EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Mathematisch-Naturwissenschaftliche Fakultät

Department of Mathematics

Module Handbook

Mathematical Physics

Master of Science

Winter Semester 2024

Version: 8th May 2024

Contents

1 Program description

1.1 Study Concept

The Master of Science Mathematical Physics is an international research-oriented two year master's program offered jointly by the departments of Mathematics and Physics within the Faculty of Science of the University of Tübingen starting every year in the winter semester. It is geared towards students with a solid background in Mathematics as well as in Physics, and it requires a bachelor's degree in physics or mathematics or an equivalent degree. The scientific discipline "Mathematical Physics" is concerned with the mathematically rigorous formulation and analysis of physical theories and models. In this master's program students will thus deepen and broaden their knowledge of Mathematics and Physics in interdisciplinary courses in Mathematical Physics as well as in disciplinary courses in Mathematics and Theoretical Physics. At the end of the program they are particularly well prepared for jobs where the typical competences of mathematicians are needed in combination with applications of physics. The program is international and cannot be pursued without a solid knowledge of the English language. Language skill on the level of B2 according to the European Framework of Reference for Languages are therefore required. All mandatory modules and a large number of facultative modules are offered only in English. Some facultative modules may sometimes be offered only in German.

1.2 Qualification Goals

Students deepen and broaden their theoretical knowledge of different areas of mathematical physics, mathematics and theoretical physics. They become proficient in general and specific methods and principles in these areas. They can connect problems and questions from physics with their counterparts in mathemtical models and are able to judge and critically question the relevance and adequacy of mathematical models and the derived consequences. They are able to report on and scrutinize the current state of research in the area of their specialisation. Graduates can apply their expanded knowledge in order to develop and successfully handle their own research projects. They are able to present, discuss, and defend the results of their research in writing and orally in front of a scientific audience. In the course of the Mathematical Physics Colloquium students practice scientific collaboration and discourse in interdisciplinary and internationally mixed groups.

Their education enables graduates in mathematical physics to successfully and professionally tackle complex mathematical modelling problems in physics and, after an appropriate familiarization with the subject, also in other areas of technology, finance or economics. They are moreover well prepared for interdisciplinary and international collaborations in mixed teams of different specialists from different cultural backgrounds, as are common nowadays in all areas of research and development.

1.3 Program Structure

The Master's Program is a two year (four terms) consecutive study program with a modular structure. Based on the foundational modules "Geometry in Physics", "Functional Analysis in Geometry", "Mathematical Quantum Theory", and "Mathematical Relativity", to be attended during the first year, students can specialise rather freely according to their personal preferences in one or more areas of Mathematical Physics, Mathematics and/or Theoretical Physics. The few restrictions are that every student must take at least one module from the Mathematics master's program and one module from the Theoretical Physics master's program, as well as a seminar. As a consequence, all graduates of the Master's Program have proven their ability to successfully conduct mathematical studies and theoretical physics studies at the master's level. A Scientific Project in the third term typically serves as a preparation for the Master Thesis (M.Sc. Thesis, 30 ECTS-points) written during the final term. During the second year students are also required to attend the Mathematical Physics Colloquium. This is a weekly colloquium where specialists lecture about recent developments in Mathematical Physics, and students have the opportunity to meet and discuss with international guest scientists and local researchers about current topics. The prescribed period of study is two years corresponding to a total of 120 ECTS points.

1.4 Mentoring

At the start of the program every student will be assigned to a mentor from the group of professors involved in the master's program for the whole duration of his/her studies. Students meet their mentor at the beginning and later at least once per term in order to plan and discuss the progress of their studies. In particular, at these meetings the study and examination plan in compliance with the examination regulations is discussed. The module selection is documented and passed on to the head of the examinations board for approval. During the first meeting possible gaps in the knowledge should be discussed in order to fill them by taking appropriate courses within the area of elective specialisation. The study and examination plan is then updated every semester during the meetings with the mentor. The mandatory mentoring program assures that students specialise in a purposeful way and select accordingly goal-oriented combinations of modules from mathematics and physics.

During the meetings with the mentor also possible time slots for a study period at a university abroad can be discussed. In principle, every semester is suitable, depending on the study progress of the student and the courses avaliable at the other institution. It is also possible to write the master's thesis during a stay abroad under the cosupervision of a scientist there.

1.5 Information for students with a bachelor's degree in Physics at the University of Tübingen

Graduates of the 4-year degree program Bachelor of Science in Physics at the University of Tübingen can already gain up to 60 credit points for the degree program Master of Science in Mathematical Physics during their bachelor studies.
In particular,

- the module BMTPKFT Klassische Feldtheorie from the bachelor's program can be credited with

9 credit points for the module MAT-40-32 Advanced Topics in Theoretical Physics in the master's program, and

- up to 21 credit points in the section Vertiefungsfach in the bachelor's program can be credited in the section Elective Studies, provided the choice is suitable.

Moreover,

- up to 27 credit points in the section Ergänzungsmodule in the bachelor's program can be gained via the modules MAT-65-11 Geometry in Physics, MAT-65-12 Mathematical Quantum Theory, MAT-65-13 Mathematical Relativity or MAT-65-14 Mathematical Statistical Physics from the master's program, and
- the bachelor's thesis can be credited with 9 credit points in the module Scientific Project.

In order to finish the Master of Science in Mathematical Physics subsequently to the bachelor's degree in Physics at the University of Tübingen it is recommended to choose in the section Vertiefungsfach in the bachelor's program courses in theoretical physics, which can be credited in the section Elective Studies in the master's program in Mathematical Physics. Moreover, it is recommended to choose in the section Ergänzungsmodule in the bachelor's program at least two of the modules MAT-65-11, MAT-65-12, MAT-65-13 or MAT-65-14 from the master's program in Mathematical Physics. Good choices would be the combinations MAT-65-11 + MAT-65-13 and MAT-65-12 + MAT-65-14. Also the combination MAT-65-11 and MAT-65-12 would be suitable.

2 Study Plans

2.1 Overview by Modules

We provide here an overview of the study plan as a table showing the modules to be taken.

