An example of such a process is the formation of a stationary black hole in gravitational collapse, however the numerical simulations of this process are very difficult. The goal of the project is to use the new formulation of Einstein's equations, based on an adaptive lapse function, to perform very long stable simulations and study nonlinear tails.

5. *Heat flow for harmonic maps (Pawel Biernat, Piotr Bizoń, Juan Velazquez).* Although this is an old subject, very little is known about the precise asymptotics of singularity formation, not to mention the continuation beyond a singularity. The goal of this project is to construct self-similar shrinking and expanding solutions by ODE techniques and analyse the (non)-uniqueness of gluing shrinking and expanding self-similar solutions through a singular point. This is a mixed analytical and numerical project; one of the key numeriacal issues is an implementation of a finite-difference moving mesh code which would be able to resolve the structure of singularity formation.

6. *Codimension-one attractors for the nonlinear Klein-Gordon equations (Piotr Bizoń, Tadek Chmaj, Nikodem Szpak).* Nonlinear Klein-Gordon equations admit unstable stationary solutions which can act as attractors for non-generic evolutions. The goal of this project is to describe in detail the intermediate asymptotics of convergence and departure from the unstable attractor.

7. *Stability of wave maps (Peter Aichelburg, Roland Donninger).*

Investigations on the stability for equivariant wave maps continued during the program. More precisely, it is known from numerical results that for co-rotational wave maps from Minkowski space into the three sphere, the self-similar ground state acts as a local attractor. However, despite of several efforts a rigorous proof of stability is still open. An essential step in proving linear stability was derived and will be presented in a forthcoming paper. Work on non-linear stability is still in progress.

Invited scientists: Peter Christian Aichelburg, Lars Andersson, Marius Beceanu, Pawel Biernat, Piotr Bizoń, Tadeusz Chmaj, Matthew Choptuik, Roland Donninger, Marek Fila, Peter Forgacs, Pierre Germain, David Klawonn, Joachim Krieger, Andras Laszlo, Philippe G. LeFloch, Marek Lipert, Jose M. Martin-Garcia, Vincent Moncrief, Istvan Racz, Pierre Raphael, Alan Rendall, Oliver Rinne, Andrzej Rostworowski, Wilhelm Schlag, Israel Michael Sigal, Walter Simon, Avraham Soffer, Michael Struwe, Nikodem Szpak, A. Shadi Tahvildar-Zadeh, Juan Velazquez, Maciej Zworski.

Quantum Field Theory on Curved Space-Times and Curved Target-Spaces

Organizers: M. Gaberdiel (Zürich), S. Hollands (Wales), V. Schomerus (Hamburg), J. Yngvason (Vienna)

Dates: March 1 - April 30, 2010

Budget: ESI € 33.897,08

Preprints contributed: [2240], [2244], [2248], [2250], [2253], [2266]

Report on the programme

The aim of the programme was to bring together leading researchers working on the mathematical foundations and analysis of quantum field theory (QFT), including its applications in string theory. QFT was invented in physics in order to reconcile the essential features of quantum mechanics and relativity theory, which in turn had only been invented shortly before at the beginning of the 20th century. However, it was soon recognized from a variety of viewpoints that, in order to get a coherent theory, new mathematical structures were needed. Despite the vast progress that has been made in the subsequent years on this subject, these structures are still being developed, and in this sense the problem has remained largely unsolved today. The fact that the mathematical construction of one particular class of QFT's, gauge theories, has been named to be one of the famous "Clay Millenium Problems" is a testimony to this.

The programme was devoted to recent progress that has been made in the understanding of the mathematical foundations of QFTs. A particular emphasis was put on structures that are essential/survive when such theories are considered in the context of general curved Euclidean or Riemannian spacetime manifolds, or also curved target space manifolds. This is needed on the one hand to get a theory that is closer to a unified theory of all fields in nature, including the gravitational field, but also in the context of string theory, where one has to deal with conformal quantum field theories on Riemannian surfaces. There were two broad themes that were touched upon, from a great variety of different viewpoints and within different approaches/frameworks, in many research talks and also informal discussions. These can be summarized under the categories (i) Algebraic structures within QFT's, especially in the context of two-dimensional conformal field theories, but also for more general theories in higher dimensions (ii) Issues related to the renormalization problem in quantum field theories, in particular the algebraic structures underlying this problem, both in the context of flat as well as on curved spacetimes. It was certainly one of the most appealing aspects/successes of this programme that these general themes were seen to relate various rather different communities in mathematical quantum field theory, hence making it possible to discuss and compare, in the setting of a prolonged programme, many of these complementary approaches. In addition to these two general themes, there were also several other interesting contributions on a variety of topics, such as on entanglement entropy, entropy/Hawking radiation in black hole spacetimes, quantum inequalities in 2d-conformal field theories, and the propagation of quantum fields on spacetimes with naked singularities. The contributed talks in the programme related to the structure of perturbation theory on curved/flat spacetimes (Kreimer, Fredenhagen), as well as the talks on QFT on curved spacetimes (Dappiaggi, Ishibashi) were complemented by the Senior Fellow lecture series of of S. Holland, and were felt to be useful in particular by graduate students from Vienna and outside.

Summary of research activities

1. *Algebraic and analytic aspects of renormalization in QFT*

    (a) *Hopf-algebras, forest formulas in perturbative renormalization* Perturbative methods are the most important tools in order to extract quantitative predictions from QFT, and they also are able to give many conceptual insights about the structure of QFT, short distance behavior, anomalous dimensions, gauge/BRST invariance etc. Any perturbative approach has to deal with the problem of renormalization, which may be solved by different methods. Recent developements in the field have in part focussed on the combinatoric/algebraic structures behind this problem, and also its relations to the problem of resolving singularities in algebraic geometry. Two talks in the programme (by Kreimer and Fredenhagen) were devoted to this topic, focussing primarily on the emergence of certain tree-like structures (see also next item) that arise in the renormalization process, and which are known to be describable by certain Hopf-algebras of rooted trees (Kreimer). Fredenhagen's talk explained how these structures can be understood–and naturally arise–within the Epstein-Glaser framework of renormalization.

    (b) *Tree structures in non-perturbative renormalization* Tree-like structures also featured in the presentation by Rivasseau on techniques for attacking the non-perturbative construction of certain quantum field theories (see also next item). In this context, trees and forests have been known to arise for quite some time, e.g., when trying to make sense of non-Gaussian perturbations of Gaussian measures, as one has to do in order to meaningfully define the Euclidean path integral of an interacting quantum field theory. These tree-like structures are related –but not identical–to those appearing in perturbative approaches (see previous item), and they can be viewed, as explained in the presentation, as a sort of diagrammatic expansion that is one level coarser than that in terms of Feynman diagrams but has better convergence properties and hence may be used where perturbation theory diverges.

    (c) *Non-perturbative construction of quantum field theories via RG-flow equations* The Wilson-Wegner-Polchinski flow equation method provides an alternative ansatz for giving a non-perturbative definition of interacting quantum field theory models. In the talk by Salmhofer, this method was reviewed. Then, work in progress was outlined how it may be combined with certain estimation techniques in order to obtain a conceptually clear and transparent non-perturbative construction of certain interacting quantum field theories in low spacetime dimensions that are not accessible to an exact solution.

2. *Algebraic structures in conformal field theories and their perturbations*

   (a) *Vertex algebras in perturbative QFTs, and related algebraic structures* Vertex algebras have for some time known to be one possible mathematical framework for 2-dimensional conformal field theories, as well as a useful tool in their analysis. In the talks by Olbermann and Nikolov, their potential importance was stressed also for higher dimensional quantum field theories, including even those without conformal invariance. In Olbermann's talk, the emphasis was put on consistency conditions for the operator product expansion (OPE) in such theories, and how such conditions can be encoded in an algebraic structure that is a generalization of the ordinary vertex algebras in 2d. Perturbation theory can then be formulated in terms of a certain Hochschild-type cohomology ring associated with this algebraic structure. A further important new insight is that, in the presence of non-linear field equations, the perturbation series can be explicitly constructed, and this leads to a potentially new technique for doing perturbative calculations [see also1)] for the OPE coefficients. However, the renormalization problem so far remains unsolved in this framework. Similar ideas related to the use of non-linear field equations were also presented by Nikolov, and his approach also seemed to have the potential to yield information about the algebraic properties of the function rings to which the n-th order perturbative contribution to an OPE coefficients belongs. There was also a presentation by Todorov on an approach to "globally conformal QFT's" in higher dimensions that is also based on various consistency conditions.

   (b) *Algebraic structures underlying 2d-conformal field theories, including boundaries* Conformal field theories on spaces with boundaries were a prominent general theme of the programme, both in many discussions, as well as in several talks. In the talk by Longo, it was explained how boundary conformal field theories (BCFT's) arise and are encoded in the operator algebraic approach to QFT. The boundary serves as an interface in order to splice together left and right-moving components, each of which are encoded in certain nets of "chiral" operator algebras. It is also possible to perturb this situation in order to obtain even non-conformal BQFT's, and Longo reported on recent joint work with Witten how such perturbations are encoded in certain 2-body S-matrices that also arise in the study of integrable QFT's.

   One may also use the knowledge of the boundary theory to reconstruct the corresponding bulk theory. In the language of tensor categories, this programme has recently been developed by Fuchs, Runkel and Schweigert for the case of 'rational' conformal field theories. More recently, Gaberdiel and Runkel have generalised the idea to a certain class of logarithmic conformal field theories. In particular, they have now managed to construct an intereresting logarithmic bulk theory at $c = 0$ [6] in this manner. Logarithmic conformal field theories at $c = 0$ play an important role in a number of statistical physics applications, as well as in the context of string theory on AdS spaces.

   Fuchs and Schweigert have also continued their analysis of defects using similar ideas [7, 10, 1, 5, 8].

   (c) *K-theoretic interpretation of the fusion ring in 2d-conformal field theories* A particular version of K-theory, the so called "twisted equivariant" version, has been known to possess an intimate connection to the Verlinde ring in 2d-CFT's since the work of Freed, Hopkins, and Teleman. This connection has been established for certain CFT's based on loop groups over a compact Lie-group G, and the K-theory ring in question is related to this group. Gannon gave an overview over these developments in two lectures, and reported on recent progress to shed further light on this correspondence (recent work with Evans).

3. *Black hole/entanglement entropy, Hawking radiation, holography*

   (a) *Holographic approach to entanglement entropy* Entanglement entropy is a measure of the correlations in a state between observables located in different regions of space. Takayanagy gave an overview of recent developments in the context of quantum field theory on curved and flat spacetimes. As is well-known from a variety of different viewpoints, the entanglement entropy associated with a given region of space is formally infinite, and has to be defined first in a theory with UV-cutoff Λ, or with a "thickened" boundary of the region. As has been known for some time, the entanglement entropy is then $\sim \Lambda^2 A$, where A is the surface area of the region, which is strongly reminiscent of the famous area law for black hole entropy by Bekenstein. One can also study subsequent terms in the expansion in Λ, however, and some of these terms have been computed recently in the context of CFT's. Another approach to the problem to these quantities is via the AdS-CFT correspondence, where the computation boils down to finding certain minimal surfaces in AdS space with a fixed boundary on the conformal boundary of AdS. Such holographic calculation give a simple but striking illustration of the emergence of various known general inequalities between entanglement entropies associated with different regions (Lieb-Ruskai), that are normally proven using trace inequalities for various density matrices.

   (b) *Construction of physical states on Schwarzschild spacetime* The analysis of quantum field theory on Schwarzschild spacetime leads to the prediction of the famous Hawking effect. However, this derivation is based on certain assumptions about the nature of the underlying quantum state, which are reasonable, but partly unproven. Dappiaggi presented work on the construction of physically interesting states on the Schwarzschild spacetime that is based on the idea of prescribing the desired state via its boundary value on certain characteristic surfaces, namely, the horizon and null-infinity. In order to make this construction work one needs detailed information about the nature of classical solutions to the wave equation on Schwarzschild spacetime, especially estimates about the asymptotic behavior of solutions for late times. Such estimates have only recently been obtained in highly acclaimed work by Dafermos and Rodniansky, and the construction of the states under consideration is based crucially on these estimates by Dafermos and Rodniansky.

4. *Other topics*

   (a) *Quantum inequalities in 2d conformal field theories* In classical Lagrangian field theory, the energy density associated with a field is normally a manifestly non-negative expression. However, the corresponding operator in QFT is known to be unbounded from below and hence can produce negative expectation values in suitable states. In many QFT's, "quantum inequalities" are known to exist which place bounds on the expectation values of weighted averages of the energy-density operator. Fewster gave a review on recent progress related to quantum inequalities for conformal field theories. Such inequalities can be stated simply in terms of the central charge. Furthermore, one can also determine analytically the full probablility distributions for the smeared energy-density operator in certain states (e.g. vacuum).

   (b) *Propagation of fields on spacetimes with singularities* Spacetimes dynamically evolving according to the field equations of general relativity have a strong tendency to form singularities. The quantum treatment and even just the classification of such singularities into "dangerous" and "harmless" is an important but largely open problem. Ishibashi presented an approach to this problem that is based on considering quantized test fields on a class of singular spacetimes whose singularities can be effectively modelled as some sort of (possibly conformal- etc.) boundary. The possible dynamical laws describing the field evolution are defined using self-adjoint extensions of the Hamiltonian. Different self adjoint extensions correspond to different boundary behavior. In some examples these can be classified.

