





**Department of Mathematics** 

# Module Handbook Mathematical Physics Master of Science

Winter Semester 2024

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# 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 mathematical 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: I	oundations						
1	MAT-65-11	Geometry in Physics	L+E	PM	НА	wr. o. or.	9
1	MAT-65-12	Mathematical Quantum Theory	L+E	PM	НА	wr. o. or.	9
2	MAT-65-13	Mathematical Relativity	L+E	PM	НА	wr. o. or.	9
Section 2: I	Knowledge E	xpansion					
1–3	MAT-40-31	Advanced Topics in Mathematics	L+E	PMW	НА	wr. o. or.	9
1–3	MAT-40-32	Advanced Topics in Theoretical Physics	L+E	PMW	НА	wr. o. or.	9
2–3	MAT-40-33	Seminar Knowledge Extension	S	PMW	s.M.	Р	3
Section 3: I	Elective Spec	ialisation					
2-3	MAT-65-14	Mathematical Statistical Physics	L+E	WPM	НА	wr. o. or.	9
2-3	MAT-65-15	Foundations of Quantum Mechanics	L+E	WPM	НА	wr. o. or.	9
2-3	MAT-65-21	Advanced Topics in Mathematical Quantum Theory	L+E	WPM	НА	wr. o. or.	9
2	MAT-65-22	Advanced Topics in Mathematical Quantum Theory (short version)	L+E	WPM	НА	wr. o. or.	6
3	MAT-65-23	Advanced Topics in Mathematical Relativity	L+E	WPM	НА	wr. o. or.	9
3	MAT-65-24	Advanced Topics in Mathematical Relativity (short version)	L+E	WPM	НА	wr. o. or.	6
2-3	MAT-65-35	Quantum Shannon Theory and Beyond	L+E	WPM	НА	wr. o. or.	9
Section 4: 9	Scientific Wo	rk					
3	MAT-40-41	Scientific Project	Р	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

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.

Term	СР	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientific Work
1.	27	27 CP			
2.	30	27 01	21 CP	30 CP	
3.	31			30 01	42 CP
4.	32				<del>1</del> 2.01

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	СР	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientif	ic Work
		Geometry in Physics (9 CP)	Linear Partial			
1.	27	Mathematical Quantum Theory (9 CP)	Differential Equations (9 CP)			
		Mathematical		Advanced Topics in Mathematical Quantum Theory (9 CP)		
2.	30	Relativity (9 CP)	Seminar(3 CP)	Mathematical Statistical Physics (9 CP)		
			Quantum Field	Advanced Topics in Mathematical Relativity (6 CP)		
3.	31		Theory and Particle Physics (9CP)	Advanced Topics in Mathematical Statistical Physics (6 CP)	Mathe- matical Physics	Scientific Project (9 CP)
4.	32				Colloquium (3 CP)	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	СР	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientif	ic Work
		Geometry in Physics (9 CP)				
1.	27	Mathematical Quantum Theory (9 CP)	Operator Theory (9 CP)			
2.	30	Mathematical Relativity (9 CP)	Quantum Field Theory and Particle Physics (9 CP)	Functional Analysis (9 CP)		
			Seminar(3 CP)			
				Advanced Topics in Mathematical Quantum Theory (9 CP)		
3.	31			Computational Methods in Physics / Astrophysics (6 CP)	Mathe-	Scientific Project
				Theoretical Condensed Matter Physics (6 CP)	matical Physics Colloquium (3 CP)	(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	СР	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientif	ic Work
		Geometry in Physics (9 CP)	Astronomy and			
1.	27	Mathematical Quantum Theory (9 CP)	Astrophysics (9 CP)			
2.	30	Mathematical Relativity (9 CP)	Introduction to Partial Differential Equations (9 CP)	Riemannian Geometry (9 CP)		
۷.			Seminar(3 CP)			
				Advanced Topics in Mathematical Relativity (9 CP)		
3.	31			Theoretical Astrophysics (6 CP)	Mathe-	Scientific Project
				Computational methods in Physics / Astrophysics (6 CP)	matical Physics Colloquium (3 CP)	(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	СР	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientif	ic Work
		Geometry in Physics (9 CP)				
1.	27	Mathematical Quantum Theory (9 CP)	Probability Theory (9 CP)			
		Mathematical	Advanced Statistical	Mathematical Statistical Physics (9 CP)		
2.	30	Relativity (9 CP)	Physics (9 CP)	Density Functional Theory (6 CP)		
				Advanced Topics in Mathematical Statistical Physics (6 CP)		Scientific
3.	31		Seminar (3CP)	Mathematical Statistics (9 CP)	Mathe- matical Physics	Project (9 CP)
4.	32				Colloquium (3 CP)	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