Suggested Term	Module Number	Module Title	Type of Course	Type of Module	Assign-ments	Type of Exam	ECTS-Points
Section 1: Foundations							
1	MAT-65-11	Geometry in Physics	L+E	PM	HA	wr. o. or.	9
1	MAT-65-12	Mathematical Quantum Theory	L+E	PM	HA	wr. o. or.	9
2	MAT-65-13	Mathematical Relativity	L+E	PM	HA	wr. o. or.	9
Section 2: Knowledge Expansion							
1–3	MAT-40-31	Advanced Topics in Mathematics	L+E	PMW	HA	wr. o. or.	9
1–3	MAT-40-32	Advanced Topics in Theoretical Physics	L+E	PMW	HA	wr. o. or.	9
2–3	MAT-40-33	Seminar Knowledge Extension	S	PMW	s.M.	P	3
Section 3: Elective Specialisation							
2-3	MAT-65-14	Mathematical Statistical Physics	L+E	WPM	HA	wr. o. or.	9
2-3	MAT-65-15	Foundations of Quantum Mechanics	L+E	WPM	HA	wr. o. or.	9
2-3	MAT-65-21	Advanced Topics in Mathematical Quantum Theory	L+E	WPM	HA	wr. o. or.	9
2	MAT-65-22	Advanced Topics in Mathematical Quantum Theory (short version)	L+E	WPM	HA	wr. o. or.	6
3	MAT-65-23	Advanced Topics in Mathematical Relativity	L+E	WPM	HA	wr. o. or.	9
3	MAT-65-24	Advanced Topics in Mathematical Relativity (short version)	L+E	WPM	HA	wr. o. or.	6
2-3	MAT-65-35	Quantum Shannon Theory and Beyond	L+E	WPM	HA	wr. o. or.	9
Section 4: Scientific Work							
3	MAT-40-41	Scientific Project	P	PM	s.M.	-	9
3–4	MAT-40-42	Mathematical Physics Colloquium	C+C	PM	-	-	3
4	MAT-40-43	Master Thesis M.Sc. Mathematical Physics	MT	PM	s.M.	MT	30

Abbreviations:
L=lecture, S=seminar, SL=seminar or lecture, E=exercise class, Pr=project work, C=colloquium, T=tutorial, IC=inverted classroom
PM=compulsory module, PMW=compulsory module with choice, WPM=elective module
HA=homework assignment, MT=master thesis, or.=oral exam, wr.=written exam, o.=or, P=presentation
s.M. = see module description

Within the area "Elective Specialization", the listed modules from the Mathematical Physics program can be chosen as well as a large number of advanced modules from the master's degree programs Mathematics, Physics, or Astro and Particle Physics, cf. Section 3.

2.2 Overview by the Course of Studies

We first provide a general study plan showing the distribution of credit points over the different areas and the general time line. On the following pages example study plans for different types of specialisation are provided, where possible courses are assigned to the modules MAT-40-31 and MAT-40-32 as well as the modules from the area of Elective Specialisation.

<table>
<tr><th>Term</th><th>CP</th><th>Foundations of Mathematical Physics</th><th>Knowledge Expansion</th><th>Elective Specialisation</th><th>Scientific Work</th></tr>
<tr><td>1.</td><td>27</td><td rowspan="2">27 CP</td><td rowspan="3">21 CP</td><td></td><td></td></tr>
<tr><td>2.</td><td>30</td><td rowspan="2">30 CP</td><td></td></tr>
<tr><td>3.</td><td>31</td><td></td><td rowspan="2">42 CP</td></tr>
<tr><td>4.</td><td>32</td><td></td><td></td><td></td></tr>
</table>

Figure 2.1: General Study Plan

2.3 Example Study Plans

The example study plans shown below shall give an idea how the individual study in the different specialisations could look like. They are not meant as a recommendation, and it is neither guaranteed that the courses listed will be offered each year, nor that they all will be given in English.

Example Study Plan without Specialisation

Term	CP	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientific Work	
1.	27	Geometry in Physics (9 CP) Mathematical Quantum Theory (9 CP)	Linear Partial Differential Equations (9 CP)			
2.	30	Mathematical Relativity (9 CP)	Seminar(3 CP)	Advanced Topics in Mathematical Quantum Theory (9 CP) Mathematical Statistical Physics (9 CP)		
3.	31		Quantum Field Theory and Particle Physics (9CP)	Advanced Topics in Mathematical Relativity (6 CP) Advanced Topics in Mathematical Statistical Physics (6 CP)	Mathe-matical Physics Colloquium (3 CP)	Scientific Project (9 CP)
4.	32					Master Thesis (30 CP)

Figure 2.2: The program Mathematical Physics can be completed to a large extent also without choosing a particular specialisation. In this case we recommend taking all four foundational modules and also all advanced courses offered. The modules from the area Knowledge Expansion should then be chosen in accordance with the planned specialisation in the Scientific Project and the Master Thesis, cf. e.g. the following study plans.

Example Study Plan Quantum Theory

Term	CP	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientific Work	
1.	27	Geometry in Physics (9 CP) Mathematical Quantum Theory (9 CP)	Operator Theory (9 CP)			
2.	30	Mathematical Relativity (9 CP)	Quantum Field Theory and Particle Physics (9 CP) Seminar(3 CP)	Functional Analysis (9 CP)		
3.	31			Advanced Topics in Mathematical Quantum Theory (9 CP) Computational Methods in Physics / Astrophysics (6 CP) Theoretical Condensed Matter Physics (6 CP)	Mathe-matical Physics Colloquium (3 CP)	Scientific Project (9 CP)
4.	32					Master Thesis (30 CP)

Figure 2.3: The mathematical foundations of quantum theory are predominantly allocated to areas of analysis. Thus we recommend that those specialising in one of the areas Mathematical Quantum Theory, Quantum Field Theory, Condensed Matter, Many-Body Quantum Systems, or Quantum Information attend mathematical courses from analysis, e.g. Operator Theory, Partial Differential Equations, Calculus of Variations, and Numerical Analysis.