(c) *Derivation of self-force and radiation-reaction on particles propagating in external fields* Wald gave an overview talk on the status of the self-force type equations and radiation reaction for particles propagating on a fixed curved spacetimes, and for charged particles propagating in an external electromagnetic field.

(d) *Dualities between 2d quantum field theories* Teschner gave an interesting new viewpoint on known self-duality of the 2-dimensional Liouville field theory. According to this perspective, if the theory is defined perturbatively for a given set of coupling parameters, then the counterterms needed for the renormalization of the divergent integrals that come up at each order generate a counterterm-Lagrangian that can be viewed as the Lagrangian of the theory with the dual coupling parameters. Evidence for this conjecture was presented, and it was also argued that a similar behavior would occur for other models with known dualities.

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Invited Scientists: Costas Bachas, Henning Bostelmann, Jacques Bros, Detlev Buchholz, Daniela Cadamuro, Sebastiano Carpi, Nils Carqueville, Ben Craps, Claudio Dappiaggi, Henri Epstein, Christopher Fewster, Klaus Fredenhagen, Jürgen Fuchs, Matthias Gaberdiel, Terry Gannon, Oliver Gray, Daniele Guido, Rudolf Haag, Jan Holland, Stefan Hollands, Akihiro Ishibashi, Wolfgang Junker, Yasuyuki Kawahigashi, Michael Kay, Anatoly Konechny, Christoph Kopper, Dirk Kreimer, Roberto Longo, Valter Moretti, Ugo Moschella, Volkhard Müller, Nikolay Mitov Nikolov, Nicola Pinamonti, Andreas Recknagel, Karl-Henning Rehren,Vincent Rivasseau, Ingo Runkel, Manfred Salmhofer, Jacobus Sanders, Volker Schomerus, Christoph Schweigert, Rafal Suszek, Tadashi Takayanagi, Jörg Teschner, Ivan Todorov, Rainer Verch, Robert M. Wald, Zhitu Wang, Jakob Yngvason, Nelson Yokomizo.

Matter and Radiation

Organizers: J. Fröhlich (Zürich), V. Bach (Vienna), J. Yngvason (Vienna)

Dates: May 5 - July 30, 2010

Budget: ESI € 40.725,63

Report on the programme

From 1-May-2010 through 31-Jul-2010, we organized a scientific program on the mathematical description of the interactions of quantum-mechanical matter and light at ESI Vienna. A central part of the program was a workshop held from 31-May-2010 through 18-Jun-2010.

Quantum electrodynamics (QED) is the theory of interactions of electrons and positrons with the quantized radiation field. Relativistic covariance requires a description of electrons and positrons in terms of the second-quantized Dirac equation. For electrons at low energy, this description can be approximated by the usual nonrelativistic Schrödinger equation. While the resulting theory, called nonrelativistic QED, violates principles of special relativity, it describes many physical phenomena qualitatively and quantitatively rather well; especially the interactions of atoms and molecules with the quantized radiation field. At the same time, nonrelativistic QED admits a sound mathematical formulation, and our understanding of basic physical phenomena such as the emission and absorption of light quanta by atoms and molecules can be confirmed by mathematical proofs.

During the past sixteen years or so, many important problems in nonrelativistic QED have been studied mathematically:

(a) Binding, i.e., existence of a ground state, of atoms and molecules coupled to the quantized radiation field,

(b) Binding in other models, like the spin-boson model, Nelson model, and translation invariant models (for a fixed total momentum),

(c) Instability of excited states and existence of resonance states of atoms and molecules coupled to the quantized radiation field,

(d) Asymptotic completeness of scattering theory at low energy,

(e) Analogous questions for open quantum systems at nonzero temperature.

Our program had two goals, namely,

- to review the diversity of results in nonrelativistic QED related to (a)-(e) established so far and
- to find new, challenging open questions that emerge from these and other results.

These objectives were clearly reflected in the workshop program. Not all contributions to the workshop were related to these two goals, but the majority was. Here we list those talks that relate to (a)-(e):

- *Edgardo Stockmeyer* has been working on the transcription of nonrelativistic QED to *pseudo*relativistic QED. This poses new challenges, as the pseudorelativistic kinetic energy yields a weaker uncertainty principle and, furthermore, is non-local.

- *Jean-Marie Barbaroux* and *David Hasler* belong to different research teams that both work on the question of analyticity of the ground state energy of a hydrogen atom coupled to the quantized radiation field as a function of the fine structure constant α. Barbaroux presented elaborate estimates that prove the presence of logarithmic factors $\alpha^p \ln(\alpha)$ in the asymptotic expansion of the ground state energy, thus ruling out analyticity. Hasler's result complement Barbaroux' very nicely. He has shown that the origin of the lack of analyticity lies in the dependence of the nuclear (proton) charge on α; if the Coulomb attraction to the nucleus were fixed then the dependence of the ground state energy on α through minimal coupling is analytic. Results similar to Barbaroux', but older and less precise, were presented by *Christian Hainzl*. *Abdelmalek Abdelsallam* demonstrated the analyticity of the ground state energy in the perturbation parameter for the spin-boson model by completely different methods that originate in statistical mechanics.

- Scattering theory of models of nonrelativistic QED was the topic of the talks by *Marcel Griesemer*, *Wojciech Dybalski*, *Jeremy Faupin*, and *Jacob Schach Møller*. Griesemer demonstrated that a scattering-theoretic definition of "the charge pushed out to infinity" in the description of the photoelectric effect is well-defined and appropriate. Dybalski presented interesting new results in scattering theory formulated in the framework of axiomatic quantum field theory. The complexity of scattering theory even for massive translation invariant Nelson-type model became transparent in Møllers talk. Faupin derived local decay estimates by establishing a limiting absorption principle for models of nonrelativistic QED.

- The role of entropy in the dynamics of classical and quantum statistical mechnical systems was clarfied in two talks presented by *Claude-Alain Pillet* and *Vojkan Jaksic*. Open quantum systems and return to thermal equilibrium/NESS was addressed by *Marco Merkli*, who showed how the formulation of nonequilibrium phenomena in terms of Liouvilleans is not only the key for understanding thermal relaxation, but also for understanding decoherence of small systems, such as qubits, when coupled to a heat bath. *Wojciech de Roeck* presented an impressive proof of thermal relaxation for models that, so far, had resisted a mathematically rigorous analysis, such as a small system consisting of a single free particle coupled to a massless quantized free field.

- Quite a few talks revolved around the mean-field limit or other effective theories of many-particle systems; e.g., the presentations by *Thomas Chen*, *Stephane de Bievre*, *Heinz Siedentop*, *Mathieu Lewin*, *Peter Pickl*, and *Benjamin Schlein*. The mean-field limit has received a lot of attention in recent years. Especially Pickl, a former postdoctoral fellow at ESI, made a strong impression by giving a simple proof for the convergence of many-body quantum dynamics to the mean-field limit.

We feel that our program achieved its goals. During and after the workshop, many collaborating teams met at ESI and continued their joint projects or communicated their reults to other teams present at the same time. They all gratefully acknowledge the hospitality at ESI. The great working conditions at ESI - in the heart of Vienna, one of the worlds major cultural centers - the friendly and very helpful ESI-staff, the lively atmosphere at the Institute, and the generous support from ESI made this program a great success!

Invited scientists: Abdelmalek Abdesselam, Walter Aschbacher, Volker Bach, Jean-Marie Barbaroux, Immanuel Bloch, Jean-Bernard Bru, Detlev Buchholz, Thomas Chen, Stephan De Bievre, Dirk-Andre Deckert, Jan Derezinski, Wojciech De Roeck, Wojciech Dybalski, Jeremy Faupin, Felix Finster, Rupert Frank, Juerg Froehlich, Christian Gerard, Gian Michele Graf, Marcel Griesemer, Jean-Claude Guillot, Christian Hainzl, David Hasler, Ira Herbst, Vojkan Jaksic, Martin Koenenberg, Carolin Kurig, Mathieu Lewin, Elliott Lieb, Philippe Martin, Oliver Matte, Marco Merkli, Walter Pedra, Peter Pickl, Claude-Alain

Pillet, Manfred Salmhofer, Jacob Schach Møller, Benjamin Schlein, Robert Seiringer, Gora Shlyapnikov, Heinz Siedentop, Israel Michael Sigal, Avy Soffer, Jan Philip Solovej, Herbert Spohn, Edgardo Stockmeyer, Stefan Teufel, Frank Verstraete, Matthias Westrich, Jakob Yngvason, Gang Zhou, Peter Zoller.

Topological String Theory, Modularity and Non-Perturbative Physics

Organizers: L. Katzarkov (Vienna), A. Klemm (Bonn), M. Kreuzer† (Vienna), D. Zagier (MPI Bonn, College de France, Paris)

Dates: June 6 - August 15, 2010

Budget: ESI € 32.592,71

Preprints contributed: [2257], [2299]

Report on the programme

The activity brought together physicists working on string theory, gauge theory and matrix models with mathematicians with expertise in the fields of homological mirror symmetry, Gromov-Witten theory and automorphic forms.

Since the formulation of topological string and field theories by Schwarz and Witten in the eighties, physical methods of of solving topological field - and string theories have lead to a multitude of highly nontrivial conjectures. Different then the ones from generic field - and string theories these conjectures are mathematical relevant, because the observable as well as the path integral in topological theories are either already mathematically well defined or at least such a definition is within reach. The most prominent examples for such conjectures are Mirror Symmetry, the S-dualities between weakly and strongly coupled field and string theories, as well as large N-dualities relating open- and closed string theories. The idea of the activity was on the one hand to make progress in formulating the above mentioned conjectures mathematically precisely, which makes them often more far more general than their physically motivated origins, and eventually turning them into theorems. On the other hand topological theories are models for and in fact subsectors of realistic physical models. Therefore more physical lessons can be drawn from them and further physical applications should be developed.

The first greater activity of the program was the workshop "D-branes, Effective Actions and Homological Mirror Symmetry." It run from the 21st -30st June of 2010 and was devoted to homological mirror symmetry and their physical applications.

Mathematically Mirror Symmetry has lead to surprising new methods to calculate Gromov-Witten and related symplectic invariants on Calabi-Yau manifolds. For example it relates the generating functions of the closed Gromov-Witten invariants or BPS invariants on the Calabi-Yau manifold M to automorphic forms reflecting discrete symmetries acting on the complex structure moduli of the mirror manifold W, which are captured by the variation of Hodge structures.

Combined with physical constructions, which map the gauge - or string coupling to complex moduli, such as Seiberg-Witten theory, type II/heterotic string duality and F-theory, the study of automorphic forms has become important to capture non-perturbative physics in gauge — and string theory.

Mirror symmetry applies also to open string theory with supersymmetric D-branes as boundaries. The latter version lead to the formulation of homological mirror symmetry (HMS) stating the equivalence of the derived category of coherent sheaves on M called $D(M)$ – a complex structure-dependent category – to the Fukaya category $F(W)$ of W, defined by Floer homology of Lagrangian sub manifolds. A somewhat simplified version is as follows: Let $\mathcal{D}(M)$ be a differential graded model for $D(M)$, and similarly $\mathcal{F}(X)$ the A_∞-category underlying $F(X)$. Then there is a full and faithful A_∞-functor

$$\mathcal{F}(W) \longrightarrow \mathcal{D}(M)$$

which becomes an equivalence after a suitable formal completion on the left hand side. In particular, $F(W)$ is identified with a full sub category of $D(M)$.

The categorical version of HMS has been proven in many cases for compact manifolds. One of main goals of this workshop was to extend HMS to open manifolds and show isomorphism of the noncommuatative Hodge structures involved. This goal was achieved in [19] and [16].

Two other directions came out of HMS - developing new categorical invariants and using HMS to attack long standing questions in classical algebraic Geometry. These directions were discussed in the lectures by Kontsevich, Katzarkov, Iliev, Ballard, Favero and were recorded in the following papers: [19], [18], [17].

In the presentations of the workshop we aimed for longer and, as far as possible, self consistent presentations on key topics of HMS:

- Mohammed Abouzaid, Ludmil Katzarkov, Maxim Kontsevich and Toni Pantev presented new results related to Fukaya categories
- Matrix factorization, effective actions, and D-brane mirror symmetry and superpotentials were summarized by the physicists Richard Garavuso, Manfred Herbst, Johanna Knapp, Emanuel Scheidegger. Nils Carqueville talked about quiver gauge theory and topological strings.
- Serguei Barannikov and Yoannis Vlassopoulos presentations centered around A_∞ algebras topological quantum field theory and matrix models.
- Albrecht Klemm and Jan Soibelmann talked about the relation of Donaldson-Thomas invariants to modular forms and integrable systems.
- Grigory Mikhalkin gave an introduction to tropical geometry and Mark Gross gave applications of the latter to mirror symmetry.
- Mixed Hodge structures were discussed in the talks by Gregory Pearlstein and related to Fukaya categories by Ludmil Katzarkov and Maxim Kontsevich
- Matt Ballard, David Favero and Ludmil Katzarkov lectured on spectra of categories.
- Denis Auroux talked about "Mirror symmetry for blowups and hypersurfaces in toric varieties."
- A. Efimov talked about "Formal completion of a category along a subcategory" and "HMS for $P^1 \setminus \{\geq 3 \text{ points}\}$." Charles Doran talked about "Modular Invariants for Lattice Polarized K3 Surfaces" and "Toric Hypersurface Normal Forms and the Kuga-Satake Hodge Conjecture."