Ove	rview by Study Progress an	d Credi	it Requirer	nents	;								
			Exam				Teaching				Те	erm	
		Exam	(min)		Weight in the final grade	Type of Course			Points (CP)	is a red Composite are ma allocate to countion on	points to commenulsory al arked as ion of Er rses is fo ily. Cred	of examo semes idation of locations such. TCTS point or informatics are o complet	ters Inly. S he nts a- nly
		Type of Exam	Duration (min)	Grading	Weight	Type of	Status	SWS	ECTS	1. CP	2. CP	3. CP	4. CP
Fou	ndations of Mathematical Pl	nysics:							27				
MAT	-65-11 Geometry in Physics							6	9				
1.	Lecture	Wr. or	90–120 or	g	9	L	О	4		6			
2.	Exercises	Or.	20–30	9		E	О	2		3			
MAT	-65-12 Mathematical Quantun	n Theor	у					6	9				
1.	Lecture	Wr.	90–120	g	9	L	o	4		6			
2.	Exercises	or Or.	or 20–30	9		Е	0	2		3			
МАТ	-65-13 Mathematical Relativity	/						6	9				
1.	Lecture	Wr.	90–120	_	9	L	0	4			6		
2.	Exercises	or Or.	or 20–30	g		E	0	2			3		
Kno	wledge Expansion:								21				
MAT	-40-31 Advanced Topics in Ma	athemat	ics					6	9				
1.	Lecture	Wr.	90–120	_	9	L	0	4		6			
2.	Exercises	or Or.	or 20–30	g	9	E	0	2		3			
MAT	-40-32 Advanced Topics in Ph							6	9				
1.	Lecture	Wr.	90–120	~	9	L	0	4			6		
2.	Exercises	or Or.	or 20–30	g	9	Е	0	2			3		
MAT	-40-33 Seminar							2	3				
1.	Seminar	Pres.	45–90	g	3	S	0	2				3	
Elec	ctive Specialisation:								30				
	Here the modules MAT-65-15 and Master's Programs in Mathem be discussed and agreed upor board.	o and	Partic	cle Physics	s, car	be cl	nosen. 1	he choi	ces nee	d to			
MAT	-65-14 Mathematical Statistica			6	9								
1.	Lecture	Wr.	90–120			L	f	4			6		
2.	Exercises	or Or.	or 20–30	g	9	E	f	2			3		
	-65-21 Advanced Topics in Ma			um Th	eory			6	9				
1.	Lecture	Wr.	90–120			L	f	4			6		
	I.	or Or	or 20_30	<sup>l</sup> g	9		<u> </u>				<u> </u>	I	1

Or.

20-30

			Exam				Teaching				Te	erm	
		Type of Exam	Duration (min)	0	Weight in the final grade	Course			Points (CP)	ECTS is a rec Composite are material allocate to count tion on	points to commer ulsory al arked as ion of E- rses is fo ily. Cred ed upon	of examo semes dation of locations such. TCTS point or informatics are occuplet	ters only. s he nts na- nly
		/be o	uratic	Grading	/eigh	Type of	Status	SMS	ECTS	1.	2.	3.	4.
	I	F,		9	>		S	S	Ш	CP	CP	CP	CP
2.	Exercises					E	f	2			3		
	F-65-22 Advanced Topics in			ım Th	eory	(short	1	4	6			I	
1.	Lecture	Wr. or	90–120 or	g	6	L	f	2			3		
2.	Exercises	Or.	20–30			E	f	2			3		
	F-65-23 Advanced Topics in		ı	ity		I		6	9			I	
1.	Lecture	Wr. or	90–120 or	g	9	L	f	2				3	
2.	Exercises	Or.	20–30			E	f	2				3	
MAT	Γ-65-24 Advanced Topics in	<u> </u>	ı	ity (sh	nort ve	ersion	1	4	6			I	
1.	Lecture	Wr. or	90–120 or	g	6	L	f	2				3	
2.	Exercises	Or.	20–30			E	f	2				3	
	entific Work								42				
MAT	Γ-40-41 Scientific Project		I	I	I	ı	I		9			I	
1.	Project	Proj.		ng	9		0					9	
MAT	Γ-40-42 Mathematical Physic	s Colloqu	ium	I	I	ı	I		3			I	
1.	Colloquium			ng			0					1	2
	Γ-40-43 Master Thesis								30			T	
1.				g	30		0						30

Status Other : o=obligatory, f=fakultative : 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 Semeste	r							
Term	1	<u> </u>							
Language of Instruction	English								
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	Classes 2 SWS, Homework A	ssignements						
Content	relevance for physics. Particle and associated notions of control of the control	cular topics are manifolds, diff	ods of differential geometry and their erential forms, Riemannian metrics ry of submanifolds, real vector bun- Physics are discussed.						
Objectives	of differential geometry. The integral calculus and experie applied within physical theor and concepts from the lecture put it into a larger framework. Through homework assignmand independent acquainta lectures. They learn how to develop solution strategies.	y develop, in particular, a deep ince through examples how the ies. Students are able to name re as well as to explain the cor c. nents and exercise classes stu- nce with the notions, stateme to transfer these methods to n	nce with the use of the listed notions per understanding of differential and emathematical notions are naturally and prove the essential statements attended in the lecture and to adents developed in the lecture and to adents developed a confident, precise, ents, and methods explained in the ew problems, to analyse them and roup. They are able to present their dessary.						