Example Study Plan Relativity

Term	CP	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientific Work	
1.	27	Geometry in Physics (9 CP) Mathematical Quantum Theory (9 CP)	Astronomy and Astrophysics (9 CP)			
2.	30	Mathematical Relativity (9 CP)	Introduction to Partial Differential Equations (9 CP) Seminar(3 CP)	Riemannian Geometry (9 CP)		
3.	31			Advanced Topics in Mathematical Relativity (9 CP) Theoretical Astrophysics (6 CP) Computational methods in Physics / Astrophysics (6 CP)	Mathe-matical Physics Colloquium (3 CP)	Scientific Project (9 CP)
4.	32					Master Thesis (30 CP)

Figure 2.4: The mathematical foundations of relativity are predominantly allocated to areas of geometry and analysis. Thus we recommend that those specialising in one of the areas Mathematical Relativity, Astronomy, Cosmology, or Astro Physics attend mathematical courses from geometry, e.g. Riemannian Geometry and Lorentz Geometry, and from analysis, e.g. Partial Differential Equations, Calculus of Variations, and Numerical Analysis.

Example Study Plan Statistical Physics

Term	CP	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientific Work	
1.	27	Geometry in Physics (9 CP) Mathematical Quantum Theory (9 CP)	Probability Theory (9 CP)			
2.	30	Mathematical Relativity (9 CP)	Advanced Statistical Physics (9 CP)	Mathematical Statistical Physics (9 CP) Density Functional Theory (6 CP)		
3.	31		Seminar (3CP)	Advanced Topics in Mathematical Statistical Physics (6 CP) Mathematical Statistics (9 CP)	Mathe-matical Physics Colloquium (3 CP)	Scientific Project (9 CP)
4.	32					Master Thesis (30 CP)

Figure 2.5: The mathematical foundations of statistical physics are predominantly allocated to areas of probability. Thus we recommend that those specialising in one of the areas Mathematical Statistical Physics, Soft Matter, or Density Functional Theory attend mathematical courses from probability, e.g. Probability Theory and Mathematical Statistics.

2.4 Overview by Study Progress and Credit Requirements

Overview by Study Progress and Credit Requirements													
		Exam				**Teaching**				**Term**			
		Type of Exam	Duration (min)	Grading	Weight in the final grade	Type of Course	Status	SWS	ECTS Points (CP)	The allocation of exams / ECTS points to semesters is a recommendation only. Compulsory allocations are marked as such. The allocation of ECTS points to courses is for information only. Credits are only awarded upon completion of the module.			
										1. CP	2. CP	3. CP	4. CP
Foundations of Mathematical Physics:									**27**				
MAT-65-11 Geometry in Physics								6	9				
1.	Lecture	Wr. or Or.	90–120 or 20–30	g	9	L	o	4		6			
2.	Exercises					E	o	2		3			
MAT-65-12 Mathematical Quantum Theory								6	9				
1.	Lecture	Wr. or Or.	90–120 or 20–30	g	9	L	o	4		6			
2.	Exercises					E	o	2		3			
MAT-65-13 Mathematical Relativity								6	9				
1.	Lecture	Wr. or Or.	90–120 or 20–30	g	9	L	o	4			6		
2.	Exercises					E	o	2			3		
Knowledge Expansion:									**21**				
MAT-40-31 Advanced Topics in Mathematics								6	9				
1.	Lecture	Wr. or Or.	90–120 or 20–30	g	9	L	o	4		6			
2.	Exercises					E	o	2		3			
MAT-40-32 Advanced Topics in Physics								6	9				
1.	Lecture	Wr. or Or.	90–120 or 20–30	g	9	L	o	4			6		
2.	Exercises					E	o	2			3		
MAT-40-33 Seminar								2	3				
1.	Seminar	Pres.	45–90	g	3	S	o	2				3	
Elective Specialisation:									**30**				
Here the modules MAT-65-15 and MAT-65-21 to MAT-65-26, as well as further suitable advanced modules from the Master's Programs in Mathematics, Physics, and Astro and Particle Physics, can be chosen. The choices need to be discussed and agreed upon with the Mentor. Modules from other areas need to be approved by the examinations board.													
MAT-65-14 Mathematical Statistical Physics								6	9				
1.	Lecture	Wr. or Or.	90–120 or 20–30	g	9	L	f	4			6		
2.	Exercises					E	f	2			3		
MAT-65-21 Advanced Topics in Mathematical Quantum Theory								6	9				
1.	Lecture	Wr. or Or.	90–120 or 20–30	g	9	L	f	4			6		

Overview by Study Progress and Credit Requirements													
		Exam				**Teaching**				**Term**			
		Type of Exam	Duration (min)	Grading	Weight in the final grade	Type of Course	Status	SWS	ECTS Points (CP)	The allocation of exams / ECTS points to semesters is a recommendation only. Compulsory allocations are marked as such. The allocation of ECTS points to courses is for information only. Credits are only awarded upon completion of the module. 1. CP	2. CP	3. CP	4. CP
2.	Exercises					E	f	2			3		
MAT-65-22 Advanced Topics in Mathematical Quantum Theory (short version)								4	6				
1.	Lecture	Wr. or Or.	90–120 or 20–30	g	6	L	f	2			3		
2.	Exercises					E	f	2			3		
MAT-65-23 Advanced Topics in Mathematical Relativity								6	9				
1.	Lecture	Wr. or Or.	90–120 or 20–30	g	9	L	f	2				3	
2.	Exercises					E	f	2				3	
MAT-65-24 Advanced Topics in Mathematical Relativity (short version)								4	6				
1.	Lecture	Wr. or Or.	90–120 or 20–30	g	6	L	f	2				3	
2.	Exercises					E	f	2				3	
Scientific Work									**42**				
MAT-40-41 Scientific Project									9				
1.	Project	Proj.		ng	9		o					9	
MAT-40-42 Mathematical Physics Colloquium									3				
1.	Colloquium			ng			o					1	2
MAT-40-43 Master Thesis									30				
1.	Thesis	Thes.		g	30		o						30

Abbreviations:

Marking system : g=graded, ng=non graded
Form of examination : MA=Master Thesis, Or.=oral exam, Wr.=written exam, Pres.=presentation
Form of teaching : L=lecture, E=exercise class, S=seminar, Proj.=project work, Coll.=colloquium
Status : o=obligatory, f=fakultative
Other : o.=or, SWS=hours in class per week, CP=credit points=ECTS points

3 Module Descriptions

Section 1: Foundations

In the case that some of the mandatory modules in this section or modules, which are essentially identical as far as the contents and competences are concerned, have been part of the Bachelor studies, which are the prerequisite for this Master's Degree Program, according to the examination regulations these modules cannot be taken in the Master's Degree Program any more. They have to be replaced by other suitable modules in the framework of the studies and examination plan.