The second greater activity was the conference "Topological Strings, Modularity and non-perturbative Physics," which took place from July 19 - 28, 2010.

Particular fruitful is the study of strong weak/coupling dualities and large N-dualities, because they turned out to be key sources of insights into the non-perturbative behavior of physical theories. To study such effects in physics from first principles, one has to consider the simplest examples, which for both gauge- and string theory are given by matrix models, which admits large N expansions. Since the early work of Penner and Kontsevich on the intersection numbers in the moduli space of curves and Matrix Airy functions, matrix model techniques have played an increasing role in the analysis of topological string theory.

As already mentioned in the context of Mirror Symmetry, the symmetries discovered in the topological theories are often automorphic groups like $SL(2,\mathbb{Z})$ and correspondingly their correlations functions are automorphic forms. For this reason we were particular lucky to have with Don Zagier a world expert on modular forms among the organizers.

The correlation functions of topological theories receive in a controlled way contributions from the BPS states of the supersymmetric theories and can be thought as generation functions for the multiplicities of the latter. In applications to gravity these BPS states carry the entropy of supersymmetric black holes. In this context the stability of BPS states and the wall-crossing formulas for their degeneracies are of utmost importance. These wall-crossing formulas are related to other interesting phenomena in mathematical physics. One incarnation of walls of marginal stability are Stokes lines as was discussed in the context of matrix model by Marcos Mariño.

As explained in the talks by Boris Pioline and Sergei Alexandrov they are also relevant to the calculation of the metric on the Hyper-Kähler moduli space of $N = 2$ supersymmetric theories. More recently it has been realized that wall-crossing effects and mock modularity are closely related. Examples for this relations were given in the talk of Don Zagier.

Many of these construction are based on symmetries which are particularly simply realized on the topological sector of supersymmetric theories. These topological sectors determine the leading terms in the low energy effective action of supersymmetric theories. Generally dualities and their application are best understood for theories with extended supersymmetry algebras labeled by the number N of super symmetry generators. The physically most interesting and mathematically most challenging situation is $N = 1$ supersymmetry in 4d as realized, e.g., by string compactification of type II string on Calabi-Yau threefolds in the presence of supersymmetric D-branes and/or fluxes.

For the conference we had four overview talks lasting up to five hours each on a subject which, as explained above, is central for the understanding of non-perturbative physics.

- Thomas Grimm explained the occurrence of "Holomorphic Couplings in effective 4d Supergravity Action from higher Dimensions." The lecture started with an overview of the geometrical properties of supersymmetric string, M- and F-theory compactification manifolds. The general constraints from super symmetry on the effective action was discussed as well as the expected duality symmetries and their constraints on moduli dependent couplings.

- Albrecht Klemm reported on "Integrability in Topological String Theory." This lecture reviewed supersymmetric localization, the A- and B- model twisting, the observables in the so defined topological theories, their relation to BPS states and stability and wall-crossing formulas for the latter. It explained the mirror principle and how the variation of Hodge structure, the relation between holomorphicity and modularity, direct integration and the gap condition leads to a solution of this theory and contrasted that to other approaches.

- Marcos Mariño described recent developments in the understanding of "Non-Perturbative effects in Matrix model, Chern-Simons Theory and Topological Strings." He started with the definitions of classical asymptotics, Stokes phenonema and Borel summability. Non-perturbative effects were then discussed in the an-harmonic oscillator, in Chern Simons theory, matrix models and topological string theory. In particular large N expansion techniques were discussed. Very useful lecture notes are available at http://www.th.physik.uni-bonn.de/People/rauch/viennamarino.pdf

- Don Zagier gave a beautiful lecture “Properties of Modular Forms and their Asymptotics” on modular forms with special emphasis on the newly discussed phenomenon of mock modularity. After developments pushed by Bringman and Zwegers large classes of the latter can be systematically completed to non holomorphic but modular forms and many properties, e.g. their asymptotics can be studied using similar methods then for ordinary modular forms.

Beside the longer lectures we had talks on recent trends in non-perturbative gauge theory and string theory. Serguei Barannikov, Andrea Brini, Nadav Drukker, Kashani-Poor, Ricardo Schiappa, Piotr Sulkowski and Pavel Putrov talked on the correspondence between matrix model, gauge theory and string theory. Alexander Belavin, Semyon Klevtsov, Alexei Morozov, Alexander Popolitov and Alexei Morozov talked on the recently by Alday, Gaiotto and Tachikawa discovered relation between 4d N=2 sypersymmetric gauge theory and Liouville Theory. Jan Manschot and Don Zagier talked on the relation between wall crossing and mock modularity, Christoph Keller on “Siegel modular forms and CFT partition functions at genus two, ” Sergei Alexandrov and Boris Pioline on the hypermultiplet moduli space, and Bengt Nilsson on the action of the M2 brane. Xenia della Ossa reported on the observations by Candelas and della Ossa relating mirror symmetry calculations in a very intriguing and not completely understood way to number theory. More detailed information and abstracts are of the talks are available at http://hep.itp.tuwien.ac.at/∼kreuzer/TSTMP.html.

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Invited Scientists: Mohammed Abouzaid, Vasyl Alba, Sergei Alexandrov,Murad Alim, Denis Auroux, Alexander Ballard, Serguei Barannikov, Marco Baumgartl, Nicolas Behr, Alexander Belavin, Klaus Bering, Guido Bonelli, Vincent Bouchard, Andreas, Braun, Volker Braun, Andrea Brini, Philip Candelas, Nils Carqueville, Xenia della Ossa, Valery Dolotin, Charles Doran, Nadav Drukker, Petr Dunin-Barkowski, Alexander Efimov, Annamaria Font, Maxime Gabella, Davide Gaiotto, Dimitriy Galakhov, Richard Garavuso, Alexei Gorodentsev, Thomas Grimm, Mark Gross, Babak Haghighat, Agapitos Hatzinikitas, Manfred Herbst, Shinobu Hikami, Ludmil Katzarkov, Amir-Kian Kashani-Poor, Michael Kay, Christoph Keller, Albrecht Klemm, Denis Klevers, Semyon Klevtsov, Johanna Knapp, Maxim Kontsevich, Maximilian Kreuzer, Svatopluk Krysl, Wolfgang Lerche, Jan Manschot, Marcos Mariño, Grigory Mikhalin, Andrei Mironov, Sergei Mironov, Greg Moore, Alexei Morozov, Andrey Morozov, Filipe Moura, Sameer Murthy, Sergei Natanzon, Bengt E. W. Nilsson, Serge E. Parkhomenko, Gregory Pearlstein, Boris Pioline, Alexander Popolitov, Olga Ptitsyna, Pavel Putrov, Marco Rauch, Yongbin Ruan, Ingo Runkel, Emanuel Scheidegger, Ricardo Schiappa, Karl-Georg Schlesinger, Martin Schlichenmaier, Yan Soibelman, Piotr Sulkowski, Alessandro Tanzini, Stefan Theisen, Andrey Vlasov, Yoannis Vlassopoulos, Peter West, Don Zagier, Egor Zenkevich, Roberto Zucchini.

AdS Holography and the Quark Gluon Plasma

Organizers: A. Rebhan (Vienna), Karl Landsteiner (Madrid), S. Husa (Palma de Mallorca)

Dates: August 02 - October 29, 2010

Budget: ESI €47.177,62 und Universität Wien €7.000,– und EMMI (Helmholtz Alliance) €15.000

Preprints contributed: [2230], [2231], [2271], [2272], [2273], [2274], [2275], [2276], [2278], [2280], [2285], [2289], [2293], [2305], [2307]

Report on the programme

Quantum Chromo Dynamics (QCD) is the theory of the strong nuclear interactions. It is an example of a non-abelian gauge theory. Such theories constitute the fundamental paradigm of modern high energy physics. Although some forty years have passed by since their invention they are still far from being understood satisfactorily. In particular phenomena such as confinement and chiral symmetry breaking are still lacking complete explanations.

QCD is an asymptotically free theory, i.e. its coupling constant runs to smaller and smaller values at high energy. Very early on this has led to the suggestion that confinement ceases to be effective at very high temperature (or density) and that the theory goes over into a deconfined phase: the quark-gluon plasma (QGP). An experimental programme has been set up at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National and at the LHC collider at CERN, Geneva, to study this new state of matter. The existing experimental results indicate that the newly created state of matter in these heavy ion collisions does indeed have properties that are consistent with a deconfined phase of QCD. Somewhat surprisingly it turned out, however, that the new state of matter created in heavy-ion collisions does not behave as a weakly interacting gas of quarks and gluons but rather as a liquid showing significant collective flow phenomena.

It even appears to be the most perfect fluid observed in nature so far, having a specific viscosity (viscosity to entropy ratio) at least an order of magnitude smaller than that of any previously observed liquid.

The temperatures reached in the heavy-ion collisions at RHIC are about twice the critical temperature of QCD. At this temperature QCD is still very strongly interacting and therefore the new state of matter created in RHIC collisions has been named the strongly coupled quark gluon plasma (sQGP). The strong coupling behaviour makes perturbative field theoretical approaches to explain the properties of the quark-gluon plasma in this temperature range a nearly impossible task. Since the lifetime of the QGP in heavy ion collisions is very short (of the order of 10 fm/c), time evolution and out-of-equilibrium physics play a central role.

During the last years a radical new approach to model the strongly interacting QGP has been proposed and developed. It relies on the by now well-tested duality between the maximally supersymmetric (N=4) gauge theory in four dimensions and type IIB string theory on anti-de Sitter space, the so called AdS/CFT correspondence first formulated by Maldacena in 1997. In this framework, the (conformal) boundary values of the five-dimensional supergravity fields provide the sources for the gauge invariant operators of the four dimensional gauge theory, which thus can be thought of as living on the conformal boundary of AdS, hence the terms anti-de Sitter holography and holographic gauge theories. This correspondence can be generalized to finite temperature, where the deconfinement phase transition in the gauge theory is mapped to the Hawking-Page phase transition of black hole formation in five-dimensional anti-de Sitter space. This approach has by now been greatly generalized to gauge theories which include matter in fundamental representations, whose dual versions involve space-time filling D-brane solutions in the supergravity setting and which generalizes the duality to non-conformal gauge theories where part (or all) of the N=4 supersymmetry is broken.

The impact and success the application of gauge-gravity duality had on the understanding of the physics of the strongly coupled quark gluon plasma has widened significantly recently and has moved towards the field of condensed matter physics. In particular the gauge-gravity duality has seen applications to the theory of quantum phase transitions and strongly interacting superfluids and superconductors. The hope is that through these techniques the understanding of the high-temperature superconductors, heavy-fermion materials or strange metals can be improved. The programme has therefore seen a significant part of its activity being devoted to these new developments.

More than 100 leading researchers from all over the world have come to ESI during the programme to intensify and deepen this already fruitful cross-fertilizing of ideas coming from string theory, from finite-temperature field theory and from condensed matter physics.

Timeline: The programme was roughly divided in a lecture and workshop phase in August and an extended programme phase during September and October.

- **Introductory lectures.** The first week of the programme, August 2 – August 6, was primarily devoted to introductory lectures given by some of the leading scientists in the various fields covered. Weak coupling results on QCD at finite temperature and density were reviewed by A. Vuorinen. Methods of numerical relativity were introduced and reviewed by S. Husa. R. Myers and A. Buchel lectured on the methods of applying the gauge gravity duality to the physics of strongly coupled non-abelian plasmas. D. Grumiller reviewed the process of holographic renormalization and S. Sugimoto gave lectures on how hadrons can be realized in holographic QCD. In addition research style seminars were held that reflected already the recent trend towards applications of the gauge-gravity duality to condensed matter physics with talks on holographic quantum liquids by M. Wapler and on Fermi surfaces by C. Johnson. The talks by B.H. Lee and Y. Seo discussed dense medium effects in holographic models. V. Filev treated the inclusion of flavor branes in supersymmetric theories on a three sphere and K.Y. Kim presented results on the phase diagram of a chiral symmetry breaking theory.

- **ESI workshop.** From August 9 – August 20, a two-week workshop was held at ESI. Some of the newest developments concerning the holographic modeling of heavy-ion collisions or the realization of superconductors were presented. Inclusion of flavors with backreaction was presented by J. Mas. How mesons can be modelled by open strings was treated by S. Sugimoto. The talks by J. Casalderrey-Solana, C. Marquet, E. Kiritsis shed light on various aspects of mechanisms of energy loss for heavy quarks in a quark gluon plasma and results on dilepton production were presented by N. Braga. K. Kajantie presented gravity duals of technicolor theories and discussed their thermodynamics and mass spectrum. Effects of the chiral anomaly for dense matter were treated by H.U. Yee. The modelling of the non-linear time evolution of the initial state of the quark gluon plasma have been discussed by A. Taliotis and M. Vazquez-Mozo. Out of equilibrium notions of black hole horizons with a view towards applications in the gauge-gravity duality were presented by M. Heller. Extremal charged AdS black holes have the unusual property of an extensive entropy at zero temperature and this somewhat puzzling situation was addressed in the talk by I. Klebanov. A. Buchel developed a holographic theory of critical transport. The talks by O. Bergmann, J. Erdmenger, M. Kaminski, A. Yarom, J. Wu and A. O'Bannon treated applications of holography to condensed matter physics such as quantum hall fluids, superconductors, Fermi surfaces and zero sound. V. Dobrev treated mathematical aspects of how the gauge gravity duality might be extended to non-relativistic systems. An informal round table discussion led by E. Iancu, A. Mueller and D. Triafantyllopoulos was held on open issues in the UV/IR correspondence and this helped to clarify and sharpen open interpretational issues in holography.

