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Structured Doctoral Education in Hannover - Joint Programme IMPRS-GW and *geo*-Q RTG

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Abstract. Two structured doctoral programmes that we have in Hannover, the IMPRS on Gravitational Wave Astronomy and SFB on relativistic geodesy and gravimetry with quantum sensors *geo*-Q, have not only become major resources for education in each field but have also started to provide substantial synergy to members of both programmes. Our strong cross-disciplinary approach to create a joint programme has received excellent feedback not only from researchers inside the programmes but also from various external committees. Building on experience that we have acquired over the last decade, we propose to set up a common doctoral programme within the international gravitational wave astronomy and physics. We envisage that with a common doctoral programme we will create a strong team of young researchers who will carry on building a strong network of third generation gravitational wave detectors and observatories.

1. Introduction

After the ground-breaking discovery of gravitational waves in 2015 [1], the overwhelming success of the LISA Pathfinder mission in 2016 [2], and the selection of the LISA mission [3] as the L3 mission in the future science programme of the European Space Agency ESA gravitational wave astronomy has more than ever a brighter and a louder future. Building space missions like LISA and third generation detectors like Einstein Telescope [4] is a long term undertaking which will be carried out by the students that we educate now. In order to bring those projects into success they need a high-quality education and a good team spirit with shared values. In Hannover we have two structured doctoral programmes that could be a model for building a strong network of the future missions and third generation detectors. One is the International Max Planck Research School on Gravitational Wave Astronomy (IMPRS-GW) and the other is a new addition called the *geo*-Q Research Training Group (RTG) for Earth scientists and physics. Recently we have successfully created a synergy between them by forming a joint doctoral programme. The merging of the two different programmes can serve as a role model for the entire field of gravitational wave research collaborators.

2. IMPRS-GW

IMPRS-GW is the single largest and most influential educational institution worldwide in the field of gravitational wave research. It has been a joint doctoral programme of the

Albert Einstein Institute (AEI)(Divisions Gravitational Wave Astronomy, and Observational Relativity & Cosmology, and the Astrophysical and Cosmological Relativity division), the Leibniz Universität Hannover (LUH) (Institute for Gravitational Physics (IGP), Institute for Quantum Optics (IQO), and Institute for Theoretical Physics), and the Laser Zentrum Hannover (Division Laser Development), and the University of Potsdam. The programme combines the different fields of gravitational wave astronomy: from laser development, interferometry and quantum optics to data analysis, astrophysics, theory, and source modelling.

2.1. Scope and curriculum

The IMPRS-GW curriculum ensures a high-quality and comprehensive graduate education. It is our goal that theorists acquire a basic understanding of the experimental foundations of laboratory work in general and of interferometry, laser physics and quantum optics in particular. And experimentalists, on the other hand, are expected to acquire a basic understanding of data analysis, relativistic astrophysics and numerical relativity. We also aim to provide a system of shared values and principles concerning scientific behaviour and methodology. In order to achieve these goals we have altered our curriculum several times over the past decade and now found an optimum compromise between the traditional way of learning on-the-job by working as independent researchers alongside experienced colleagues and helpful peers on the one hand, and the best elements brought by the structured doctoral programme such as attending tailored lectures, group experiences and transferable skills education on the other hand. These transferable skills courses include intensive training from world's top-class trainers on "Scientific Writing", "Scientific Presenting", "Project Management", and " Good Scientific Practice". All of our students receive intensive advising through their own Thesis Advisory Committee consisting of at least three supervisors who they choose when they enrol at the university to study at our institute. We also provide ample opportunity to all our doctoral students to spend several months at an international collaborating research institution and all our doctoral students make presentations at one international conference and many German meetings and present their thesis work. The curriculum of the IMPRS-GW is based on three pillars of our education. They are the specialised lectures offered regularly at LUH, specialised lectures by AEI scientists which are video-transmitted to the other part of the institute, and our so-called IMPRS Lecture Weeks, introduced in 2008.

2.2. IMPRS-GW Lecture Weeks

These are weeks of block lectures in general relativity, theoretical astrophysics, data analysis & statistics, numerical relativity (alternating), and experimental gravitational wave physics (with changing topics), taking place at "isolated" locations in the surroundings of Europe. We have three lecture weeks per year. With this concept, we want to ensure that experimentalists also get some basic knowledge in the theoretical fields of gravitational wave astronomy and physics and theorists learn the basics of the experimental fields. The second important goal of these weeks is to bring the students of the different research fields and both institute locations together. Three lectures are given every day with a good balance of theoretical topics and experimental topics in the first two lecture weeks. In the afternoon and in the evening students are given plenty of time to deepen their understanding by asking questions, to present their thesis work, and to get to know each other and building network. In the third week a one-week project by student teams composed of theorists and experimentalists as well as advanced students and beginners is added. This project work is increasing considerably the active student participation through hands-on experience. Details of topics given at three lecture weeks are shown in figure 1.