Module Number: **MAT-65-11**	**Module Title:** Geometry in Physics		**Type of Module:** Compulsory Module
ECTS-Points	9		
Workload **- Time in Class** **- Self-Study**	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h
Duration	1 Semester		
Frequency	regularly in Winter Semester		
Term	1		
Language of Instruction	English		
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements		
Content	The module provides an introduction to fundamental methods of differential geometry and their relevance for physics. Particular topics are manifolds, differential forms, Riemannian metrics and associated notions of curvature, Riemannian geometry of submanifolds, real vector bundles, and connections. Applications of these concepts in Physics are discussed.		
Objectives	Students obtain knowledge, understanding, and acquaintance with the use of the listed notions of differential geometry. They develop, in particular, a deeper understanding of differential and integral calculus and experience through examples how the mathematical notions are naturally applied within physical theories. Students are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.		

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Geometry in Physics	L	o	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
		E	o	2	3					
	In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.									
Literature	**Exemplary Literature:** • John Lee: Introduction to smooth manifolds. Springer 2012. • John Lee: Riemannian manifolds: An introduction. Springer 1997. • Chris Isham: Modern differential geometry for physicists. World Scientific 1999. • Mikio Nakahara: Geometry, Topology and Physics. IOP Publishing 2003.									
Transfer	Participation in the module is a prerequisite for participation in the module Mathematical Relativity. Successful completion of the module may be a prerequisite for participation in the module Seminar Knowledge Extension and is so for the participation in the module Scientific Project.									
Prerequisites	-									
Responsible Persons	Christoph Bohle, Carla Cederbaum, Stefan Teufel									

Abbreviations:

f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom

<table>
<tr><td>Module Number:
MAT-65-12</td><td colspan="2">Module Title:
Mathematical Quantum Theory</td><td>Type of Module:
Compulsory Module</td></tr>
<tr><td>ECTS-Points</td><td colspan="3">9</td></tr>
<tr><td>Workload
- Time in Class
- Self-Study</td><td>Workload:
270 h</td><td>Time in Class:
90 h</td><td>Self-Study:
180 h</td></tr>
<tr><td>Duration</td><td colspan="3">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="3">regularly in Winter Semester</td></tr>
<tr><td>Term</td><td colspan="3">1</td></tr>
<tr><td>Language of Instruction</td><td colspan="3">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="3">Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements</td></tr>
<tr><td>Content</td><td colspan="3">The module provides an introduction to mathematical methods that play an essential role in the formulation and analysis of quantum theories. Topics include the Fourier transform, distributions, Hilbert spaces, unitary groups and their generators, spectral theory of self-adjacent operators, spectral theorem, tensor products, POVMs, spectral measures, and trace class operators. In addition, basic ideas from more specific methods such as Rayleigh-Schrödinger perturbation theory, Hartree resp. Hartree-Fock theory, the Fock space formalism, scattering theory, adiabatic theory or semiclassical analysis can be discussed. The mentioned mathematical methods and areas are motivated in the lecture from quantum theory and applied to examples from quantum theory.</td></tr>
<tr><td>Objectives</td><td colspan="3">Students know and understand the terms and methods mentioned above and can use them to analyse known and new questions from quantum theory. They are able to understand and explain the statements and proofs of the lecture. Furthermore, they link physical problems and their mathematical modelling and are able to question the relevance and adequacy of mathematical modelling and the mathematical results derived from it. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.</td></tr>
<tr><td>Requirements for Obtaining Credit, Grading, Weight if applicable</td><td colspan="3">
<table>
<tr><th>Title</th><th>Type of Course</th><th>Status</th><th>SWS</th><th>ECTS</th><th>Assignments</th><th>Type of Exam</th><th>Dur. of Exam (min)</th><th>Grading</th><th>Weight for Grade</th></tr>
<tr><td rowspan="2">Mathematical Quantum Theory</td><td>L</td><td>o</td><td>4</td><td>6</td><td rowspan="2">yes</td><td rowspan="2">wr. o.
or.</td><td rowspan="2">90-180
o. 20-30</td><td rowspan="2">g</td><td rowspan="2">100</td></tr>
<tr><td>E</td><td>o</td><td>2</td><td>3</td></tr>
</table>
In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.</td></tr>
<tr><td>Transfer</td><td colspan="3">Successful completion of module Mathematical Quantum Theory is a prerequisite for the participation in the module Advanced Topics in Mathematical Quantum Theory. Successful completion of one of the modules Mathematical Quantum Theory and Mathematical Relativity is a prerequisite for the participation in the module Scientific Project.</td></tr>
<tr><td>Prerequisites</td><td colspan="3">-</td></tr>
<tr><td>Responsible Persons</td><td colspan="3">Stefan Teufel</td></tr>
</table>

Abbreviations:

f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom

Module Number: MAT-65-13	**Module Title:** Mathematical Relativity	**Type of Module:** Compulsory Module
ECTS-Points	9	
Workload - Time in Class - Self-Study	Workload: 270 h / Time in Class: 90 h	Self-Study: 180 h
Duration	1 Semester	
Frequency	regularly in Summer Semester	
Term	2	
Language of Instruction	English	
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements	
Content	The module provides an introduction to the mathematical theory of relativity. Particular topics are Newton's theory of gravity, special theory of relativity, relativistic effects, Einstein's equation, Schwarzschild model. Optionally, other topics such as cosmological models, matter models, black holes, Cauchy problem and ADM decomposition, singularity theorems or gravitational waves can be discussed.	
Objectives	Students obtain knowledge and understanding of the listed notions and methods and can use them to analyse known and new problems from the theory of relativity. They are able to interrelate physical problems in cosmology and astrophysics and their mathematical models through methods from differential geometry and to question the relevance and adequacy of the mathematical model and of the results derived from it. Thereby, they enhance their knowledge on methods and subjects gained throughout the first semester, in particular in module MAT-65-11. Students are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.	