- **EMMI workshop.** Within the ESI-Workshop, a 5-day EMMI workshop with the title "Hot Matter – Quasiparticles or Quasinormal Mode" was organized by A. Rebhan together with R. Baier and O. Kaczmarek from the University of Bielefeld and P. Romatschke from the Frankfurt Institute for Advanced Studies (FIAS). Support for this ExtreMe Matter Institute (EMMI) workshop was provided by the German Helmholtz Alliance under the programme "Extremes of Density and Temperature: Cosmic Matter in the Laboratory" and this helped to partially fill the budget cut that had to be applied to the encompassing ESI-Workshop. The EMMI workshop was focused on comparing the gauge/gravity-duality approach to the physics of the quark-gluon plasma with methods applicable at weak coupling, namely perturbation theory and resummations thereof. Hence the title which refers to the quasiparticles that are the fundamental objects in resummed perturbation theory and to the quasinormal modes of black holes, which according to the membrame paradigm are used to describe the hydrodynamic aspects of strongly interacting matter in the holographic setup.

  After an opening lecture by R. Baier, who gave an overview of the issues under discussion and a short presentation of EMMI and its role in the German Helmholtz Alliance, A. Mueller presented a detailled comparison of perturbative QCD and AdS/CFT views of hot matter. S.P. Kumar discussed the different analytic structures expected for Green's functions at weak and strong coupling whereas K. Landsteiner discussed quasinormal modes in general and in recent superconductor applications. J.P. Blaizot gave a theoretical overview of some of the outstanding questions regarding the idea of sQGP, whereas B. Jacak, who is spokeswoman of one the experimental collaborations at RHIC, gave an overview of the experimental program exploring the sQGP. On the following day this was continued by an overview of nonperturbative results from lattice gauge theory by W. Söldner, more on hydrodynamical descriptions at strong and weak coupling by D. Teaney and P. Kovtun, resummed perturbation theory and the quasiparticle picture by J. Andersen, and gauge-gravity dual descriptions of heavy-ion collisions by A. Taliotis. On the third day, another experimental overview talk was provided by P. Kuijer from CERN, who described the physics potential of the by now initiated heavy-ion collider programme at the LHC. E. Iancu then presented new results for heavy-quark energy loss in a strongly coupled plasma, while V. Cardoso and P. Chesler covered nonequilibrium aspects at strong coupling through black hole physics. A. Vuorinen presented new perturbative results on the equation of state of cold nuclear matter as relevant for neutron star physics. On the fourth day, M. Strickland reviewed the status of nonabelian plasma instabilities at weak coupling, while G. Moore, J. Tarrio, S.P. Kumar, K. Schade and A. Schmitt covered various aspects of transport phenomena and screening behaviour in the holographic setup. On the last day, P. Benincasa discussed phase transitions in strongly coupled gauge theories and A. Ipp presented new ideas on yoctosecond photon physics at the LHC and related projects at other heavy-ion facilities.

The EMMI workshop was a very productive addition to the general, somewhat more theoretically oriented ESI programme. It was very well attended and stimulated a lot of discussions. It also drew the attention of a BBC reporter, who visited ESI during this workshop, interviewing some of the key speakers and informing himself about the ESI as an internationally recognized research institution.

- **Extended Programme.** Applications of the gauge-gravity duality to condensed matter physics were a particularly prominent theme during the extended phase of the programme in September and October with seminars on holographic superfluids by D. Arean, materials of negative refraction index by G. Policastro and fractional topological insulators by C. Hoyos. Effective holographic theories for condensed matter physics applications were discussed by R. Meyer. The time evolution of entanglement entropy in holographic models was the topic of a talk by E. Lopez. C. Krishnan introduced black hole tomograms and J. Shock discussed strings on bubbling geometries. N. Evans explored chiral phase transitions on models based on probe branes. L. Yaffe discussed the volume independence of large N gauge theories and E. Megias presented results on gluon condensates in holographic QCD. The nearly perfect fluidity of cold atomic gases and the quark gluon plasma were the main focus of the talks of T. Schaefer whereas M. Paulos discussed how the viscosity of holographic models can be lowered even below the conjectured holographic bound by considering higher derivative gravity actions.

All lectures and seminar presentations, except those held as pure blackboard talks, have been made publicly accessible through the website of the programme, http://quark.itp.tuwien.ac.at/~ads, which will remain on-line.

Invited Scientists: Javier Abajo, Janne Alanen, Irene Amado, Martin Ammon, Jens Andersen, Joao Aparicio, Daniel Arean, Dumitru Astefanesei, Andrey Bagrov, Rolf Baier, Paolo Benincasa, Oren Bergman, Matteo Bertolini, Guillaume Beuf, Sahoo Bindusar, Jean-Paul Blaizot, Nelson Braga, Alex Buchel, Nele Callebaut, Vitor Cardoso, Jorge Casalderray-Solana, Paul Chesler, Vladimir Dobrev, Johanna Erdmenger, Nick Evans, Carlo Ewerz, Andrej Ficnar, Veselin Filev, Omar Foda, Astrid Gebauer, Michal Heller, Defu Hou, Carlos Hoyos, Sascha Husa, Edmond Iancu, Barbara Jacak, Vinod Kumar Jena, Clifford Johnson, Keijo Kajantie, Matthias Kaminski, Patrick Kerner, Keun Young Kim, Seok Kim, Elias Kiritsis, Ingo Kirsch, Igor Klebanov, Peter Koroteev, Pavel Kovtun, Ulrike Krämmer, Chethan Krishnan, Paul Kuijer, Prem Kumar, Karl Landsteiner, Gilad Lifschytz, Shu Lin, Esperanza Lopez, Maria Magou, Cyrille Marquet, Javier Mas, Eugenio Megias, Rene Meyer, David Miller, Guy Moore, Alfred Müller, Rob Myers, Andy O'Bannon, Ioannis Papadimitriou, Miguel Paulos, Francisco Pena-Benitez, Tassos Petkou, Giuseppe Policastro, Radoslav Rashkov, Anton Rebhan, Paul Romatschke, Tadakatsu Sakai, Konrad Schade, Thomas Schäfer, Yunseok Seo, Jonathan Shock, Wolfgang Söldner, Wieland Stässens, Mike Strickland, Shigeki Sugimoto, Piotr Surowka, Ville Suur-Uski, Anastasios Taliotis, Javier Tarrio, Derek Teaney, Dionysis Triantafyllopoulos, Miguel Vazquez-Mozo, Aleksi Vuorinen, Matthias Wapler, Bin Wu, Jackson Wu, Lawrence Yaffe, Amos Yarom, Ho-Ung Yee, Ismail Zahed, Andrei Zayakin, Hongbao Zhang.

Higher Structures in Mathematics and Physics

Organizers: A. Alekseev (Genf), H. Bursztyn (Rio de Janeiro), T. Strobl (Lyon)

Dates: September 1 - November 11, 2010

Budget: ESI €50.388,95 plus ESF €10.000,– plus other external funding €37.630,–

Preprints contributed: [2265], [2277], [2279], [2281], [2282], [2283]

Report on the programme

The broad field of *Higher Structures* encompasses new algebraic and geometric structures which have become central tools in various domains of mathematics as well as mathematical and theoretical physics. An important example of a "higher structure" is Drinfeld's theory of associators, which originated in the theory of quantum groups and plays a key role in the theory of finite-type invariants in low-dimensional topology and in the theory of quantization. Another example is the theory of strong homotopy algebras (e.g. A_∞, L_∞, etc), which arose in algebraic topology and homotopy theory around 40 years ago and has recently found very important applications in deformation quantization, e.g. in Kontsevich's formality theorem, and in symplectic topology, particularly in Kontsevich's homological formulation of Mirror Symmetry. Other examples include the fields of generalized geometry and graded manifolds (e.g. Courant algebroids and generalized complex structures), abelian and nonabelian gerbes and more general higher gauge theories, as well as twisted K-theory, which have all become increasingly important tools in string theory. These various aspects of higher structures actively interact with one another and they have all undergone intense developments in recent years. The main emphasis of the program was put on the latest advances in the field as well as on the interaction between specialists from different branches.

The first 6 weeks of the program were structured around 5 mini-courses, which offered foundational material and recent results on selected topics:

1. *An introduction to modern category theory*, C. Lazaroiu (Dublin):

   Assuming the standard definition of categories to be known, Lazaroiu re-explained them using the category language on a meta level. In particular categories can then be seen as "categorifications" of monoids, or, as explained in detail in the course, categories are monoid objects in monoidal categories of graphs. With such a language at hand, the transition to higher categories, polycategories, multicategories, operads, properads etc, becomes more transparent and can be understood from a more systematic point of view.

2. *Supergeometry and differential graded manifolds*, by D. Roytenberg (Utrecht) and T. Voronov (Manchester):

   Roytenberg and Voronov shared 6 lectures to provide a thorough introduction to the foundations of supergeometry, Q-manifolds, and more general differential graded (dg) manifolds. They highlighted main results of monographs on part of the subject while collecting from a systematical perspective other more recent developments that partially are found only in original articles. The lectures contained classification theorems on supermanifolds, Q-manifolds (dg manifolds for $\mathbb{Z}_2$-grading) and lower degree dg-manifolds with $\mathbb{N}$-grading, they dealt with derived and higher derived brackets, yielding generalizations of L_∞ algebras, discussed Lie algebroids and higher analogues from the supergeometric perspective and finished with an outlook for higher Lie theory, the question of how to integrate dg manifolds into Lie n-groupoids, by adopting the perspective of appropriate Q-morphisms modulo Q-homotopies in generalization of the construction for $n = 1$. The minicourse was accompanied by a sequence of spontaneously organized discussion sessions on the subject where in particular younger participants could ask questions, further details on selected topics of the course were provided, and the relation to talks of senior researchers were given. One example for the latter was how the double vector bundles and double Lie algebroids and Lie bialgebroids, presented by K. Mackenzie within two afternoon talks, were revisited in an enlightening way by Voronov from the supergeometric perspective.

3. *Introduction to higher gauge theories*, by C. Laurent-Gengoux (Coimbra), U. Schreiber (Utrecht) and T. Strobl (Lyon):

   The course introduced higher gauge theories as a generalization of Yang-Mills theories to higher form degrees of the gauge fields. The three speakers represented three different perspectives on the same subject. Schreiber described higher generalizations of principal bundles with connection using the tools of higher category theory. In this picture higher bundles are described by functors from the Cech groupoid of the base manifold with a good cover to the structural n-group. For the $n = 2$ case, i.e. non abelian gerbes, Laurent-Genoux showed that this can be equivalently described as an adapted group-extension of the Cech groupoid, where the role of an isomorphism is played by Morita equivalence. This extension is an ordinary (1-)Lie groupoid, which leads one back into the realm of more standard differential geometry. Strobl showed that whenever one discusses higher gauge theories, one is lead to bundles in the category of differential graded manifolds (Q-bundles). The relation of this description to the categorical one is a generalization of the one of an Atyiah algebroid to its underlying principal bundle. Strobl also provided a link to supergravity theories by showing that the use of Q-bundles permits to reformulate open gauge algebras, known to appear in supergravity theories, in terms of an ordinary Lie algebra of appropriate vertical vector fields on the Q-bundle.

4. *Introduction to gauged super gravity*, H. Samtleben (Lyon):

   The course first presented the basic supergravity theories as they are obtained e.g. from dimensional reductions along a torus from the unique supergravity in 11 dimensions. Such theories have higher form degree gauge fields, all having abelian gauge symmetry, as well as scalar fields defining a sigma model with coset space as target, but also entering the couplings of the gauge fields. So-called gauged supergravity theories are obtained from those by an appropriate gauging mechanism of a global symmetry of the coset models. In the resulting theories the gauge fields receive a non-abelian gauge symmetry, the different form degrees being coupled to one another within generalized field strengths. Further leading discussions indicated that methods from the course on higher gauge theories should be applicable here as well and that it would be interesting to unravel e.g. the hidden Q-structure in the gauge sector of contemporary gauge supergravity theories.

5. *Categorified symplectic geometry*, C. Rogers (Riverside):

   The lectures described the viewpoint on multisymplectic geometry (i.e., geometry of manifolds equipped with a nondegenerate closed k-form, for $k > 2$) as "categorified" symplectic geometry. The lecturer reported on his recent work explaining how Lie n-algebras naturally arise as higher versions of the Poisson algebra of observables, and the role of Courant algebroids and gerbes in higher versions of geometric prequantization.