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	0	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
		E	0	2	3		Oi.	0. 20 00		
	In this module students need the exam. The type of examin							in order to	be adn	nitted to
Literature	Exemplary Literature:									
	John Lee: Introduction	to sn	nooth	n ma	nifolo	ds. Spri	inger 2012.			
	John Lee: Riemannian	man	ifolds	: An	intro	ductio	n. Springer	1997.		
	Chris Isham: Modern c	liffere	ntial	geor	netry	v for ph	vsicists. Wo	orld Scientifi	c 1999	
	Mikio Nakahara: Geom			•	•		•			
Transfer	ativity. Successful completion	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 Ceder	baum	, Ste	fan <sup>-</sup>	Teufe	el				

Module Number: MAT-65-12	Module Title: Mathematical Quantum Theo	ory						of Module: ulsory Modu	le	
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:		
Duration	1 Semester									
Frequency	regularly in Winter Semester									
Term	1									
Language of Instruction	English	nglish								
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	Classe	s 2 S	SWS	, Hor	meworl	( Assignem	ents		
Content	The module provides an intrest the formulation and analysis butions, Hilbert spaces, units operators, spectral theorem, erators. In addition, basic ic perturbation theory, Hartree theory, adiabatic theory or sematical methods and areas examples from quantum theoretic theory.	of qua ary gro tensor leas fr resp. emicla are mo	intun oups or prod om r Harti issica	n the and ducts nore ree-F al an	ories their s, PO spec ock alysi	s. Topic gener WMs, s cific me theory, s can I	s include thators, spectpectral meanthods such the Fock spectos discussed	ne Fourier tra tral theory of asures, and n as Rayleig pace formalied. The mer	ansforr of self-a trace of h-Sch ism, so ntioned	m, distri- adjacent lass op- rödinger cattering mathe-
Objectives	Students know and understate to analyse known and new quexplain the statements and and their mathematical modelling and assignments and exercise cacquaintance with the notion how to transfer these methods trategies on their own and stand for them in a critical distance.	uestio proofs elling the r lasses s, state ods to within	ns from and and nather students and nather men	om che le are emat dents hts, a pro-	uant ecture able ical ical dev and n blem	tum theme. Further to que results velop and thodes, to a sey are	hermore, the stion the rederived fro confident, as explained nalyse ther	are able to uney link physelevance and it. Throuprecise, and in the lecture and to de	nderst sical p d adec ugh ho d inde es. Th evelop	and and roblems quacy of mework pendent ey learn solution
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 Quantum Theory	L E	0	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module students need to successfully complete assignments in order to be admitted the exam. The type of examination is set by the instructor.								mitted to	
Transfer	ticipation in the module Adva	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.								
Prerequisites	-									
Responsible Persons	Stefan Teufel									

Module Number: MAT-65-13	Module Title: Mathematical Relativity							of Module: ulsory Modu	le		
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	tudy:			
Duration	1 Semester										
Frequency	regularly in Summer Semest	er									
Term	2										
Language of Instruction	English										
Forms of Teaching and Learning	Lectures 4 SWS + Exercise (	Classe	es 2 S	SWS	, Hor	meworł	( Assignem	ents			
Content	ics are Newton's theory of g equation, Schwarzschild mod ter models, black holes, Car	module provides an introduction to the mathematical theory of relativity. Particular top- re Newton's theory of gravity, special theory of relativity, relativistic effects, Einstein's tion, Schwarzschild model. Optionally, other topics such as cosmological models, mat- odels, black holes, Cauchy problem and ADM decomposition, singularity theorems or ational waves can be discussed.									
Objectives	Students obtain knowledge use them to analyse known interrelate physical problems through methods from differe mathematical model and of the on methods and subjects ga 65-11. Students are able to lecture as well as to explain framework.  Through homework assignment independent acquaintar lectures. They learn how to to develop solution strategies solutions and to stand for the	and no in contial greens the contract and the contract an	ew prosmoleome onte:  and pronte:  and extended the theore onte:  the theore one onte:  and extended the theore one one one one one one one one one on	roble ogy etry a lerive ghou orove xt de xerci e not ese wn a	ms f and to and to ed fro t the e the evelop se cl tions meth	rom the astroph of quest of quest of quest of the first second in the assessing assessing the first second of the first second	e theory of nysics and to the relet hereby, the emester, in tial statementhe lecture students dements, and new problegroup. The	relativity. The their mather wance and a yenhance the particular irents and con and to put evelop a contents, to ana	ney are natical dequa- neir kno n modu cepts it into fident, splaine lyse th	e able to models cy of the owledge ale MAT- from the a larger precise, d in the eem and	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title  Mathematical Relativity	ш Гуре of Course	o o Status	SMS 4	6 3	se Assignments	Type of Exam o. o.	Our. of Exam (min) 0.20-30	ص Grading	Weight for Grade	
	In this module students need the exam. The type of exami							s in order to	be adr	mitted to	
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 G	eome	try in	Phy	sics	is a pre	erequisite.				
Responsible Persons	Carla Cederbaum, Gerhard I	Carla Cederbaum, Gerhard Huisken, Frank Loose									