Requirements for Obtaining Credit, Grading, Weight if applicable

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Mathematical Relativity	L	o	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	E	o	2	3					

In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.

Transfer	Successful completion of module Mathematical Relativity is a prerequisite for the participation in the module Advanced Topics in Mathematical Relativity. Successful completion of one of the modules Mathematical Relativity or Mathematical Quantum Theory is a prerequisite for the participation in the module Scientific Project.
Prerequisites	Participation in the module Geometry in Physics is a prerequisite.
Responsible Persons	Carla Cederbaum, Gerhard Huisken, Frank Loose

Abbreviations:

f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom

Section 2: Knowledge Expansion

Module Number: MAT-40-31	**Module Title:** Advanced Topics in Mathematics		**Type of Module:** Compulsory Module with Choice
ECTS-Points	9		
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h
Duration	1 Semester		
Frequency	Every Semester		
Term	1–3		
Language of Instruction	English or German		
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements		
Content	It is required to attend one or more lectures as well as the respective exercise classes with the correspondent SWS-coverage from the Master's degree program in Mathematics. Recommended subjects are for instance Partial differential equations, Numerics of differential equations, Harmonic analysis, Lie groups, Nonlinear functional analysis, Operator theory, Stochastic processes, Calculus of variations, Symplectic geometry, Algebraic topology or Algebraic geometry. Further details can be found in the module handbook of the degree program M.Sc. Mathematics.		
Objectives	The students aquire deepend knowledge in one selected area of mathematics independently of physical applications. They broaden the basis of their mathematical knowledge and extend the methods at hand to tackle mathematical problems. The further qualification goals, in particular the concrete content related qualifaction goals, will follow from the module description of the chosen course in the module handbook for the M.Sc. Mathematics.		

Requirements for Obtaining Credit, Grading, Weight if applicable

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Advanced Topics in Mathematics	L	o	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	E	o	2	3					

In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.

Transfer	The module may be a prerequisite for the master thesis.
Prerequisites	See prerequisites in the Module Handbook M.Sc. Mathematics.
Responsible Persons	Die Studiendekanin oder der Studiendekan des Fachbereichs Mathematik

Abbreviations:

f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom

Module Number: MAT-40-32	**Module Title:** Advanced Topics in Theoretical Physics		**Type of Module:** Compulsory Module with Choice
ECTS-Points	9		
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h
Duration	1 Semester		
Frequency	Every Semester		
Term	1–3		
Language of Instruction	English or German		
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements		
Content	It is required to attend one or more advanced-level lectures from the field of theoretical physics as well as the respective exercise classes with the correspondent SWS-coverage from the Master's degree program in Physics or the Master's degree program Astro and Particls Physics. Recommended subjects are for instance Quantum field theory and Particle physics, Theoretical astrophysics, Relativistic astrophysics, Many-particle quantum systems, Advanced statistical physics, Yang-Mills theory, Condensed matter physics, Theoretical quantum optics, Quantum information theory, Cosmology, Numerical methods in physics and astrophysics, Current topics in theoretical physics. Further details can be found in the module handbook of the corresponding degree programs.		
Objectives	The students aquire deepend knowledge in one selected area of theoretical physics independently of rigorous mathematical formalism. They broaden the basis of their knowledge in theoretical physics and extend the methods at hand to tackle problems in physics. The further qualification goals, in particular the concrete content related qualifaction goals, will follow from the module description of the chosen course in the module handbook for the M.Sc. Pysics or the M.Sc. Astro and Particle Physics.		

Requirements for Obtaining Credit, Grading, Weight if applicable

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Advanced Topics in Theoretical Physics	L	o	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	E	o	2	3					

In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.

Transfer	The module may be a prerequisite for the master thesis.
Prerequisites	See prerequisites in the Module Handbook M.Sc. Physics or M.Sc. Astro and Particle Physics.
Responsible Persons	Die Studiendekanin oder der Studiendekan des Fachbereichs Physik

Abbreviations:
f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom

Module Number: MAT-40-33	**Module Title:** Seminar Knowledge Extension		**Type of Module:** Compulsory Module with Choice
ECTS-Points	3		
Workload - Time in Class - Self-Study	Workload: 90 h	Time in Class: 30 h	Self-Study: 60 h
Duration	1 Semester		
Frequency	Every Semester		
Term	2–3		
Language of Instruction	English or German		
Forms of Teaching and Learning	Seminar: Presentation, Discussion, Teamwork, Handout		
Content	Various topics from various areas of Mathematical Physics, Mathematics or Theoretical Physics.		
Objectives	The students have learnt to develop independently or in team an acquaintance with an advanced topic in Mathematics or Physics by applying scientific methods and to present it in form of an oral presentation. They have improved their skills in the presentation of mathematical or physical results and are able to argue for these results in critical discussions.		

Requirements for Obtaining Credit, Grading, Weight if applicable

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Seminar	S	o	2	3	yes	P	45–90	g	100

Transfer	The module may be a prerequisite for the master thesis.
Prerequisites	Successful completion of one of the modules from the section "Foundations of Mathematical Physics".
Responsible Persons	Stefan Teufel

Abbreviations:

f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom

Section 3: Elective Specialisation

Within the study area Elective Specialization students can choose modules from the Master Programs Mathematical Physics, Mathematics, Physics, and Astro and Particle Physics according to their individual interests. In particular, courses listed in the module descriptions MAT-40-31 and MAT-40-32 but not chosen there, the module MAT-65-13 respectively MAT-65-14 not yet chosen in the area Foundations, the modules MAT-65-15 and MAT-65-21 to MAT-65-24, as well as other appropriate advanced modules from the programs Mathematical Physics, Mathematics, Physics, and Astro and Particle Physics are available. Note that not all modules can be offered every year, but there is always a broad choice. Also note that some modules from other programs might be offered only in german, but also here a choice of english courses is ensured. The selection of modules within the area Elective Specialisation must be discussed and decided together with the mentor. Each module can be selected only once. In agreement with the mentor and upon request at the examinations board, 9 ECTS points within the area of Elective Specialisation can be allocated for modules that serve to close knowledge gaps either in mathematics or physics.