Several new results were discussed during the daily seminars by participants during the program, most of which related directly to one or more of the above minicourses. We mention some of them: M. Trigangte showed that gauged supergravity theories in four dimensions can be obtained by a dimensional reduction in the presence of fluxes, i.e. of non-vanishing curvatures of higher form degree gauge fields. In his talk, A. Kotov showed how the Chern-Weil characteristic map, the relative characteristic classes of flat bundles, as well as Rozansky-Witten classes can all be obtained from a joint formalism of characteristic classes of differential graded principal bundles. J. Mickelsson talked about the appearance of gerbes and (twisted) K-theory in the context of quantum field theories, e.g. as they arise in the context of a second quantization of the Dirac operator coupled to an ordinary gauge field. His talk related the Dixmier-Douady classes, supersymmetric WZW models, Dirac operators, and quantum affine algebras. Another topic that received a great deal of attention during the program, particularly from Junior Fellows, was that of *representations up to homotopy*; this notion arises when one tries to make sense of the adjoint representation of a Lie algebroid. Representations up to homotopy were the main subject of collaboration of Arias-Abad and Schaetz, and served as a new tool for the investigations of Ortiz on Dirac structures. An introduction to the theme, including motivations and applications, was presented by M. Crainic in the Higher-Structures conference described below.

School and conference on Higher Structures:

In the last two weeks of October, the program hosted the *School on Higher Structures* and the conference *Higher Structures in Mathematics and Physics 2010*, which was the fourth edition of a series of annual international meetings on higher structures.

The School consisted of four minicourses: *Conformal Nets*, by A. Henriques (Utrecht), *Cluster algebras and triangulated categories*, by B. Keller (Paris), *Categorifying quantum groups*, by A. Lauda (Columbia), and *M. Kontsevich's graph complex and the Grothendieck-Teichmuller Lie algebra*, by T. Willwacher (Harvard). Henriques gave a thorough introduction to conformal nets, a subject with roots in the axiomatic approach to quantum field theory. The mini-course included the lecturer's recent work on the relation between conformal nets and higher structures arising from conformal field theory, and one of its main results consisted of new relations between conformal nets and the representation theory of loop groups. Keller's minicourse offered an introduction to cluster algebras and cluster categories; its highlight was the lecturer's recent application of cluster algebras to give a complete proof of the Zamolodchikov's periodicity conjecture for Y-systems. Lauda, in his mini-course, explained the concept of categorification for quantum groups and knot invariants as well as their many potential applications (e.g. to low-dimensional topology, topological quantum field theory, and representation theory). This theory is an outgrowth of Khovanov's original results on the categorification of the Jones polynomials. Lauda discussed his approach to categorified quantum groups based on a graphical calculus. Willwacher lectured on the relation between two mysterious objects in mathematical physics: the Kontsevich graph complex and the Grothendieck-Teichmuler (GRT) group. The most important result presented in the mini-course, due to the lecturer, asserts that the cohomology of the graph complex (in a certain degree) is isomorphic to the Lie algebra of the GRT group.

The conference consisted of 18 one-hour talks and covered a number of advanced research topics, including: higher structures in symplectic topology (talks by K. Fukaya and M. Abouzaid), A_∞-algebras (talks by S. Barannikov and C.-H. Cho), deformation quantization (talks by D. Calaque and B. Tsygan), generalized geometry/Lie algebroids and groupoids (talks by G. Cavalcanti, P. Severa, R. Fernandes, D. Roytenberg, M. Crainic), loop groups and integrability (talks by G. Felder and X. Zhu), topological quantum field theory (talks by M. Zabzine and A. Cattaneo), deformation theory and category theory (talks by C. Douglas, J. Francis and W. Lowen). Some of the most important advances presented at the conference were: the use of higher structures in connection with Lagrangian Floer theory and mirror symmetry, by Fukaya; an unexpected link between A_∞-algebras and matrix algebras, by Barannikov; a new approach to Lagrangian field theory, exposed by Cattaneo; some deep applications, due to Tamarkin, of higher structures and microlocal analysis to symplectic topology (e.g.to non-displaceability problems), presented by Tsygan along with a collection of open problems in deformation quantization.

Various rounds of discussions complemented the activities.

Invited scientists: Mohammed Abouzaid, Anton Alekseev, Paolo Aschieri, Yves Barmaz, Serguei Barannikov, Glenn Barnich, Matija Basic, Laurent Baulieu, Klaus Bering, Christian Blohmann, Giuseppe Bonavolonta, Francesco Bonechi, Nicolas Bovetto, Olivier Brahic, Paul Bressler, Henrique Bursztyn, Alejandro Cabrera, Damien Calaque, Alberto Cattaneo, Gil Cavalcanti, Cheol-Hyun Cho, Ivan Contreras, Marius Crainic, Fernando Del Carpio-Marek, Irina Davydenkova, Christopher Douglas, Thiago Drummond, Giovanni Felder, Rui Fernandes, John Francis, Yael Fregier, Kenji Fukaya, Michail Gorsky, Janusz Grabowski, Maxim Grigoriev, Melchior Grützmann, Andre Henriques, Marc Henneaux, Nigel Hitchin, Eduardo Höfel, Ivan Horozov, Seungjoon Hyun, Noriaki Ikeda, Branislav Jurco, Dmitry Kaparulin, Johan Källen, Bernhard Keller, David Khudaverdyan, Noah Kieserman, Tae-Su Kim, Yvette Kosmann-Schwarzbach, Alexei Kotov, Aaron Lauda, Camille Laurent, Calin Lazaroiu, Sangwook Lee, Ulf Lindström, Andrey Losev, Wendy Lowen, Simon L. Lyakhovich, Kirill Mackenzie, Ahsis Mandal, David Martinez Torres, Sergei Merkulov, Jean-Philippe Michel, Jouko Mickelsson, Pavel Mnev, Ieke Moerdijk, Samuel Monnier, Elena Mosman, Thomas Niklaus, Francesco Noseda, Jae-Suk Park, Norbert Poncin, Maria Podkopaeva, Pietro Polesello, Fan Qin, Jian Qiu, Volodya Roubtsov, Dmitry Roytenberg, Stefan Sakalos, Henning Samtleben, Jenny Santoso, Laura Schaposnik, Urs Schreiber, Pavol Severa, Michael Semenov, Alexey Sharapov, Eric Sharpe, Zoran Skoda, Denis Sullivan, Ulrich Theis, Alessandro Tomasiello, Giorgio Trentingalia, Mario Trigiante, Boris Tsygan, Bernardo Uribe, Theodore Voronov, Stefan Waldmann, Konrad Waldorf, Thomas Willwacher, Frederik Witt, Maxim Zabzine, Marco Zambon, Xinwen Zhu.

Workshops Organized Outside the Main Programmes

May Seminar in Number Theory

Organizer: J. Schwermer (Vienna)

Dates: May 2 - 9, 2010

Budget: ESI €4.464,07 plus EUR 8.540,– ESI JRF-Funding

Report on the programme

The aim of this workshop was to introduce young researchers at the PhD and post doc level to exciting recent developements of current research at the crossroads of number theory and related fields. Several mini-courses and invited research talks on a variety of topics ranging from number theory proper over automorphic forms and arithmetic quantum chaos were given by leading experts. Graduate students and post docs from various countries attended the seminar. Informal discussions between the students from Princeton, Zürich, Bonn, Essen Tel Aviv, Austin among others and the students of the Vienna based mathematical community took place right away from the start of this enterprise. This also led to a fruitful interaction between the participants and the lecturers through all the week.

Emanuel Kowalski, ETH Zürich, gave a series of lectures on *Sieve methods and some recent applications*. Sieve methods have been used for more than a century to extract information about the distribution of prime numbers. There are now many variants available, and recent years have seen striking successes and developments of sieve principles, sometimes in surprising areas. The lecturer gave a survey of some of the techniques and results, emphasizing the recent and more surprising applications (for instance, sieving in the context of discrete groups, the work of Holowinsky and Soundararajan on Arithmetic Quantum Unique Ergodicity, and that of Goldston, Pintz and Yildirim on gaps between primes)

Zeev Rudnick, currently at the Institute for Advanced Study, Princeton, discussed *Topics in arithmetic quantum chaos* in his minicourse. He gave an introduction to a collection of recent results and conjectures on the spectrum and the eigenfunctions of the Laplacian, with emphasis on arithmetic models. In particular, he discussed

- The universality conjectures for spectral statistics and relations with the classical subjects of uniform distribution and lattice point problems, zeros of zeta functions and Random Matrix Theory.
- Nodal lines of eigenfunctions of the Laplacian and lattice points on circles and spheres.

David Masser, University Basel, presented in his talks recent results on *Unlikely intersections*. Solving polynomial equations in integers or algebraic integers $x, y, \ldots$ is far too hard, so one might try to solve for example with x a power of 2, y a power of $3, \ldots$ This problem when suitably generalized is associated with the names of Mordell-Lang. Or one might try to solve in roots of unity, a problem similarly associated with Manin-Mumford. Both of these topics are fairly well understood. Independently Zilber in 2002 and Pink in 2005 used a concept of unlikely intersections to create a common generalization going far beyond the union of both topics. In fact some related work started already in 1999 and since then there has been enormous progress, particularly in the last two years.

Neven Grbac, University Rijeka, a Senior Research Fellow at the ESI in the summer term 2010, gave a minicourse entitled *Eisenstein series in arithmetic and geometry*. He dealt with the spectral decomposition of the space of square-integrable automorphic forms, an important problem in the arithmetic theory of automorphic forms on the adelic points of a (connected) reductive algebraic group defined over a number field. The geometric importance of the space of all automorphic forms is seen from their relation to the cohomology of arithmetic (congruence) subgroups. In approaching both problems the Eisenstein series play one of the key roles. Grbac explained here recent results in both directions. Although essentially of different nature, the common ground for these results is the study of analytic properties of Eisenstein series.

Robert Tichy, Graz, lectured on *Metric Discrepancy Theory* among other topics. He presented recent probabilistic results in number theory and in the theory of point distributions. This work combined methods from Fourier analysis as well as martingale inequalities and combinatorial techniques. The main results were limit theorems for discrepancies and related counting functions.

Unfortunately, *Alan Reid*, U Texas, Austin, had to cancel his envisaged course *The Geometry and Topology of Arithmetic Hyperbolic 3-Manifolds* on short notice.

The lecture *Arithmetic formulas for topological invariants of modular varieties* by *J. Rohlfs, University Eichstätt,* discussed the notion of Lefschetz numbers for arithmetically defined locally symmetric spaces and presented some methods to derive arithmetic formulas for them. These encode important number theoretical information on the underlying varieties. *J. Schwermer*, University of Vienna, pursued this topic in his lecture *On the cohomology of arithmetically defined groups and automorphic forms*. Starting of from the case of arithmetically defined hyperbolic 3-manifolds he explained the close relation between the cohomology of these spaces and the theory of automorphic forms, in particular, Eisenstein series. With this frame work in place he discussed some recent results regarding the construction of non-vanishing cohomology classes for arithmetically defined groups.

Invited scientists: Neven Grbac, Emmanuel Kowalski, David Masser, Alan Reid, Zeev Rudnick, Giedrius Alkauskas, Sascha Biberhofer, David Brink, Igor Ciganovic, Jakob J. Ditchen, Daniel File, Luca Antonio Forte, Christopher Frei, Dominik Gruber, Christoph Harrach, Steffen Kionke, Angelika Kroner, Grant Lakeland, Simon Marshall, Ivan Matic, Chen Meiri, Lior Rosenzweig, Abhishek Saha, Claudia Scheimbauer, Susanne Schimpf, Mehmet Haluk Sengun, Anders Sodergren, Andreas Steiger, Jacob Tsimerman, Henrik Überschär, Andja Valent, Christoph Waldner, Per Kurlberg

Symposium Diskrete Mathematik

Organizer: C. Krattenthaler (University of Vienna)

Dates: May 14 - 15, 2010

Report on the programme

This symposium of the "Fachgruppe Diskrete Mathematik" of the German Mathematical Society (DMV) was sponsored by the National Research Network "Analytic Combinatorics and Probabilistic Number Theory" of the Austrian Science Fund (FWF), and the Springer Publishing Company. The programme can be found on the website
http://homepage.univie.ac.at/summerschool.mathematik/symp10/

Invited scientists: Martin Aigner, Christos Athanasiadis, Bela Bajnok, Julia Böttcher, Cesar Ceballos, Maria Chudnovsky, Timo de Wolff, Anton Dochtermann, Michael Drmota, Friedrich Eisenbrand, Thomas Feierl, Stefan Felsner, Ilse Fischer, Ehud Friedgut, Markus Fulmek, Agelos Georgakopoulos, Markus Hablesreiter, Mihyun Kang, Jeong Han Kim, Alfred Köhnle, Matja Konvalinka, Anisse Kasraoui, Christian Krattenthaler, Bernhard Krön, Raffaele Marcovecchio, Tobias Müller, Philippe Nadeau, Katarzyna Paluch, Konstantinos Panagiotou, Konrad Podloucky, Thomas Rothvo, Raman Sanyal, Michael Schlosser, Martin Skutella, Reto Spöhel, Philipp Sprüssel, Angelika Steger, Johannes Stemeseder, Rüdiger Stephan, Sebastian Stiller, Volker Strehl, Anusch Taraz, Thorsten Theobald, Alessandro Tomazic, Stephan Wagner, Volkmar Welker.