# **Section 2: Knowledge Expansion**

Module Title: Advanced Topics in Mathema	7.5											
9												
Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:					
1 Semester						·						
Every Semester												
1–3												
English or German												
Lectures 4 SWS + Exercise C	ures 4 SWS + Exercise Classes 2 SWS, Homework Assignements											
the correspondent SWS-cove mended subjects are for insta- tions, Harmonic analysis, Lie tic processes, Calculus of va	rage f ance f group triatio	from Partia s, N ns, S	the Nal dif onlin Symp	Maste feren ear f olecti	er's deq itial equunction c geon	gree programuations, Numer land analysis, netry, Algeb	m in Mathem merics of dif Operator the graic topolog	natics. ferentia eory, S y or A	Recom- al equa- tochas- lgebraic			
of physical applications. They the methods at hand to tackle ticular the concrete content re	broa matle elatec	den nema I qua	the batical	asis prolition (	of thei olems. goals, v	r mathemati The further vill follow fro	ical knowled qualificatior om the mode	ge and goals	extend in par-			
Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
Advanced Topics in Mathematics	L E	0	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100			
							s in order to	be adn	nitted to			
The module may be a prereq	uisite	for th	ne m	aste	r thesis							
See prerequisites in the Mod	ule Ha	andb	ook l	M.Sc	. Math	ematics.						
Die Studiendekanin oder der	Die Studiendekanin oder der Studiendekan des Fachbereichs Mathematik											
	9 Workload: 270 h  1 Semester Every Semester 1–3 English or German Lectures 4 SWS + Exercise Content of the correspondent SWS-cover mended subjects are for instations, Harmonic analysis, Lie tic processes, Calculus of vargeometry. Further details can Mathematics.  The students aquire deepend of physical applications. They the methods at hand to tackle ticular the concrete content reconstruction of the chosen course in the module students need the exam. The type of examing The module may be a prerequisites in the Module See prerequisites	Workload: 270 h  1 Semester  Every Semester  1–3  English or German  Lectures 4 SWS + Exercise Classes  It is required to attend one or more the correspondent SWS-coverage mended subjects are for instance of tions, Harmonic analysis, Lie group tic processes, Calculus of variation geometry. Further details can be for Mathematics.  The students aquire deepend know of physical applications. They broat the methods at hand to tackle math ticular the concrete content related of the chosen course in the module of the chosen course in the module.  Title  Advanced Topics in Mathematics  L In this module students need to such the exam. The type of examination.  The module may be a prerequisite.	Workload: 270 h  1 Semester  Every Semester  1–3  English or German  Lectures 4 SWS + Exercise Classes 2 Sementer of the correspondent SWS-coverage from mended subjects are for instance Partiations, Harmonic analysis, Lie groups, Notic processes, Calculus of variations, Segeometry. Further details can be found Mathematics.  The students aquire deepend knowledge of physical applications. They broaden the methods at hand to tackle mathematicular the concrete content related qual of the chosen course in the module hard.  Title  Advanced Topics in Mathematics  The module students need to success the exam. The type of examination is seen the module may be a prerequisite for the See prerequisites in the Module Handberg in the Modul	Workload: 270 h  1 Semester  Every Semester  1–3  English or German  Lectures 4 SWS + Exercise Classes 2 SWS  It is required to attend one or more lecture the correspondent SWS-coverage from the finance Partial diftions, Harmonic analysis, Lie groups, Nonlin tic processes, Calculus of variations, Sympgeometry. Further details can be found in the Mathematics.  The students aquire deepend knowledge in of physical applications. They broaden the buther methods at hand to tackle mathematical ticular the concrete content related qualifact of the chosen course in the module handbook of the chos	Workload: 270 h  1 Semester  Every Semester  1–3  English or German  Lectures 4 SWS + Exercise Classes 2 SWS, How the correspondent SWS-coverage from the Mast mended subjects are for instance Partial differentions, Harmonic analysis, Lie groups, Nonlinear fit processes, Calculus of variations, Symplecti geometry. Further details can be found in the module may be a prerequisite for the master for the concrete content related qualifaction of the chosen course in the module handbook for the mathematics.  The students aquire deepend knowledge in one of physical applications. They broaden the basis the methods at hand to tackle mathematical profiticular the concrete content related qualifaction of the chosen course in the module handbook for the chosen course in the formation in t	Workload: 270 h  1 Semester  Every Semester  1–3  English or German  Lectures 4 SWS + Exercise Classes 2 SWS, Homework the correspondent SWS-coverage from the Master's degmended subjects are for instance Partial differential equitions, Harmonic analysis, Lie groups, Nonlinear function tic processes, Calculus of variations, Symplectic geom geometry. Further details can be found in the module hamatics.  The students aquire deepend knowledge in one selected of physical applications. They broaden the basis of their the methods at hand to tackle mathematical problems, ticular the concrete content related qualifaction goals, wo of the chosen course in the module handbook for the Mathematics  Title  Advanced Topics in Mathematics  In this module students need to successfully complete a the exam. The type of examination is set by the instruct.  The module may be a prerequisite for the master thesis. See prerequisites in the Module Handbook M.Sc. Mathematics.	Advanced Topics in Mathematics    Self-St   Se	Workload: 270 h  Time in Class: 90 h  Self-Study: 180 h  1 Semester  Every Semester  1–3  English or German  Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements  It is required to attend one or more lectures as well as the respective exercis the correspondent SWS-coverage from the Master's degree program in Mathem mended subjects are for instance Partial differential equations, Numerics of difficient to processes, Calculus of variations, Symplectic geometry, Algebraic topolog geometry. Further details can be found in the module handbook of the degree Mathematics.  The students aquire deepend knowledge in one selected area of mathematics of physical applications. They broaden the basis of their mathematical knowled the methods at hand to tackle mathematical problems. The further qualification ticular the concrete content related qualifaction goals, will follow from the mod of the chosen course in the module handbook for the M.Sc. Mathematics.  Title  Advanced Topics in  Mathematics  L 0 4 6 yes wr. 0. 90-180 o. 20-30  In this module students need to successfully complete assignments in order to the exam. The type of examination is set by the instructor.  The module may be a prerequisite for the master thesis.	Workload: 270 h  Workload: 270 h  Self-Study: 180 h  1 Semester  Every Semester  1-3  English or German  Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements  It is required to attend one or more lectures as well as the respective exercise class the correspondent SWS-coverage from the Master's degree program in Mathematics. mended subjects are for instance Partial differential equations, Numerics of differentiations, Harmonic analysis, Lie groups, Nonlinear functional analysis, Operator theory, Stic processes, Calculus of variations, Symplectic geometry, Algebraic topology or Algeometry. Further details can be found in the module handbook of the degree program Mathematics.  The students aquire deepend knowledge in one selected area of mathematics indeper of physical applications. They broaden the basis of their mathematical knowledge and the methods at hand to tackle mathematical problems. The further qualification goals ticular the concrete content related qualifaction goals, will follow from the module desort the chosen course in the module handbook for the M.Sc. Mathematics.    Page   Page			