Within the area of Elective Specialisation students obtain relevant skills. They learn to independently judge which additional qualifications and competences are relevant to their studies and to select courses accordingly. They are able to acquire specific knowledge also beyond the mandatory parts of the study program. Within the area of their specialisation they can report on and scrutinize the current state of research. In the exercise classes students learn to work confidently, precisely and independently with the notions, statements and methods presented during the lectures. They also learn how to apply methods to new problems and to analyse and solve them alone or in groups.

Module Number: **MAT-65-14**	**Module Title:** Mathematical Statistical Physics		**Type of Module:** Elective Module
ECTS-Points	9		
Workload **- Time in Class** **- Self-Study**	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h
Duration	1 Semester		
Frequency	not regularly, in Summer Semester		
Term	2-3		
Language of Instruction	English		
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements		
Content	The module provides an introduction to mathematical statistical physics. Particular topics are concepts of probability theory, classical statistical mechanics of gases (equivalence of ensembles, thermal equilibrium, Boltzmann equation, entropy), Brownian motion (stochastic processes, Wiener process), lattice models (Ising model, Gibbs measure, thermodynamic limit, phase transitions), statistical quantum mechanics (quantum mechanical ensembles, transition to thermal equilibrium, Bose-Einstein condensate). Optionally, other topics such as open quantum systems, transport phenomena, renormalization group theory and the fluctuation-dissipation theorem can be discussed.		
Objectives	Students obtain knowledge and understanding of the listed notions and methods and can use them to analyse known and new problems from statistical physics. They are able to interrelate fundamental physical concepts, such as equilibrium, irreversability and entropy, and their mathematical models vie probabilistic methods and to question the relevance and adequacy of the mathematical model and of the results derived from it. Thereby, they enhance their knowledge on methods and subjects gained throughout the first semester, in particular on probability theory. Students are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.		

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Mathematical Statistical Physics	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
		E	f	2	3					
	In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.									
Transfer	Successful completion of module is a prerequisite for the participation in the module Advanced Topics in Mathematical Statistical Physics.									
Prerequisites	-									
Responsible Persons	Roderich Tumulka									

Abbreviations:

f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom

Module Number: MAT-65-15	**Module Title:** Foundations of Quantum Mechanics		**Type of Module:** Elective Module
ECTS-Points	9		
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h
Duration	1 Semester		
Frequency	regularly every two years		
Term	2-3		
Language of Instruction	English		
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements		
Content	The module provides an introduction to foundational questions of quantum mechanics, including their mathematical and philosophical aspects. Different interpretations such as Copenhagen, Bohmian mechanics, many worlds, and spontaneous wave function collapse are introduced and analysed mathematically and physically. Further topics include the Born rule, Heisenberg's uncertainty relation, the quantum measurement problem, Bell's non-locality theorem, identical particles, and no-hidden-variables theorems.		
Objectives	Students know and can apply the rules of quantum mechanics in various settings, and they understand several important theories of how the quantum world works. They acquire mathematical knowledge relevant to using these rules and theories and can connect the mathematical treatment to the physical meaning. They familiarise themselves with the surprising phenomena and paradoxes of quantum mechanics. They appreciate what is controversial about the orthodox interpretation and why, and are able to follow contemporary debate on foundational issues. Students are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.		

Requirements for Obtaining Credit, Grading, Weight if applicable

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Foundations of Quantum Mechanics	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	E	f	2	3					

In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.

Transfer	-
Prerequisites	The basic modules on Analysis and Linear Algebra are required.
Responsible Persons	Roderich Tumulka

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Module Number: MAT-65-21	**Module Title:** Advanced Topics in Mathematical Quantum Theory		**Type of Module:** Elective Module
ECTS-Points	9		
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h
Duration	1 Semester		
Frequency	not regularly		
Term	2-3		
Language of Instruction	English		
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements		
Content	The module provides an introduction to an advanced topic of mathematical quantum theory, like Hartree and Hartree-Fock theory, BCS theory, adiabate theory, renormalisation group, mathematical models in quantum field theory and transport in interdependent ferminon systems. It will present both the fundamental mathematical results and physical notions of the particular area, as well as provide an insight into the current state of research and the existing open problems.		
Objectives	Students obtain knowledge and understanding of the acquired notions and methods and are able to apply them in the analysis of known and new problems from the specific area of Mathematical Quantum Theory. Students are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. They are able to describe and critically challenge the current state of research in the specific area. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.		
Requirements for Obtaining Credit, Grading, Weight if applicable	(see table below)		

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Advanced Topics in Mathematical Quantum Theory	L	o	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	E	o	2	3					

In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.

Transfer	The module may be a prerequisite for the master thesis.
Prerequisites	Knowledge from the module Mathematical Quantum Theory is assumed.
Responsible Persons	Stefan Teufel

Abbreviations:

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Module Number: MAT-65-22	**Module Title:** Advanced Topics in Mathematical Quantum Theory (short version)		**Type of Module:** Elective Module
ECTS-Points	6		
Workload - Time in Class - Self-Study	Workload: 180 h	Time in Class: 60 h	Self-Study: 120 h
Duration	1 Semester		
Frequency	not regularly, in Summer Semester		
Term	2		
Language of Instruction	English		
Forms of Teaching and Learning	Lectures 2 SWS + Exercise Classes 2 SWS, Homework Assignements		
Content	The module provides a short introduction to an advanced topic of mathematical quantum theory, like Hartree and Hartree-Fock theory, BCS theory, adiabate theory, renormalisation group, mathematical models in quantum field theory and transport in interdependent ferminon systems. It will present both the fundamental mathematical results and physical notions of the particular area, as well as provide an insight into the current state of research and the existing open problems.		
Objectives	Students obtain knowledge and understanding of the acquired notions and methods and are able to apply them in the analysis of known and new problems from the specific area of Mathematical Quantum Theory. Students are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. They are able to describe and in parts also critically challenge the current state of research in the specific area. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.		

Requirements for Obtaining Credit, Grading, Weight if applicable

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Advanced Topics in Mathematical Quantum Theory	L	o	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	E	o	2	3					

In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.