7th Vienna Central European Seminar on Particle Physics and Quantum Field theory and COST MP0801 Workshop, Complex Stochastic Dynamics

Organizers: H. Hüffel (Vienna)

Dates: November 26 - 28, 2010

Budget: ESI €560,– additionally supported by the High Energy Physics Institute of the Austrian Academy of Sciences, the Austrian Federal Ministry of Science and Research, the Faculty of Physics, University of Vienna, the Vienna Convention Bureau, and COST MP0801.

Report on the programme

The meeting took place at the Faculty of Physics of the University of Vienna.

The workshop provided stimulating interactions between leading researchers and promising junior physicists. A considerable number of junior scientists participated in these meeting, speakers were selected from among them and discussion rounds were held. The innovative character of the meeting was especially important to us, and scientific contacts and collaborations were enhanced.

Complex systems and nonlinear stochastic dynamics of dissipative open systems have attracted extensive research interest over the past years. Significant impacts have been made on a wide range of different areas including physics, economics, biology and social sciences. As challenges to a fundamental understanding are persisting and demanding, the seminar aimed to cover both theoretical advances and cross-disciplinary applications.

Out of the many valuable contributions the highly appreciated introductory lecture by Peter Talkner (Augsburg) on Driven Stochastic Processes with Metastabel States: Fokker-Planck versus Master Equations should be mentioned. Methods were presented for reconstructing the long time dynamics of the continuous Fokker-Planck process from the master equation.

The meeting closed with the lecture Maximal Entropy Random Walk by Zdzislaw Burda (Krakov). He presented a new class of random walk processes that maximize entropy on irregular lattices. The importance of these investigations for a proper definition of path integrals in curved space was pointed out - just to name quantum particle propagation in Lorentzian quantum gravity.

At the first evening a Public Lecture on Complex Networks was held by Frank Schweitzer, Chair of Systems Design, ETH Zurich, Switzerland. The lecture was followed by an inspiring discussion session.

The full programme and the slide presentations of the lectures can be found on the website www.univie.ac.at/vienna.seminar/2010/index.html

The $\bar{\partial}$-Neumann Problem: Analysis, Geometry, and Potential Theory

Organizer: F. Haslinger (Vienna), B. Lamel (Vienna), E. Straube (Texas)

Dates: December 13 - 22, 2010

Budget: ESI €11.851,64 (A number of participants were supported through other funding, amounting to approximately €6.000,–)

Preprints contributed: [2211], [2212], [2214], [2215], [2216], [2217], [2218], [2220], [2221], [2222], [2223], [2224], [2225], [2227], [2232], [2238], [2239], [2255], [2258], [2263], [2267], [2270—, [2288], [2290], [2291], [2295], [2296], [2297], [2298], [2300], [2301], [2302]

Report on the programme

This follow-up to a program of 2009 brought together 44 scientists working in Several Complex Variables and closely related areas in order to discuss current research in the field. The main theme of the followup was again the $\bar{\partial}$–Neumann problem. It has its roots in the 1950s, and ties together the analysis of several complex variables with analysis, geometry, and potential theory. Many modern techniques in Several Complex Variables have their roots in the analysis of the $\bar{\partial}$–Neumann problem, and the problem itself has opened up whole new fields during the development of tools for its analysis.

The original program had initiated a number of new collaborations and inspired new research (as can be seen from the number of preprints contributed), some of which was reported on in the 2009 report; the last preprints actually originated from the follow-up itself.

Another aspect in which the follow-up brought the original program to a conclusion was by the final lectures of the senior fellow Jeff McNeal, who because of personal reasons was not able to finish his lecture course in 2009. In these, he presented a far-reaching generalization of Fefferman's mapping theorem, i.e. that biholomorphic maps of smoothly bounded pseudoconvex domains extend smoothly to the boundary; this problem had been open since Fefferman's original result in 1974. The followup workshop was the first event in which McNeal discussed details of his approach and proof.

Presentations during the workshop centered around the following scientific themes:

- Regularity in the $\bar{\partial}$–Neumann problem
- Analytic properties of the $\Box_b$ and $\bar{\partial}_b$ operator
- Connections with algebraic geometry
- CR geometry
- The Bergman and Szegö kernel functions

There were also lectures which made connections to applications in operator theory and engineering.

Regularity in the $\bar{\partial}$–Neumann problem

Regularity in the $\bar{\partial}$–Neumann problem has been one of the driving forces of the theory. This problem is the prototype of an elliptic PDE coupled with a boundary condition that is not coercive, and the special flavor of the theory of several complex variables often manifests itself when trying to understand how much boundary structure is needed in order to gain regularity.

As already mentioned, some recent advances in the theory have been presented during the followup in the form of McNeals' lectures.

Ruppenthal reported on his new results on compactness of the $\bar{\partial}$–Neumann operator on singular complex spaces, a work begun last year during his junior fellowship at the ESI.

Chakrabarti talked about his joint work with Mei-Chi Shaw on Sobolev regularity of the $\bar{\partial}$–equation on product manifolds.

While in the $\bar{\partial}$–Neumann problem one often has (at least a bit) of a gain of regularity, it still comes as a surprise that there are partial differential equations of a very similar type which actually lose derivatives. Kohn gave a summary of his recent results into that direction.

Boundary operators

Raich and Boggess reported on their continuing work on $\Box_b$ on quadrics, in particular on the exponential decay of the heat kernel associated with $\Box_b$ on these model domains. A particularly interesting aspect of this work is Raichs' use of quantitative smoothness estimates (which relate to the decay via the Fourier transform).

Straube and Munasinghe reported on their recent work concerning compactness of the complex Green operator on CR submanifolds of $\mathbb{C}^n$ of hypersurface type.

Connections with algebraic geometry

Huang presented his work on isometries from a hermitian manifold into a product manifold with Kähler-Einstein metric, which is closely related to the conjecture of Clozel-Ullmo.

CR geometry

Laurent reported on her work on embeddability of CR manifolds, and Mir on his joint work with Lamel on algebraic approximation of biholomorphic maps between real-algebraic CR manifolds.

A more analytic result was presented by Berhanu, who talked about joint work with Hounie in which they constructed a new form of FBI transform which can be used to prove analytic hypoellipticity of the boundary operators in more general circumstances.

Kernel Functions

The Bergman and Szegö kernels are basic objects in the complex analysis of several variables. Fu reported on his work comparing the growth of these kernel functions on the diagonal for smoothly bounded pseudoconvex domains of finite D'Angelo type. Ohsawa talked about variations of the Bergman kernel and the cone of Kähler deformability tangents, again tying with the subject of analytic algebraic geometry.

Invited scientists: Shif Berhanu, Al Boggess, Debraj Chakrabarti, Olivia Constantin, Zeljko Cuckovic, Giuseppe Della Sala, Eleonora Di Nezza, Klas Diederich, Duc Thai Do, Hans Feichtinger, John-Erik Fornaess, Franc Forstneric, Sigi Fu, Klaus Gansberger, Friedrich Haslinger, Anne-Katrin Herbig, Xiaojun Huang, Robert Juhlin, Tran Vu Khanh, Joseph Kohn, Martin Kolar, Berhard Lamel, Christine Laurent, Ingo Lieb, Jeff McNeal, Francine Meylan, Abdelhamid Meziani, Nordine Mir, Samangi Munasinghe, Stephanie Nivoche, Takeo Ohsawa, Margit Pap, Joe Perez, Andrew Raich, Jean Ruppenthal, Emil Straube, Dmitri Zaitsev, Giuseppe Zampieri.

Junior Research Fellows Programme

Established in 2004 and funded by the Austrian government, the Junior Research Fellows Programme provides support for PhD students and young post-docs to participate in the scientific activities of the Institute and to collaborate with its visitors and members of the local scientific community.

Due to its international reputation and to its membership in the European Post-Doc Institute the ESI received many applications from highly qualified post-docs for funding of extended visits (ranging from two to six months) only some of which could be covered by the Junior Fellows Programme. In view of the close and well-established links between the ESI and many leading Eastern European academic institutions this programme was particularly beneficial to young researchers from Eastern Europe and Russia. The presence of the Junior Research Fellows contributed significantly to the positive and dynamic atmosphere at the ESI.

The figures for applications in 2010 were as follows:

Deadline: 12.02.2010
Number of applications: 21
Number of accepted applicants: 9
Number of months granted: 27

Junior Research Fellowships in 2010

Name	Gender	Duration	Nationality
Slawomir Dinew	male	01/01 - 28/02	Poland/Bulgaria
Zywomir Dinew	male	01/01 - 28/02	Poland/Bulgaria
Claudio Dappiaggi	male	01/01 - 31/03	Italy
Wolfgang Moens	male	01/01 - 31/03	Belgium
Piotr Przytyczki	male	10/01 - 28/02	Poland
Christiane Losert	female	01/03 - 30/06	Austria
Richard Green	male	01/03 - 31/07	Australia
Helge Krüger	male	15/05 - 15/09	Germany
Rika Hagihara	female	01/06 - 30/06	Japan
Matthias Westrich	male	01/06 - 30/06	Germany
Matteo Cardella	male	01/06 - 31/07	Italy
Rongmin Lu	male	01/06 - 30/11	Singapore
Kostyantyn Medynets	male	30/06 - 30/07	Ukraine
Myrto Kallipoliti	female	02/08 - 19/12	Greece
Angelika Kroner	female	01/07 - 31/12	Austria
Alexander Fish	male	02/07 - 02/08	Israel
Marcel Vonk	male	19/07 - 18/08	The Netherlands
Susanne Schimpf	female	01/08 - 30/09	Germany
Chris Rogers	male	01/09 - 31/10	USA
Florian Schätz	male	01/09 - 31/10	Austria
Camilo Arias Abad	male	01/09 - 30/11	Colombia
Christian Ortiz	male	01/09 - 30/11	Chile
Vladimir N. Salnikov	male	01/09 - 30/11	Russia
Nora Seeliger	female	01/09 - 31/12	Germany
Wojciech Krynski	male	01/09 - 31/12	Poland
Mark Williamson	male	01/10 - 31/12	Great Britain
Matthias Hammerl	male	01/12 - 31/12	Austria

Preprints contributed: [2214], [2236], [2259], [2260], [2264], [2229]

Senior Research Fellows Programme

To stimulate the interaction with the local scientific community the ESI offers lecture courses on an advanced graduate level. These courses are taught by Senior Research Fellows of the ESI whose stays in Vienna are financed by the Austrian Ministry of Education, Science and Culture and the University of Vienna. This programme also includes long-term research stays of small groups or individual distinguished researchers. The coordinator of this programme was Joachim Schwermer.

This year's programme concentrated on the following lecture courses:

Peter West (King's College, London, UK), Summer 2010: *E Theory*
Neven Grbac (University of Rijeka), Summer 2010: *Eisenstein Series*
Stefan Hollands (Cardiff University), Summer 2010: *Quantum Field Theory on Curved Spacetimes*
Tayakal N. Venkataramana (Tata Institute of Fundamental Research, Mumbai), Winter 2010/11: *Representations contributing to Cohomology of Arithmetic Groups*

Long term Visitors within the Senior Research Fellowship Framework:
David Masser (University of Basel), March 25 - May 25, 2010

Peter West: E Theory

Course: During my visit to the ESI in June 2010, I gave ten lectures on Lie algebras, Kac-Moody algebras and the conjectured E_{11} symmetry of strings and branes. These began with an account of the finite dimensional semi-simple Lie algebras, their Serre presentation leading to the listing of Cartan. I then formulated Kac-Moody algebras and discussed the properties of a subclass, the Lorentzian algebras. Finally, I illustrated the ideas with the Kac-Moody algebra E_{11} and explained how this was linked to the maximal supergravity theories.

Research: I carried out research on two topics during my stay. One was the generalised geometry encoded in the E_{11} non-linear realisation. I carried out the construction of the non-linear realisation including the generalised space-time encoded in one of its representations of the IIA theory at lowest level. I was helped in this work by Christian Hillmann who visited me at the ESI with funds the institute provided. This work was published as "E11, generalised space-time and IIA string theory" , arXiv:1009.2624 and will be published in Physics Letters B.

I also took part in many discussions and seminars at the Vienna University of Technology with members of the theoretical physics group. In particular I had extensive discussions with Andreas Braun on the way gauge symmetries arise in string theory and how F theory fits into an E_{11} framework. We are continuing with this work and we hope to publish a paper on it eventually.

I enjoyed my visit to Vienna at the ESI and found it a productive visit.

Neven Grbac: Eisenstein series

Course: The graduate course delivered at the ESI as a part of my stay as a Senior Research Fellow in 2010 was meant to be an introductory course to Eisenstein series at the graduate level. Eisenstein series play an important role in the spectral decomposition of the space of square-integrable automorphic forms on the adèlic points of a reductive algebraic group defined over a number field. In particular, the continuous part of the spectrum can be described using direct integrals of Eisenstein series, while the non-cuspidal part of the discrete spectrum is spanned by certain residues of Eisenstein series. Their importance goes beyond square-integrability in view of the fact that the space of all automorphic forms can be described using the residues and principal values of the derivatives of Eisenstein series.