	Lecture Week 1	Lecture Week 2	Lecture Week 3
General Relativity/ Astrophysics	- Special Relativity - Curved Coordinates, Equivalence Principle - Tensors and physics in a curved spacetime - Einstein equations, initial-value formulation - Linearized GWs	- Linearized theory, action on detect - Generation of GWs in linearized theory - Black holes I - Black holes II - Spherical stars	- Massive black holes in the Universe - Massive black hole dynamics - Evolution of single stars - Evolution of binary systems and stellar remnants
GW Interferome try	- GWs and their effect - Detection principle - Interferometer basics - Signal detection theory - Detector noise sources	- Power Spectral Density - Signal to Noise ratio - Adv. Ifo configurations - Control theory & practice - Gaussian optics	- Thermal Noise - Fluctuation-Dissipation Theorem - Non-classical light - Generation of squeezed light - Squ. light application & Standard Quantum Limit
Statistics/ Data Analysis	- Discrete differential operators - 3+1 split of spacetime - Different formulations of Einstein equations - Gauges, initial data and GW extraction - Introduction to relativistic hydro-dynamics	-Bayesian, Neyman- Pearson - Likelihood, matched filtering - Signal vetoes, chi-square, significance of signal - Gaussian and non-Gaussian noise and statistics - Multiple detector burst searches	Project Week

Figure 1. IMPRS-GW Lecture Week yearly curriculum. Three lectures are given every day, as a rule starting with a lecture with experimental topics, followed by a theory lecture, then another experimental lecture to keep a good balance of topics.

2.3. Outcome of the education

After 10 years of continuous effort in operating IMPRS-GW, 91 doctoral students have graduated and all of them have obtained PhD degrees. Assuming that the first set of doctoral students took four years to graduate, our alumni have been on the job market for the past six years. All of IMPRS-GW alumni have obtained a job as they graduated. As of today, more than half are working as postdocs all over the world, 25% have obtained a job in industry, a few alumni became professors in physics and others became teachers in high schools, as shown in figure 2. Our experience allows us to foresee that more alumni will shift into industry the longer they are on the market. Our approach to avoid turning graduate research and study into a type of rigid higher-level school system but to combine the best elements from all approaches have produced young researchers who are equipped with knowledge and skills that are highly sought after in both academic world and industry. This dual career nature of our alumni is a clear indicator that we have been successfully educating our doctoral students.

2.4. Evolving IMPRS-GW

Not only doctoral students but also postdocs and senior researchers from all over the world have joined our programme. For example in this Amaldi conference there were five scientists who participated in our lecture weeks as lecturers and we also found that one out of every five speakers of the conference have participated in our lecture weeks. This shows that we have become a major resource of education in the field of gravitational wave astronomy and physics. Recently we started to expand our programme by inviting people from outside of our