Transfer	The module may be a prerequisite for the master thesis.
Prerequisites	Knowledge from the module Mathematical Quantum Theory is assumed.
Responsible Persons	Stefan Teufel

Abbreviations:

f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom

Module Number: **MAT-65-23**	**Module Title:** Advanced Topics in Mathematical Relativity		**Type of Module:** Elective Module
ECTS-Points	9		
Workload **- Time in Class** **- Self-Study**	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h
Duration	1 Semester		
Frequency	not regularly, in Winter Semester		
Term	3		
Language of Instruction	English		
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements		
Content	The module provides an introduction to an advanced topic of mathematical theory of relativity. It will present both the fundamental mathematical results and physical notions of the particular area, as well as provide an insight into the current state of research and the existing open problems.		
Objectives	Students obtain deepend knowledge on selected questions in mathematical relativity. They learn analytic and geometric techniques in order to prove existence of solutions of Einstein equations and to examine these. Moreover, they do understand the physical relevance of the mathematical solutions. Students are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. They are able to describe and critically challenge the current state of research in the specific area. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.		

Requirements for Obtaining Credit, Grading, Weight if applicable

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Advanced Topics in Mathematical Relativity	L	o	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	E	o	2	3					

In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.

Transfer	The module may be a prerequisite for the master thesis.
Prerequisites	Knowledge from the module Mathematical Relativity is assumed.
Responsible Persons	Carla Cederbaum, Gerhard Huisken, Frank Loose

Abbreviations:

f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom

Module Number: MAT-65-24	**Module Title:** Advanced Topics in Mathematical Relativity (short version)	**Type of Module:** Elective Module
ECTS-Points	6	
Workload - Time in Class - Self-Study	Workload: 180 h; Time in Class: 60 h	Self-Study: 120 h
Duration	1 Semester	
Frequency	not regularly, in Winter Semester	
Term	3	
Language of Instruction	English	
Forms of Teaching and Learning	Lectures 2 SWS + Exercise Classes 2 SWS, Homework Assignements	
Content	The module provides a short introduction to an advanced topic of mathematical theory of relativity. It will present both the fundamental mathematical results and physical notions of the particular area, as well as provide an insight into the current state of research and the existing open problems.	
Objectives	Students obtain deepend knowledge on selected questions in mathematical relativity. They learn analytic and geometric techniques in order to prove existence of solutions of Einstein equations and to examine these. Moreover, they do understand the physical relevance of the mathematical solutions. Students are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. They are able to describe and in parts also critically challenge the current state of research in the specific area. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.	

Requirements for Obtaining Credit, Grading, Weight if applicable

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Advanced Topics in Mathematical Relativity	L	o	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	E	o	2	3					

In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor. – In exceptional cases the module can be offered by the lecturer without exercises, in this case, only 3 credit points are awarded for the module instead of 6.

Transfer	The module may be a prerequisite for the master thesis.
Prerequisites	Knowledge from the module Mathematical Relativity is assumed.
Responsible Persons	Carla Cederbaum, Gerhard Huisken, Frank Loose

Abbreviations:

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<table>
<tr><td>Module Number:
MAT-65-35</td><td colspan="2">Module Title:
Quantum Shannon Theory and Beyond</td><td>Type of Module:
Elective Module</td></tr>
<tr><td>ECTS-Points</td><td colspan="3">9</td></tr>
<tr><td>Workload
- Time in Class
- Self-Study</td><td>Workload:
270 h</td><td>Time in Class:
90 h</td><td>Self-Study:
180 h</td></tr>
<tr><td>Duration</td><td colspan="3">1 Semester</td></tr>
<tr><td>Frequency</td><td colspan="3">not regularly</td></tr>
<tr><td>Term</td><td colspan="3">2-3</td></tr>
<tr><td>Language of Instruction</td><td colspan="3">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="3">Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements</td></tr>
<tr><td>Content</td><td colspan="3">Contents:
Introduction to fundamental concepts and the basic formalism: Pure/mixed states, evolution, completely positive maps, measurements Schmidt decomposition.
Quantum channels, Kraus representation, Choi matrices, POVM formalism. Interpretation of channels and their application to coherent communication and purification.
Trace distance, fidelity and entropy measures. Quantum relative entropy and quantum entropy inequalities. Hypothesis testing.
Monotonicity, recoverability and quantum data compression. Classical and quantum data communication.
Entanglement in dense coding, quantum teleportation and quantum cryptography. Use of Bell inequalities to characterize quantum weirdness of entanglement and non-locality.</td></tr>
<tr><td>Objectives</td><td colspan="3">In this course, the students have learned about the transmission of information over a noisy quantum communication channel. They know how to use diverse quantum entropic measures for several quantum information processing tasks, such as quantum tomography, quantum estimation and quantum hypothesis testing. Students are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework.
Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.</td></tr>
<tr><td>Requirements for Obtaining Credit, Grading, Weight if applicable</td><td colspan="3">
<table>
<tr><th>Title</th><th>Type of Course</th><th>Status</th><th>SWS</th><th>ECTS</th><th>Assignments</th><th>Type of Exam</th><th>Dur. of Exam (min)</th><th>Grading</th><th>Weight for Grade</th></tr>
<tr><td rowspan="2">Quantum Shannon Theory and Beyond</td><td>L</td><td>f</td><td>4</td><td>6</td><td rowspan="2">yes</td><td rowspan="2">wr. o. or.</td><td rowspan="2">90-180
o. 20-30</td><td rowspan="2">g</td><td rowspan="2">100</td></tr>
<tr><td>E</td><td>f</td><td>2</td><td>3</td></tr>
</table>
In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor.</td></tr>
</table>

Literature	**Exemplary Literature:** • Michael A. Nielsen, Isaac L. Chuang: Quantum Computation and Quantum Information. CUP 2010. • Mark M. Wilde: From Classical to Quantum Shannon Theory. arXiv 2019. • John Watrous: The theory of quantum information. CUP 2018. • Eric A. Carlen: Trace inequalities and quantum entropy. Rutgers 2009. • Michael A. Wolf: Quantum Channels and Operations Guided Tour. Lecture Notes 2012.
Transfer	-
Prerequisites	The basic modules on Analysis and Linear Algebra are required.
Responsible Persons	Angela Capel Cuevas
Abbreviations: f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom	