#### Abbreviations:

Module Number: MAT-40-32	Module Title: Advanced Topics in Theoretic	cal Ph	ysics	i				f Module: Ilsory Modul	le with	Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:		
Duration	1 Semester									
Frequency	Every Semester									
Term	1–3									
Language of Instruction	English or German									
Forms of Teaching and Learning	Lectures 4 SWS + Exercise (	Classe	s 2 S	SWS	, Hoi	mework	( Assigneme	ents		
Content	It is required to attend one physics as well as the resp from the Master's degree proticls Physics. Recommended physics, Theoretical astrophysics, tum optics, Quantum information trophysics, Current topics in handbook of the correspondi	ective ogram ed sub ysics, Yang- ation t theore	exer in Pl jects Rela Mills heor etical	rcise nysic are tivist theo y, Co phy	clas s or for ic as ory, C osmo sics.	sses wi the Ma instand strophys Conden blogy, N Furthe	th the correster's degree Quantum sics, Many-pased matter lumerical m	espondent See program And Infield theoronarticle quale physics, The ethods in pl	SWS-ca Astro a y and ntum s eoretica hysics	overage and Par- Particle ystems, al quan- and as-
Objectives	The students aquire deeper pendently of rigorous mather theoretical physics and exten qualification goals, in particul the module description of the the M.Sc. Astro and Particle	matica d the ar the chos	I form meth cond en co	nalis ods crete	m. 7 at ha con	They brand to ta tent rela	oaden the b ackle proble ated qualifa	pasis of their ms in physic ction goals,	r know cs. The will foll	edge in further ow from
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 E	0	4 2	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module students need the exam. The type of exami	to su	cces	sfully	con			in order to	be adr	nitted to
Transfer	The module may be a prerec	The module may be a prerequisite for the master thesis.								
Prerequisites	See prerequisites in the Mode	ule Ha	ndbo	ok M	1.Sc.	Physic	s or M.Sc.	Astro and Pa	article I	Physics.
Responsible Persons	Die Studiendekanin oder der	Die Studiendekanin oder der Studiendekan des Fachbereichs Physik								

Module Number: MAT-40-33	Module Title: Seminar Knowledge Extension	on						of Module: ulsory Modu	le with	Choice
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	lass	:		Self-S	tudy:		
Duration	1 Semester									
Frequency	Every Semester	ery Semester								
Term	2–3									
Language of Instruction	English or German									
Forms of Teaching and Learning	Seminar: Presentation, Disci	ussion	, Tea	amwo	ork, F	Handou	t			
Content	Various topics from various Physics.	area	s of	Mat	hem	atical I	Physics, M	athematics	or The	eoretical
Objectives	The students have learnt to vanced topic in Mathematics form of an oral presentation. ical or physical results and a	or P They	hysio have	s by	app rove	olying s d their s	cientific me skills in the	ethods and to presentation	to pres	ent it in
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	0	2	3	yes	Р	45–90	g	100
Transfer	The module may be a prerec	uisite	for th	ne m	aster	r thesis		·		
Prerequisites	Successful completion of on Physics".	uccessful completion of one of the modules from the section "Foundations of Mathematical hysics".								
Responsible Persons	Stefan Teufel									