In order to illustrate general results on Eisenstein series for a reductive algebraic group defined over a number field, the course considered the example of the general linear group GL_2, and the special linear group SL_2, defined over a number field. For that example complete proofs of the analytic continuation and functional equation of the Eisenstein series are given. The passage from the classical upper half-plane setting to the setting of the Lie group $SL_2(\mathbb{R})$, and finally to the adèlic group $GL_2(\mathbb{A})$ were carefully explained.

Lecture series at the ESI May Seminar in Number Theory: A series of four lectures entitled Eisenstein Series in Arithmetic and Geometry delivered at the ESI May Seminar in Number Theory in 2010 was a natural continuation of the graduate course on Eisenstein series. It consisted of two parts. In the first part the application of Eisenstein series and their analytic properties in the spectral decomposition of the space of square-integrable automorphic forms on the adèlic points of a (connected) reductive algebraic group defined over a number field was considered. In the second part the role of the Eisenstein series in the Franke filtration of the space of all automorphic forms was explained, and the application to the study of the cohomology of congruence subgroups was discussed.

More precisely, in the first part of the lecture series, the Langlands approach to the spectral decomposition of L^2 automorphic forms was discussed. In particular, the decomposition of the non-cuspidal part of the discrete spectrum was studied. The constituents of this decomposition are determined as residues of Eisenstein series at poles. This shows the importance of understanding the analytic behavior of the Eisenstein series. These are studied via the constant term, which in turn may be written as a sum of certain intertwining operators. Hence, the Langlands-Shahidi method for normalization of interwining operators was covered. This method relates the poles of intertwining operators to those of certain automorphic L-functions.

The second part of the series showed that the space of all automorphic forms has a filtration defined by Franke by means of principal values of derivatives of (degenerate) Eisenstein series. This filtration implies that all automorphic forms may be written as a residue or the principal value of a derivative of Eisenstein series. On the other hand, the cohomology of a congruence subgroup has an interpretation in the adèlic setting in terms of the so-called automorphic cohomology, that is the relative Lie algebra cohomology of the space of all automorphic forms. The lecture series ended with the most recent results, obtained in a joint work with Joachim Schwermer, which describe certain vanishing results for automorphic cohomology for classical groups, and in particular, the consequences of these to the case of the symplectic group.

Research: In a stimulating and inspiring environment of the ESI, the research was quite fruitful. During my stay as a Senior Research Fellow, I was involved in several projects.

My collaboration with Joachim Schwermer, that has already lasted for a couple of years, was continued. During my stay we wrote a paper for a special volume on the occasion of Stephen S. Kudla's 60^{th} birthday. The main goal of the paper is to compare the automorphic cohomology of a general linear group to that of its inner form. In particular, we consider the case of $GL(4)$ over a totally real number field k, and its inner form defined as the general linear group $GL(2, D)$ over a quaternion algebra D central over k. We were trying to understand what kind of relationship between the cohomology classes is induced by the global Jacquet-Langlands correspondence of Badulescu and Badulescu-Renard. We also discussed possible directions of our research in future.

I also studied, in collaboration with Harald Grobner, the Eisenstein cohomology of the split symplectic group Sp_4 of rank two defined over a totally real number field. Shortly after I left, we finished a paper on that subject. We approach the problem by decomposing the Eisenstein cohomology along the cuspidal support. For each summand in that decomposition, we provide an explicit description of the Franke filtration of the relevant part of the space of automorphic forms. This enables computation of the cohomology by considering the long exact sequences in cohomology induced by the short exact sequences given by the filtration.

Stefan Hollands: Quantum field theory in curved spacetimes

Course: The lecture course was intended to give an introduction to the subject of quantum field theory on curved spacetime manifolds, leading up to current research topics in this area. It was designed in order to have as few as possible pre-requisites so as to make it accessible to graduate-level students or students in their fourth year having a background in quantum mechanics, classical field theory, and basic notions of differential geometry, but not necessarily quantum field theory. The course was attended by about 10-15 students, consisting of two hours of lectures per week plus one seminar per week. The seminars consisted mostly of student presentations. These were intended to go deeper into various topics that were only touched upon in the lectures. These topics were suggested by me, and the details of the student presentations was discussed individually with the students beforehand. A full set of lecture notes of about 100pp was prepared for the course and made available to the students at the beginning of the course.
The main subjects covered in the lectures were in detail:

1. *Classical field theory:* Fundamental solutions for hyperbolic equations; algebraic structure associated with classical field theory; Peierls bracket; perturbation series in classical field theory.

2. *Linear quantum field theory on curved spacetimes:* Algebraic formulation; quasi-free states; GNS-representation; Hadamard states; microlocal spectrum condition; curved spacetime examples: DeSitter spacetime, Schwarzschild spacetime; Hawking effect

3. *Perturbative interacting quantum field theory:* Retarded and time-ordered products; quantum field theory as deformation quantization of classical field theory; perturbation series for interacting fields; locality and covariance in quantum field theory; renormalization and renormalization ambiguities.

Research: The ESI provided an absolutely wonderful and inspiring atmosphere for pursuing my ongoing research activities, as well as to be inspired to new work through the interactions with other scientists in my research area. I mention 3 projects which have, at least partly, originated in discussion/work sessions with collegues during my fellowship:

1. Through several discussions with Profs. J. Bros, H. Epstein (CNRS, France), and U. Moschella, which I was able to invite through the ESI programme "Quantum field theory in curved spacetimes and curved target spaces", I was made aware of several interesting features and open issues related to the theory of quantized fields on a deSitter spacetime. The specific question that materialized in the course of these discussions was how to give a reasonably explicit prescription for constructing correlators in renormalized perturbation theory in such a spacetime. Extensive discussions with my invitee Prof. A. Ishibashi (KEK, Japan) helped me to understand why–and what particular aspects of–quantities like this are of considerable physical interest in cosmology. The nature of the prescription(s) as well as their interpretation is currently much debated in the physics literature. At the same time, these quantities are also of mathematical interest and display, e.g., an interesting interplay between the theory of special functions ("generalized hypergeometric functions", or H-functions), graph theory, and the representation theory of the group $SO(D,1)$. The

research I started while an ESI fellow culminated in a 57pp long paper that was put on the archives several month later, see arXiv:1010.5367 [gr-qc]. In this paper, a prescription how to compute Feynman integrals for an arbitrary graph in deSitter spacetime was given. The resulting representation by means of certain iterated contour integrals allows one to deduce the long-time behavior of correlation functions in perturbative deSitter QFT, which in turn have a rather direct physical significance. The final explicit formula for the contribution of an individual Feynman graph G is:

$$I_G(X_1, \dots, X_E) = K_G \int_{\vec{w}} \Gamma_G(\vec{w}) \prod_{1 \le r \ne s \le E} (1 - Z_{rs})^{\sum_{F \in \mathbb{T}_E(r,s)} w_F} . \quad (1)$$

Γ_G is a kernel made from products of gamma-functions, and the quantities Z_{rs} are deSitter space invariants related in a simple way to the signed squared geodesic distance between each pair of deSitter points X_r and X_s. There is one path of integration over a complex variable w_F for each "forest" F in the underlying Feynman graph G, and the forests appearing in the exponent are precisely those connecting the external leg X_r with X_s. This work is also described in the ESI News Vol. **5**, Issue 2, pp. 3–9.

2. During my time as an ESI Senior Fellow, I was able to continue my ongoing scientific collaboration with Prof. Ch. Kopper (Ecole Polytechnique, France) on the convergence properties of the so-called "operator product expansion", which is an important structure in quantum field theory. During his visit in April, we were able to make significant progress on this project by verifying certain key bounds that are needed in order to describe the convergence properties of this expansion. The main new finding of this work, which is in the final writing up stage at present, is that the operator product expansion

$$\langle \phi_A(x_1)\phi_B(x_2)\; X(p_1, \dots, p_n)\rangle = \sum_C C_{AB}^C(x_1 - x_2)\langle \phi_C(x_2)\; X(p_1, \dots, p_n)\rangle \quad (2)$$

is convergent for a wide class of "spectator fields $X(...)$", for arbitrary $x_1 \neq x_2$, and to arbitrary but fixed order in renormalized perturbation theory. This result confirms, and actually goes well-beyond earlier conjectures about the convergence properties of the expansion. Such earlier conjectures had normally suggested that such an expansion might be asymptotic for small $|x_1 - x_2| \to 0$. But the actual (absolute) convergence of the expansion was quite unexpected, and has interesting consequences for the general structure of quantum field theory. While working on this project, I have benefitted also from conversations with Prof. H. Grosse from the Physics Department at Vienna University.

3. I also had many working discussions with Prof. P. Chrusciel from the Physics Department at Vienna University about the nature of higher dimensional black holes. The ideas developed during these discussions might lead to a paper on black hole instabilities in the context of certain Kaluza-Klein theories.

Programme and Workshop Organization: My tenure as ESI Senior Fellow was greatly enhanced by the ESI programme on "Quantum field theory in curved spacetimes and curved target spaces", jointly organized with Profs. M. Gaberdiel (ETHZ), and V. Schomerus (Hamburg U., DESY). This programme and the associated workshop, which is documented in the corresponding ESI-report, as well as extra funds provided by the ESI Senior Fellowship, allowed me to concentrate at the ESI a great number of collegues working in the area of quantum field theory. I have profited enormously from the personal interactions that were made possible by this programme, in particular from those with Profs. R.M. Wald (U. Chicago, USA), K. Fredenhagen (Hamburg U.), J. Teschner (Hamburg U.), I. Runkel (Hamburg U.), N. Nikolov (Sofia), A. Ishibashi (KEK acceleartor, Japan), T. Takanagy (Kyoto U., Japan), Y. Kawahigashi (Tokyo U., Japan), in addition to those already mentioned above.

Tayakal N. Venkataramana: Representations contributing to Cohomology of Arithmetic Groups

Course: The deRham cohomology groups of a locally symmetric space are closely related to Lie algebra cohomology groups. In this way questions about the former groups can sometimes be translated into questions about cohomological properties of infinite-dimensional representations of the underlying real Lie group G. This leads to the basic problem of determining (up to infinitesimal equivalence) the irreducible unitary representations of G with non-vanishing relative Lie algebra cohomology. This problem was solved by Vogan-Zuckerman, based on previous work of Kumaresan and Parthasarathy. To understand their solution, we have to know what it means to describe a unitary representation. Since an explicit realization for the representations with non-zero cohomology is not at hand they have to be desribed by specifying some invariants which any unitary representation has. The invariants needed are the eigenvalue of the Casimir operator of the representation, and the restriction of the representation of G to a maximal compact subgroup $K \subset G$.

The following topics were covered in this course.

(1) We first considered the cohomology of a compact locally symmetric space $X = \Gamma \setminus G/K$ (with Γ a discrete subgroup in G) and proved the Matsushima formula relating the Hodge Laplacian of forms of degree p on X with the action of the Casimir on functions on $\Gamma \setminus G$. This was then easily translated into a problem of classifying representations π of the group G on which the Casimir of G vanishes and which share a K-type with the exterior algebra of $\mathfrak{p}$ (the orthocomplement of $\mathfrak{k}$ in the Lie algebra g of G).

(2) Next we analysed the structure of the spinor module S associated to $\mathfrak{p}$ as a representation of K, and related it to the exterior algebra of $\mathfrak{p}$. We proved Parthasarathy's Dirac Operator Inequality and used this to analyse the representations common with S and $S \otimes \pi$.

(3) We proved Kumaresan's result on which K-types can occur in common with the exterior algebra of $\mathfrak{p}$ and a cohomological representation π. This was fairly involved and we spent four lectures on this.

(4) We proved the result of Vogan-Zuckerman that the only representations with cohomology which can be unitary are the $A_{\mathfrak{q}}$ representations.

(5) Then we constructed (following Vogan-Zuckerman) the representations $A_{\mathfrak{q}}$.

(6) Using the Weil representation, we then indicated in some special cases that the $A_{\mathfrak{q}}$ representations indeed contribute to cohomology of arithmetic groups.

Research: During my stay I worked with the visitor Jürgen Rohlfs on questions related to the Steinberg representation and its reducibility behaviour. In some special cases we could prove that the Steinberg Representation is irreducible. This is work in progress.

With Joachim Schwermer, I discussed the non-vanishing of modular symbols in the cohomology of arithmetic groups, in particular, in the cases where the underlying algebraic group is of exceptional type. The methodological approach relies on some work of Franke. We could exhibit some so-called ghost classes in cases of arithmetic subgroups of a split algebraic k-group of type F_4.

Longterm Visitor: David Masser

Research: I arrived at ESI with a definite plan of research, but I needed some encouragement to start, because I knew it would probably entail some tedious calculation. This encouragement was very soon provided by discussions with Klaus Schmidt.

In February 2010 Harm Derksen and I had already written some notes on non-mixing sets for dynamical actions of algebraic origin. Earlier in 2006 we had been able to answer a question of Klaus Schmidt on how to find effectively the smallest possible cardinality of such sets. He had responded to this work by asking if one could find, also effectively, all the non-mixing sets of that cardinality. The notes of Derksen and myself gave a positive answer and also proved that in reasonable circumstances there are only finitely many such sets under a natural equivalence relation. We thought it would be a good test of the techniques to work out some examples; but preliminary skirmishings indicated that the calculations might be rather tedious.