Section 4: Scientific Work

Module Number: MAT-40-41	**Module Title:** Scientific Project		**Type of Module:** Compulsory Module
ECTS-Points	9		
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 15 h	Self-Study: 255 h
Duration	1 Semester		
Frequency	Every Semester		
Term	3		
Language of Instruction	English		
Forms of Teaching and Learning	Individual supervision by a mentor, study of scientific works.		
Content	Content: • Definition of an advanced scientific project in coordination with the mentor. • Independent search and study of the relevant scientific literature. • Formulation of specific problems and methodical approach to their solution. • Written presentation of the project in conext of current state of research on 5-10 pages. This module serves generally as a preparation for the Master Thesis		
Objectives	Students • develop skills to systematically familiarize themselves with a new subject, • learn to work critically and to form a substantiated, professional and interdisciplinary judgement, • acquire qualifications in such areas as literature research, identification of relevant problems and appropriate methods, as well as in the written presentation of a research proposal.		

Requirements for Obtaining Credit, Grading, Weight if applicable

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Scientific Project	P	o	1	9	yes	-	-	ng	-

Transfer	Successful completion of this module is a prerequisite for participation in module Master Thesis.
Prerequisites	Successful completion of module Geometry in Physics and of one of the modules Mathematical Quantum Theory or Mathematical Relativity.
Responsible Persons	Stefan Teufel, Werner Vogelsang.

Abbreviations:

f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom

<table>
<tr><td>Module Number:
MAT-40-42</td><td colspan="2">Module Title:
Mathematical Physics Colloquium</td><td>Type of Module:
Compulsory Module</td></tr>
<tr><td>ECTS-Points</td><td colspan="3">3</td></tr>
<tr><td>Workload
- Time in Class
- Self-Study</td><td>Workload:
90 h</td><td>Time in Class:
60 h</td><td>Self-Study:
30 h</td></tr>
<tr><td>Duration</td><td colspan="3">2 Semester</td></tr>
<tr><td>Frequency</td><td colspan="3">Every Semester</td></tr>
<tr><td>Term</td><td colspan="3">3–4</td></tr>
<tr><td>Language of Instruction</td><td colspan="3">English</td></tr>
<tr><td>Forms of Teaching and Learning</td><td colspan="3">Presentations, discussions.
Specific form of study: during the final semester students present their Master thesis.</td></tr>
<tr><td>Content</td><td colspan="3">During each semester on 15 appointed dates (2 h each) there will take place presentations and discussions on current topics in mathematical physics. Speakers are the researchers of the involved departments, guest scientists and master's students, who present the results of their Master Thesis.</td></tr>
<tr><td>Objectives</td><td colspan="3">Students gain an insight into the current development of mathematical physics beyond the area of their own specialization. They develop the ability to follow scientific presentations and to discuss and challenge them within a larger group of scholars. They therefore also obtain interdisciplinary and intercultural competencies through regular cooperation and discussion in mixed groups.</td></tr>
<tr><td>Requirements for Obtaining Credit, Grading, Weight if applicable</td><td colspan="3">
<table>
<tr><th>Title</th><th>Type of Course</th><th>Status</th><th>SWS</th><th>ECTS</th><th>Assignments</th><th>Type of Exam</th><th>Dur. of Exam (min)</th><th>Grading</th><th>Weight for Grade</th></tr>
<tr><td>Colloquium Winter Semester</td><td>C</td><td>o</td><td>2</td><td>1</td><td>no</td><td>-</td><td>-</td><td>ng</td><td>-</td></tr>
<tr><td>Colloquium Summer Semester</td><td>C</td><td>o</td><td>2</td><td>2</td><td>no</td><td>-</td><td>-</td><td>ng</td><td>-</td></tr>
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</td></tr>
<tr><td>Transfer</td><td colspan="3">-</td></tr>
<tr><td>Prerequisites</td><td colspan="3">-</td></tr>
<tr><td>Responsible Persons</td><td colspan="3">Carla Cederbaum, Stefan Teufel</td></tr>
<tr><td colspan="4">Abbreviations:
f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom</td></tr>
</table>

Module Number: MAT-40-43	**Module Title:** Master Thesis M.Sc. Mathematical Physics		**Type of Module:** Compulsory Module
ECTS-Points	30		
Workload - Time in Class - Self-Study	Workload: 900 h	Time in Class: 0 h	Self-Study: 900 h
Duration	1 Semester		
Frequency	Every Semester		
Term	4		
Language of Instruction	English or German		
Forms of Teaching and Learning	Master thesis		
Content	Students are assigned to workgroups and participate in seminars of the group. Under the supervision of the mentor students have to handle a concrete problem from mathematical physics by applying scientific methods and present it in written form in English or German. In particular this includes: • Definition of an advanced scientific task in coordination with the mentor; • Independent search and study of the relevant scientific literature; • Formulation of appropriate questions and methodical approach to their answers; • Independent execution and written presention of the project and the results in the context of the current state of research; • Presentation of the results in English in Mathematical Physics Colloquium.		
Objectives	Students are able to • develop acquaintance with a new problem within a given period of time and treat it with increasing independence by applying scientific methods; • develop acquaintance with scientific literature on a new topic; • critically interpret scientific results and integrate them into their state of knowledge; • present their results in written form based on principles of Good Scientific Practice; • present their work in an international scientific environment.		
Requirements for Obtaining Credit, Grading, Weight if applicable	see table below		
Transfer	-		

Requirements for Obtaining Credit, Grading, Weight if applicable

Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Master Thesis	MT	o	-	30	no	MT	-	g	100

Prerequisites	• 27 CP from the compulsory elective section Foundations of Mathematical Physics, • a total of 18 CP from the sections Knowledge Expansion and Elective Specialisation, • Successful completion of module Scientific Project.
Responsible Persons	Stefan Teufel, Werner Vogelsang.

Abbreviations:
f=facultatitve, g=graded, h=hour, wr.=written exam, MT=master thesis, or.=oral exam, ng=not graded, o=obligatory, o.=or, P=presentation, S=seminar, SL=seminar or lecture, SWS=hours per week in class, E=exercise class, L=lecture, T=tutorial, IC=inverted classroom