# **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 Phy	sics	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 Ser	mester	
Term	2-3		
Language of Instruction	English		
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	Classes 2 SWS, Homework A	ssignements
Content	concepts of probability theor bles, thermal equilibrium, E cesses, Wiener process), la phase transitions), statistica tion to thermal equilibrium, E	y, classical statistical mechanicoltzmann equation, entropy), ttice models (Ising model, Gikil quantum mechanics (quant Bose-Einstein condensate). Optophenomena, renormalization	stical physics. Particular topics are cs of gases (equivalence of ensem-Brownian motion (stochastic probs measure, thermodynamic limit, um mechanical ensembles, transiptionally, other topics such as open a group theory and the fluctuation-
Objectives	use them to analyse knowr interrelate fundamental phy and their mathematical mod adequacy of the mathematic their knowledge on methods on probability theory. Stude concepts from the lecture as it into a larger framework. Through homework assignment independent acquaintal lectures. They learn how to develop solution strategie	and new problems from state sical concepts, such as equilels vie probabilistic methods all model and of the results deres and subjects gained through ents are able to name and personal well as to explain the context ents and exercise classes stunce with the notions, statement transfer these methods to ne	ted notions and methods and can atistical physics. They are able to librium, irreversability and entropy, and to question the relevance and ived from it. Thereby, they enhance to the first semester, in particular rove the essential statements and developed in the lecture and to put dents develop a confident, precise, ints, and methods explained in the lew problems, to analyse them and oup. They are able to present their cessary.

Requirements for Obtaining Credit, Grading, Weight if applicable	Title  Mathematical Statistical Physics  In this module students need the exam. The type of examin					Onr. of Exam (min) 90-180 o. 20-30	g Grading	Meight for Grade
Transfer	Successful completion of mod Topics in Mathematical Statist		uisite	for the	participatio	n in the mod	dule Ac	Ivanced
Prerequisites	-							
Responsible Persons	Roderich Tumulka							

Module Number: MAT-65-15	Module Title: Foundations of Quantum Me	Module Title:Type of Module:Foundations of Quantum MechanicsElective Module												
ECTS-Points	9													
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	tudy:						
Duration	1 Semester													
Frequency	regularly every two years													
Term	2-3													
Language of Instruction	English													
Forms of Teaching and Learning	Lectures 4 SWS + Exercise (	Classe	s 2 S	SWS	, Hor	mework	Assignem	ents						
Content	ing their mathematical and phagen, Bohmian mechanics troduced and analysed math Heisenberg's uncertainty relations.	ne module provides an introduction to foundational questions of quantum mechanics, includge their mathematical and philosophical aspects. Different interpretations such as Copenagen, Bohmian mechanics, many worlds, and spontaneous wave function collapse are induced and analysed mathematically and physically. Further topics include the Born rule, eisenberg's uncertainty relation, the quantum measurement problem, Bell's non-locality theem, identical particles, and no-hidden-variables theorems.												
Objectives	Students know and can app understand several importan ematical knowledge relevant matical treatment to the phy phenomena and paradoxes about the orthodox interpret foundational issues. Student cepts from the lecture as we into a larger framework. Through homework assignm and independent acquaintar lectures. They learn how to to develop solution strategies solutions and to stand for the	t theo to us sical r of qua ation s are ll as to ents a ace wir transis on th	ries of ing the mean turn and the able on expended the the fer the ineir of the ine	of ho hese ning. n me why, to na blain xerci e no lese own a	w the rule The echain and the constitutions method with and with an and with an and with an and with an analysis of the constitution of the co	e quan es and ey fami nics. I are at and pro context asses a , state nods to vithin a	tum world watheories and liarise them. They appreadle to follow ove the essented developed students dements, and a new problegroup. The	works. They d can connected the contempore ential statem in the lecture evelop a contempore methods exems, to ana	acquirect the subsect the subsect the subsect the subsect that is contrary denents are and fident, eplaine lyse the	re math- mathe- irprising roversial bate on and con- to put it precise, d in the em and				
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 E	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100				
		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 Analy	sis an	d Lin	ear A	Algeb	ora are	required.							
Responsible Persons	Roderich Tumulka													

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 90 h	in C	lass	:		Self-Si 180 h	tudy:				
Duration	1 Semester											
Frequency	not regularly											
Term	2-3											
Language of Instruction	English											
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	Classe	es 2 9	SWS	, Hoi	meworl	k Assignem	ents				
Content	The module provides an intr like Hartree and Hartree-Fo mathematical models in qua tems. It will present both th particular area, as well as pro open problems.	ck the ntum t e fund	ory, field lame	BCS theo ntal	the ry ar math	ory, ad nd trans nematic	iabate theo sport in inte al results a	ory, renorma erdependent and physical	lisatior fermin notion	group, on sys- s of the		
Objectives	Students obtain knowledge a able to apply them in the anal ematical Quantum Theory. S concepts from the lecture as it into a larger framework. The of research in the specific arthrough homework assignment and independent acquaintar lectures. They learn how to develop solution strategies solutions and to stand for the	Ilysis of tudent well a ney are ea. ents a nce with transf s on th	of knoods are as to dead and each and each and the fer the	own and a second a	and retornation the descriptions the descriptions and retornations and ret	new proname and control aribe and asses are asset asset asset asset asset asset asset asset asset as a sec	oblems from nd prove the ext developed critically students de ments, and new problegroup. The	n the specific e essential s ed in the lec challenge th evelop a cont methods ex ems, to ana	tarea of tatementure and e currenture fident, oplaine lyse the	of Math- ents and d to put ent state precise, d in the em and		
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	L	0	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module students need the exam. The type of exami						 assignment		be adr	nitted to		
Transfer	The module may be a prerec	uisite	for th	ne m	aste	r thesis						
Prerequisites	Knowledge from the module	Mathe	emati	cal C	Quan	tum Th	eory is ass	umed.				
Responsible Persons	Stefan Teufel											