After the much-needed encouragement I started work. A prime ideal of a Laurent polynomial ring over the rational integers $\mathbf{Z}$ determines a dynamical action. I warmed up with

$$(2,\ 1+x+x^3+x^5+x^6+y) \tag{$*$}$$

in $\mathbf{Z}[x,y,x^{-1},y^{-1}]$. The non-mixing sets are in $\mathbf{Z}^2$, and the example

$$\{(0,0),(3,0),(6,0),(0,1)\}$$

was already known; it comes from the non-constant generator in $(*)$. I managed to find four others namely

$$\{(0,0),(9,0),(6,1),(0,2)\},\quad \{(0,0),(9,0),(0,1),(3,1)\}$$
$$\{(0,0),(18,0),(3,2),(0,3)\},\quad \{(3,0),(12,0),(0,1),(0,2)\}$$

and to prove that these give all the equivalence classes.

Now it seemed that most ideals treated in the literature were principal as in $(*)$, at least after going down to a finite field. Already Derksen and I had settled on

$$(2,\ 1+x+x^2+y,\ 1+x+x^3+z) \tag{$**$}$$

in $\mathbf{Z}[x,y,z,x^{-1},y^{-1},z^{-1}]$ as a promising non-principal example. The generators give the non-mixing sets

$$\{(0,0,0),(1,0,0),(2,0,0),(0,1,0)\},\quad \{(0,0,0),(1,0,0),(3,0,0),(0,0,1)\}$$

in $\mathbf{Z}^3$. By noticing similarly short elements in the ideal, Derksen and I had found two more, namely

$$\{(2,0,0),(3,0,0),(0,1,0),(0,0,1)\},\quad \{(1,0,0),(0,1,0),(0,0,1),(1,1,0)\},$$

and it was clear that there would be a few others.

I happily started the calculations with Maple, and continued them over Easter in a country house near Murau. To my surprise more and more examples turned up. I stuck to it, supposing that they would sort themselves into relatively few equivalence classes. But no! In the end no less than 137 non-mixing sets emerged, the most complicated being

$$\{(21,0,3),(20,1,0),(0,12,0),(0,0,4)\},\quad \{(25,0,0),(20,1,1),(0,12,0),(0,0,4)\}.$$

So indeed effective; but only just! The work was written up and incorporated in the finiteness notes but as yet there is no final version that I can put in a ESI-preprint. For one thing it must be checked that I didn't miss anything in the last example above (the calculations needed 20 hours of close interactive concentration), and I have given a Master Student here this task.

While at ESI I also met my Doctoral Student Dominik Leitner who is writing up his Master Thesis on $U+V-W=1$ which amounts to the determination of all non-mixing sets of cardinality 4 for the prime ideal $(p,\ x+y-1)$ in $\mathbf{Z}[x,y,x^{-1},y^{-1}]$. But here the cardinality is not minimal, so there is no simple finiteness result. It turns out that in characteristic $p = 2$ his results coincide with those in a 2008 paper of Arenas-Carmona, Berend and Bergelson.

Since leaving ESI I have developed the work in the related but not equivalent context of "shortest polynomials in a given ideal" which should interest algebraists who know nothing of dynamical systems.

I gave four talks at ESI. One "Multiple mixing and short polynomials" explained the work of Derksen and myself described above. The three others "Unlikely Intersections I, II, III" were in the context of the "May seminar in number theory" organised by Joachim Schwermer. A year ago I would have said that the two titles were entirely unrelated; but since then it has become clear to me that the corresponding topics are capable of intimate intertwining. This is also confirmed by some recent work with Dale Brownawell on Drinfeld modules and F-modules.

Seminars and colloquia

2010 01 12, J. Krieger: "Concentration Compactness for Critical Wave Maps."
2010 01 12 , P. Raphaël: "Stable blow up dynamics for wave maps and Yang Mills in the presence of symmetries"
2010 01 14, A. Soffer: "Soliton Dynamics and Scattering in Mathematics and Physics"
2010 01 14 , S. Tahvildar Zadeh: "Static Electrovacuum Solutions with No Event Horizons"
2010 01 18 , M. Struwe: "Global well-posedness for the critical semi-linear wave equation on $\mathbb{R}^{2+1}$ with radial symmetry"
2010 01 19 , R. Donninger : "Price's law for Schwarzschild black holes"
2010 01 19 , W. Schlag: "Local decay estimates for waves on a Schwarzschild background"
2010 01 21 , M. Beceanu: "Center stable manifolds for unstable evolution equations"
2010 01 21 , P. Germain: "Global existence for the water-wave equation"
2010 01 26, M. Choptuik: "Ultra Relativistic Particle Collisions"
2010 01 26 , P. Forgacs: "Localized breather-type objects in field theories"
2010 01 28, A. Rendall: "Relations between Gowdy and Bianchi spacetimes"
2010 01 28 , J. Velazquez: "The construction of singular solutions for kinetic equations."
2010 02 02, M. Zworski: "Resonances/Quasinormal modes: an introduction."
2010 02 02 , P. LeFloch: "Einstein spacetimes with distributional curvature"
2010 02 04 , A. Laszlo: "The Use of GridRipper in Solving 3+1 Dynamical Problems."
2010 02 04 , I. Racz: "Numerical investigation of spacetime singularities"
2010 02 05, M. Zworski: "Quasinormal modes for black holes"
2010 02 09, J. Martín-García: "An Updated Review on Critical Phenomena in Gravitational Collapse"
2010 02 11, J. Velazquez: "Type II blow-up in parabolic problems"
2010 02 16, L. Andersson: "Hidden symmetries and linear fields on Kerr"
2010 02 16 , N. Szpak: "Pointwise decay estimates and asymptotics for semilinear wave equations with small and large data"
2010 02 18, O. Rinne: "Axisymmetric constrained evolution to future null infinity"
2010 02 18 , V. Moncrief: "Regularity of Einstein's equations at future null infinity"
2010 02 23 , I. Sigal: "Collapse dynamics in Yang-Mills and wave map equations"
2010 03 22 , I. Runkel: "Conformal Field Theory with Boundaries"
2010 03 23 , H. Olbermann: "Vertex Algebras in Quantum Field Theory"
2010 03 23 , T. Gannon: "The Exoticness and Realisability of Haagerup-Izumi Modular Data"
2010 03 24 , N. Nikolov: "Field Equations in Vertex Algebras"
2010 03 24 , T. Gannon: "Modular Invariants and Twisted Equivariant K-theory"
2010 03 25 , C. Dappiaggi: "Beyond the event horizon: the Hadamard property of the Unruh state"
2010 03 25 , D. Kreimer: "Powercounting in Quantum Gravity"
2010 03 25 , R. Wald: "Self-Force and Back-Reaction on a Classical Point Charge"
2010 03 26 , K. Fredenhagen: "A Forest Formula for Epstein-Glaser Renormalization"
2010 03 26 , M. Salmhofer: "Trees in Wilsonian Renormalization"
2010 04 07 , A. Konechny: "Gradient formula for the beta function of a 2D quantum field theory"
2010 04 08 , B. Craps: "D-Brane Potentials from Multi-Trace Deformations in AdS/CFT"

2010 04 12, Y. Kawahigashi: “Superconformal field theories and operator algebras”
2010 04 15, C. Fewster: “Probability distributions of smeared quantum stress tensors”
2010 04 15, U. Moschella: “QFT in deSitter space: Recent results”
2010 04 16, K. Sanders: “Singularities of n-point distributions in QFT on curved spacetimes”
2010 04 16, R. Longo: “An algebraic construction of boundary QFT”
2010 04 20, A. Ishibashi: “Quantum field propagation near spacetime singularities”
2010 04 23, M. Struwe: “Quantization Results in Geometric Analysis”
2010 04 26, I. Todorov: “4D Vertex Algebras and CFT models”
2010 04 28 , V. Rivasseau: “New tools for quantum field theory”
2010 04 29, T. Takayanagi: “Holographic Entanglement Entropy”
2010 04 30, J. Teschner: “Remarks on some sigma model dualities”
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FBY = Matter and Radiation
GHS = Quantum Field Theory in Curved Spacetime
HLS = The $\bar{\partial}$-Neumann Problem: Analysis, Geometry, and Potential Theory
HRL = AdS Holography and the Quark Gluon Plasma
JF = Junior Research Fellow
KRT = Diskrete Mathematik
KKZ = Topological String Theory, Modularity and Non-Perturbative Physics
MSS = ESI May Seminar 2011 in Number Theory
SCH = Guest of Prof. Schmidt
SCHW = Guest of Prof. Schwermer
SF = Senior Research Fellow
SFS = Senior Research Fellow Share
THI = Guest of Prof. Thirring
VS = 7th Vienna Central European Seminar on Particle Physics and Quantum Field Theory
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Papadimitriou Ioannis, CERN, Genève, Theory Division; 17.08.2010 – 22.08.2010, HRL;
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Park Jae-Suk, Yonsei University, Seoul; 19.10.2010 – 25.10.2010, BAS;
Parkhomenko Sergey, L. D. Landau Institute for Theoretical Physics, Moscow; 19.07.2010 – 29.07.2010, KKZ;
Pearlstein Gregory James, Michigan State University; 27.06.2010 – 29.06.2010, KKZ;
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Perez Joe J., University of Vienna; 13.12.2010 – 23.12.2010, HLS;
Petkou Anastasios, University of Crete, Dept. of Physics; 17.08.2010 – 28.08.2010, HRL;
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Poncin Norbert, University of Luxembourg; 18.10.2010 – 27.10.2010, BAS;
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Preis Florian, Technical University of Vienna; 02.08.2010 – 28.08.2010, HRL;
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Ptitsyna Olga, ITEP, Moscow; 19.07.2010 – 24.07.2010, KKZ;
Putrov Pavel, Université de Genève, Section de mathematiques; 20.06.2010 – 30.06.2010, KKZ; 19.07.2010 – 23.07.2010, KKZ;
Qin Fan, Université Paris 7 Diderot; 18.10.2010 – 23.10.2010, BAS;
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Rácz István, RMKI, Budapest; 31.01.2010 – 14.02.2010, ABS; 17.02.2010 – 19.02.2010, ABS;
Raich Andrew, University of Arkansas, Fayetteville; 12.12.2010 – 19.12.2010, HLS;
Raphael Pierre, Université de Paul Sabatier, Toulouse; 11.01.2010 – 15.01.2010, ABS;
Rashkov Radoslav, Sofia University, Faculty of Physics; 21.06.2010 – 28.06.2010, KKZ; 02.08.2010 – 28.08.2010, HRL;
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Rebhan Anton, ITP, Technical University Vienna; 02.08.2010 – 29.10.2010, HRL;
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Rendall Alan, MPI für Gravitationsphysik, Golm; 17.01.2010 – 29.01.2010, ABS;
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Rinne Oliver, DAMTP, University of Cambridge; 15.02.2010 – 19.02.2010, ABS;
Rogers Christopher Lee, University of California, Riverside, Department of Mathematics; 01.09.2010 – 31.10.2010, JF;
Rohlfs Jürgen, Universität Eichstätt-Ingolstadt; 24.04.2010 – 09.05.2010, SCHW; 01.12.2010 – 12.12.2010, SCHW;
Romatschke Paul, FIAS Frankfurt; 09.08.2010 – 11.08.2010, HRL; 23.08.2010 – 27.08.2010, HRL;
Rosenzweig Lior, Tel Aviv University, School of Mathematical Siences; 02.05.2010 – 09.05.2010, MSS;
Roubtsov Vladimir, Université d'Angers, Départment de Mathématiques; 10.10.2010 – 21.10.2010, BAS;
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Roytenberg Dmitry, Utrecht University, Department of Mathematics; 04.09.2010 – 19.09.2010, BAS; 24.10.2010 – 29.10.2010, BAS;
Ruan Yongbin, University of Michigan, Department of Mathematics; 20.07.2010 – 25.07.2010, KKZ;
Rudnick Zeev, Tel Aviv University; 03.05.2010 – 08.05.2010, MSS;
Runkel Ingo, Universität Hamburg; 19.03.2010 – 28.03.2010, GHS;
Ruppenthal Jean, Bergische Universität Wuppertal; 12.12.2010 – 17.12.2010, HLS;
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Sakai Tadakatsu, Nagoya University; 14.08.2010 – 21.08.2010, HRL;
Sakalos Stefan, University of Geneva; 19.10.2010 – 22.10.2010, BAS;
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Schlesinger Karl-Georg, Universität Wien, Fakultät Physik; 21.06.2010 – 30.06.2010, KKZ;
Schlichenmaier Martin, University of Luxembourg; 15.07.2010 – 22.07.2010, KKZ;
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Schöbel Konrad, Friedrich-Schiller-Universität Jena, Mathematisches Institut; 26.07.2010 – 30.07.2010, CAP;
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Tsygan Boris, Northwestern University, Chicago; 24.10.2010 – 29.10.2010, BAS;
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Vacaru Sergiu, Universitatea Alexandru Ioan Cuza, Iasi; 03.11.2010 – 05.11.2010, YNG;
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Wald Robert, University of Chicago, Physics Department; 18.03.2010 – 27.03.2010, GHS;
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Westrich Matthias, Aarhus University; 30.05.2010 – 01.06.2010, FBY; 01.06.2010 – 30.06.2010, JF; 19.07.2010 – 25.07.2010, FBY;
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