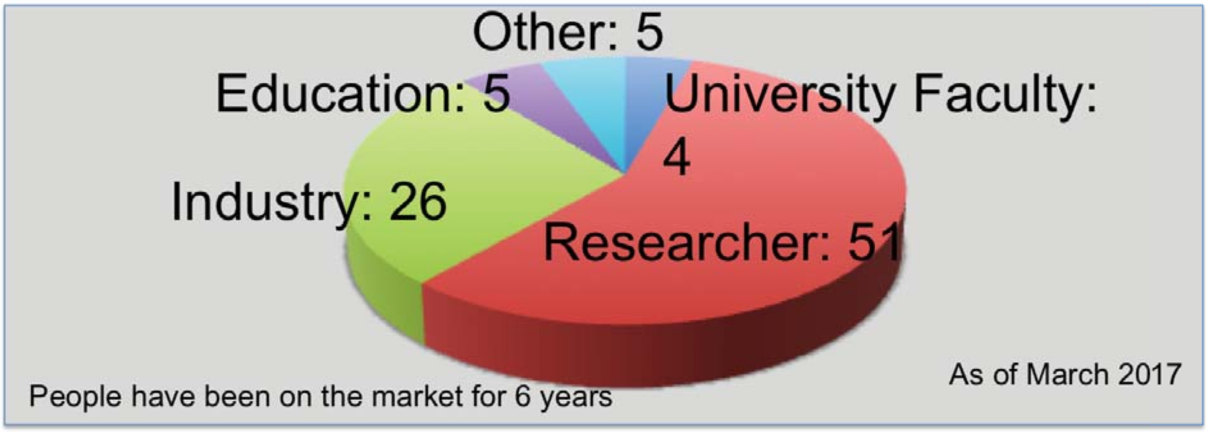

Figure 2. Type of jobs obtained by IMPRS-GW alumni. The result shows a dual career nature. We can foresee that more alumni will obtain jobs in industry the longer they are on the job market.

own institute to provide specialised experience that we do not have and to bring people of different groups together, e.g. "Quantum Optomechanics" by Markus Aspelmeyer (University of Vienna), Joint week with International Max Planck Partnership IMPP with University of Glasgow in 2015 and 2017, Earth scientists from University of Balearic Island, and lecturers from space industry.

2.5. Merging IMPRS-GW and geo-Q programme

IMPRS-GW is constantly evolving. Recently we put two graduate school programmes together. The other programme is the Sonderforschungsbereich (SFB)[1] *geo*-Q, which is supported by the German Research Foundation. The group consists of IGP, IQO and Institut of Geodesy (IfE) at the LUH, The National Metrology Institute of Germany (PTB) in Braunschweig near Hannover, and Center of Applied Space Technology and Microgravity (ZARM) in Bremen. *geo*-Q is centered at LUH, and there are some overlaps between the research topics and principal investigators (PIs) of the two programmes. Merging the two programmes allows us to therefore not only optimise learning process but also reduce teaching effort, since otherwise the PIs would have two programmes to support. In addition, by the merging method we obtain an increased level of interdisciplinarity which allows our students to acquire broadened and deepened understanding of their research field.

3. *geo*-Q

geo-Q aims to obtain better knowledge of the Earth gravity field by combining three pillars together. They are better accuracy of global gravity field using satellites with laser interferometer, measuring gravitational redshift to get very accurate gravitational potential with atomic clocks, and obtaining local gravity acceleration with quantum gravimeter. These are very different fields, but the structured doctoral programme of *geo*-Q, the *geo*-Q RTG, brings them together to form a strong team. All doctoral students of *geo*-Q are members of the *geo*-Q RTG, and they learn topics of relativity, theoretical geodesy, experimental geodesy, satellite designs, data analysis & statistics, and various experimental topics including optical clocks, matter wave interferometers, and laser interferometry. It is our goal that they will be the first generation of

[1] In English it is called the Special Research Area

relativistic geodesists who have understanding of all of these fields. The *geo*-Q RTG curriculum is based on that of the IMPRS-GW.

4. Joint programmes

At first we did not know to what level the two programmes could be merged but after a few trials we found that lecture weeks and transferable skills courses could be very well combined. Our joint lecture weeks host common lectures to students from both IMPRS-GW and the *geo*-Q RTG, such as basics of special relativity, basics of data analysis & statistics, and laser interferometry, and parallel sessions in which two separate lecturers are given for the two groups. In addition we have guest lectures for general education, and those are for students from both programmes. Such guest lectures include e.g. oceanography and astrophysics. Obtaining one additional seminar room enabled us to transform a normal lecture week into a joint lecture week. Students as well as lecturers have given excellent feedback on this joint programme and we are open to new suggestions of improvement when needed.

5. Conclusion and outlook

Not only have we created the joint programme between the IMPRS-GW and the *geo*-Q RTG, but also we aim to expand our activities to start a European wide structured doctoral programme in the future. Currently all our students involved in LISA and GEO600 [5] are our IMPRS-GW members. Our vision is to develop a world-wide educational programme in gravitational wave astronomy and physics, and to create a new generation of gravitational wave physicists who will carry on the projects of third generation detector network and future missions. As a first step we submitted a proposal for a joint European-wide doctoral programme with University of Lyon. We have already been actively exchanging students within the collaboration. However that is not enough, and we need a common curriculum, common advising, and possibly even a real joint doctoral degrees among our collaborating institutions. We strongly propose to let us build a world-wide programme for third generation detectors and future missions network together. It is straightforward to start based on an already functioning model like IMPRS-GW programme, which has successfully demonstrated a possible method for merging with a different programme such as *geo*-Q RTG. We envisage that it is relatively easy to start an European-wide joint lecture week. It is not complete nor perfect, but it is a start.

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