Module Number: MAT-65-22	Module Title: Advanced Topics in Mathema version)	atical C	Quan	tum <sup>-</sup>	Theo	ry (sho		of Module: re Module			
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	_	lass	:		Self-S 120 h	tudy:			
Duration	1 Semester										
Frequency	not regularly, in Summer Ser	nester									
Term	2										
Language of Instruction	English										
Forms of Teaching and Learning	Lectures 2 SWS + Exercise	ectures 2 SWS + Exercise Classes 2 SWS, Homework Assignements									
Content	The module provides a shotheory, like Hartree and Hargroup, mathematical models systems. It will present both particular area, as well as propen problems.	tree-F in qua the fur	ock antun adam	theo n field nenta	ry, B d the Il ma	CS the ory and themat	ory, adiaba d transport ical results	ate theory, re in interdeper and physica	enormandent for the contract of the contract o	alisation erminon as of the	
Objectives	Students obtain knowledge a able to apply them in the anal ematical Quantum Theory. S concepts from the lecture as it into a larger framework. The current state of research in the Through homework assignment and independent acquaintar lectures. They learn how to develop solution strategies solutions and to stand for the	Ilysis of tudent well an ney ar ne spe ents an ice with transis	of knoods are able controlled to the controlled	own a able explained to a control of the control of the control of the control own a c	and retornation the descriptions the descriptions the descriptions and retornations and retornations the descriptions the descriptions and retornations the descriptions are descriptions and retornations the descriptions are descriptions and retornations are descriptions and retornations are descriptions and retornations are descriptions are descriptions and retornations are descriptions are described as described as described as described are described as descri	new proname and control archeduced archeduce	bblems fron nd prove th ext develop d in parts a students de ments, and new probl group. The	n the specific e essential s ed in the lec also critically evelop a cont methods ex ems, to ana	tarea of tatement are	of Mathents and ad to put enge the precise, d in the em and	
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	L	0	2	3	yes	wr. o.	90-180 o. 20-30	g	100	
	In this module students need the exam. The type of exami					nplete a				nitted to	
Transfer	The module may be a prerec	uisite	for th	ne m	aste	r thesis					
Prerequisites	Knowledge from the module	Mathe	emati	cal C	Quan	tum Th	eory is ass	umed.			
Responsible Persons	Stefan Teufel										

Module Number: MAT-65-23	Module Title: Advanced Topics in Mathema	Module Title: Type of Module: Advanced Topics in Mathematical Relativity Elective Module											
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		lass	•		Self-St 180 h	udy:					
Duration	1 Semester												
Frequency	not regularly, in Winter Seme	ster											
Term	3												
Language of Instruction	English												
Forms of Teaching and Learning	Lectures 4 SWS + Exercise (	Classe	s 2 S	SWS	, Hoi	mework	Assignem	ents					
Content	It will present both the fundar	e module provides an introduction to an advanced topic of mathematical theory of relativity. ill present both the fundamental mathematical results and physical notions of the particular a, as well as provide an insight into the current state of research and the existing open blems.											
Objectives	Students obtain deepend kn learn analytic and geometric equations and to examine th mathematical solutions. Stuconcepts from the lecture as it into a larger framework. The of research in the specific are Through homework assignm and independent acquaintar lectures. They learn how to to develop solution strategies solutions and to stand for the	e technese. Note that the control of	nique Mored are a s to e abl nd e th the fer th	es in over, able expla e to xerci e no nese own a	orde they to na ain th desc se cl tions meth and v	er to provide ame and e contestibe and existence and exist	ove existenderstand the derstand the derstand the ext developed critically destudents dements, and new problegroup. The	ce of solution of	ons of elevance tatementure and e current fident, explaine lyse th	Einstein e of the ints and d to put ent state precise, d in the em and			
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 E	0	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100			
	In this module students need the exam. The type of exami	to su	cces	sfully	con			in order to	be adr	nitted to			
Transfer	The module may be a prerec	uisite	for th	ne m	aste	r thesis							
Prerequisites	Knowledge from the module	Mathe	mati	cal F	Relati	ivity is	assumed.						
Responsible Persons	Carla Cederbaum, Gerhard Huisken, Frank Loose												

Module Number: MAT-65-24	Module Title: Advanced Topics in Mathen sion)	natical	Rel	ativit	y (sl	hort ve		of Module: e Module				
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass			Self-St 120 h	tudy:				
Duration	1 Semester						·					
Frequency	not regularly, in Winter Seme	ster										
Term	3											
Language of Instruction	English											
Forms of Teaching and Learning	Lectures 2 SWS + Exercise (	Classe	s 2 S	SWS	, Hoi	mework	Assignem	ents				
Content	relativity. It will present both t	module provides a short introduction to an advanced topic of mathematical theory of tivity. It will present both the fundamental mathematical results and physical notions of the ticular area, as well as provide an insight into the current state of research and the existing n problems.										
Objectives	Students obtain deepend kn learn analytic and geometric equations and to examine the mathematical solutions. Student concepts from the lecture as it into a larger framework. The current state of research in the Through homework assignment independent acquaintant lectures. They learn how to to develop solution strategies solutions and to stand for the	e technese. Note that the control of	nique Aorec are a s to e able cific nd e th the er the	es in over, able to explain area exercise not ese own a	orde they to na tin th desc se cl tions meth	er to provide ame and e contection and e	ove existen derstand the derstand the derstand the ext developed in parts a students dements, and new problegroup. The	ce of solution of the control of the cessential section of the lector of the cester of	ons of elevand tateme ture ar challe fident, cplaine lyse th	Einstein se of the ents and do to put enge the precise, d in the em and		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title  Advanced Topics in	г Type of Course	o Status	SMS 2	ω ECTS	Assignments	Type of Exam	Dur. of Exam (min)	۵ Grading	Weight for Grade		
	Mathematical Relativity	Е	0	2	3	,55	or.	o. 20-30	9			
	the exam. The type of exami	this module students need to successfully complete assignments in order to be admitted to e exam. The type of examination is set by the instructor. – In exceptional cases the module in be offered by the lecturer without exercises, in this case, only 3 credit points are awarded										
Transfer	The module may be a prereq	uisite	for th	ne m	aste	r thesis	•					
Prerequisites	Knowledge from the module	Mathe	mati	cal F	Relati	ivity is a	assumed.					
Responsible Persons	Carla Cederbaum, Gerhard Huisken, Frank Loose											

Module Number: MAT-65-35	Module Title: Quantum Shannon Theory a	ınd Bey	ond/					of Module: e Module					
ECTS-Points	9						'						
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:					
Duration	1 Semester												
Frequency	not regularly												
Term	2-3												
Language of Instruction	English	nglish											
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	Classe	s 2 S	SWS	, Hor	neworl	( Assignem	ents					
Content	Contents:	ontents:											
		<ul> <li>Introduction to fundamental concepts and the basic formalism: Pure/mixed states, evo lution, completely positive maps, measurements Schmidt decomposition.</li> </ul>											
	Quantum channels, K tion of channels and t												
	Trace distance, fidelity     entropy inequalities. If	y and e Hypothe	entro esis	py m testi	ieasu ng.	ıres. Q	uantum rela	ative entropy	and c	luantum			
	<ul> <li>Monotonicity, recover data communication.</li> </ul>	ability	and	quai	ntum	data d	compression	n. Classical	and c	luantum			
	<ul> <li>Entanglement in der Use of Bell inequalitie locality.</li> </ul>												
Objectives	In this course, the students quantum communication cha for several quantum information and quantum hypostatements and concepts frow lecture and to put it into a lare through homework assignment independent acquaintal lectures. They learn how to develop solution strategies solutions and to stand for the	annel. I ation prothesis om the ger fra- ents ar nce with transfe s on the	They roce test lectures mew nd e h the er the	knowssing ssing ing. Sure a vork. xerci e nows ese wwn a	w how task Students we se cland tions, methand w	w to us	e diverse quent as quant e able to na explain the students de ments, and new proble group. The	uantum entre tum tomogra me and prove e context de velop a cont methods ex ems, to ana	opic maphy, controlled the endinger of the end	easures quantum issential and in the precise, d in the em and			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Solutions and to stand for them in a critical discourse if necessary.  Status SWS SWS Assignments Assignments Our. of Exam Weight for Grade  Title											
	Quantum Shannon Theory and Beyond	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100			
	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:
	<ul> <li>Michael A. Nielsen, Isaac L. Chuang: Quantum Computation and Quantum Information. CUP 2010.</li> </ul>
	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

# **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	Self-S 255 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	<ul> <li>Definition of an advanced scientific project in coordination with the mentor.</li> <li>Independent search and study of the relevant scientific literature.</li> <li>Formulation of specific problems and methodical approach to their solution.</li> <li>Written presentation of the project in conext of current state of research on 5-10 pages.</li> <li>This module serves generally as a preparation for the Master Thesis</li> </ul>									
Objectives	• 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 Scientific Project	т Type of Course	o Status	SMS 1	© ECTS	y Assignments	Type of Exam	Dur. of Exam (min)	b Grading	Weight for Grade
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.									

Module Number: MAT-40-42	Module Title:  Mathematical Physics Colloquium						Type of Module: Compulsory Module			
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: Time in Class: 60 h				Self-St 30 h	Self-Study: 30 h				
Duration	2 Semester									
Frequency	Every Semester									
Term	3–4	3–4								
Language of Instruction	English									
Forms of Teaching and Learning	Presentations, discussions. Specific form of study: during the final semester students present their Master thesis.									
Content	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.									
Objectives	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.									
Requirements for Obtaining Credit, Grading, Weight in	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
applicable	Colloquium Winter Semester	С	0	2	1	no	-	-	ng	-
	Colloquium Summer Semester	С	0	2	2	no	-	-	ng	-
Transfer	-		1	1	1	-	ı	1	1	1
Prerequisites	-									
Responsible Persons	Carla Cederbaum, Stefan Te	ufel								

Module Number: MAT-40-43	Module Title: Master Thesis M.Sc. Mathematical Physics							of Module: ulsory Mod		
ECTS-Points	30									
Workload - Time in Class - Self-Study	Workload: 900 h	Time 0 h	in C	Class	:		Self-S 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	Title  Master Thesis	Type of Course	o Status	SWS	00 ECTS	S Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
Transfer	-									

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.