Fundamental Physics with Astronomical Observations: Testing Gravity and Extreme States of Matter

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Executive Summary

The main themes/questions in the field of fundament physics, especially in testing gravity and extreme states of matter for the upcoming 10-15 years are:

- Gravity and matter under extreme conditions: relativistic velocities, highly dynamical and strong curvature
- Gravitational-wave detection: the blooming of gravitational-wave astronomy
- Relativistic computational astrophysics: modelling of supernovae and gamma-ray bursts
- Physics and astrophysics of compact-objects: black holes and neutron stars
- Nuclear astrophysics: nucleosynthesis in supernovae and binary neutron stars mergers
- Cosmological-scale gravity: nature of dark matter and dark energy.

Currently, there is a strong visibility and involvement of the German community in all the relevant areas (tests of gravity, gravitational waves detection and modelling neutron-star physics and nuclear astrophysics) both theoretically and experimentally. These include pulsar observations, gravitational-wave research, Galactic centre research and the efforts in instrumentation, observations and theory. When considering all aspects of research in gravity and extreme matter (theory/experiment), no other country has similar involvement apart from USA. At the same time German nuclear astrophysics has a long tradition and is reference at worldwide level.
This is evident from a number of prominent achievements and successes over the past decade. These include:

- First direct detection of gravitational waves from a binary black-hole merger
- Best tests of general relativity and alternative theories involving pulsars
- Tighter constraints on equation of state (EOS) of matter at supranuclear densities
- Stringent limits on a low-frequency gravitational wave background from Pulsar Timing Arrays.
- Numerical and analytical general-relativistic calculations of the dynamics of compact objects
- Fully nonlinear simulation of catastrophic events such as supernovae and gamma-ray burst.
- Observations and stellar dynamics at GC and discovery of a magnetar in the GC.

Access to 3rd generation gravitational-wave detectors, SKA, LISA and HPC facilities are the most important conditions to ensure the continuing access of the German community in this exciting research field

1. Introduction

The fundamental laws of physics describe the world that we live in, the Universe, how it began and how it evolves. Their understanding is therefore also of fundamental importance and the subject of research across many disciplines. Astronomy and astrophysics provide insight that is unattainable somewhere else, especially when it comes to understand gravity and the physics under extreme conditions. It is therefore no surprise that the first question formulated in the ASTRONET Science Vision is “Do we understand the extremes of the Universe?” While astronomy provides cosmic laboratories of scales and conditions that cannot be matched or created on Earth, obtaining, interpreting and understanding such observational data is key when confronting the theories derived on Earth with experimental data. These data are gathered with instruments exploiting different windows to the Universe; they are compared to theory with often-massive computer simulations in order to understand selection effects and biases or the physics itself, and they complement each other. However, astronomical observations do not only test predictions of theories, but they also drive their development. Deviations from accepted models demand and trigger new theoretical insight. Past has shown that this new insight has huge implications on many other areas or even creates new fields (e.g. relativistic astrophysics). These developments also have impact on practical applications like the International Earth Rotation and Reference systems Service and relativistic geodesy, and further contribute to our fundamental understanding of space and time. As we will argue in the following, pushing the studied physical conditions to an extreme using astronomical observations will continue to be a fundamental pillar and driving force in our understanding of the Universe and the fundamental physics that governs it. We will first discuss aspects of gravity before we consider extreme states of matter.

1.1 Gravity

At the heart of understanding the Universe lays our understanding of nature's arguably most fundamental force, gravity. The study of gravity has thereby strong links with the field of cosmology and its aspects, which is treated specifically elsewhere in this document (see Chapter 8 and 9). While it is therefore difficult or impossible to cleanly separate them, we focus here on the aspects of the fundamental force itself.

In order to test and understand gravity, we need to probe a very wide range of scales and velocities using various objects and phenomena. As general relativity (GR) describes gravity by the curvature of spacetime, we summarize the parameter space to be probed as shown in Fig. 1, where we plot the curvature of spacetime (which is measured in terms of the inverse of the curvature radius squared) as a function of how "relativistic" a given astrophysical system is (which is measured in terms of the dimensionless velocity of the system in units of the speed of light).

On the bottom part of the diagram, we encounter the Universe itself and its large-scale structure, directly relating to its unknown aspects such as dark matter, dark energy or inflation – as also discussed in Chapters 8 and 9. Experiments in the solar system are indicated in the upper half of the diagram, at a curvature of about ~ 10^{-24} cm^{-2} with dimensionless velocities $(v/c)^2 \leq 10^{-5}$.

Pulsars allow high-precision tests of gravity in the quasi-stationary strong-field and radiative regime at curvatures of order 10^{-11} cm^{-2} and $(v/c)^2$ exceeding 10^{-6}.

The strongest gravitational fields are related to black holes. Black holes are one of the most outstanding predictions of General Relativity with strange and unexpected properties as horizons, singularities, the possibility to allow time travel, etc. Today there is considerable observational evidence that black holes really exist. One of the most important tasks in relativistic astrophysics is to further explore and understand the physics of black holes through stellar motion, accretion, jets, light-distortion effects, and by gravitational waves: The most top-right corner of Fig.1 is occupied by observations enabled by ground-based gravitational wave detectors, where the first direct detections of gravitational waves from binary black-hole mergers was recently made (Abbott et al. 2016a). This portion of the diagram represents a new window on the Universe and a precious tool to study gravity and in its most extreme manifestations.

Other future detections, such as those possible with eLISA, Pulsar Timing Arrays (PTAs), or direct imaging of a black hole, all described below, mark the other entries in this diagram.

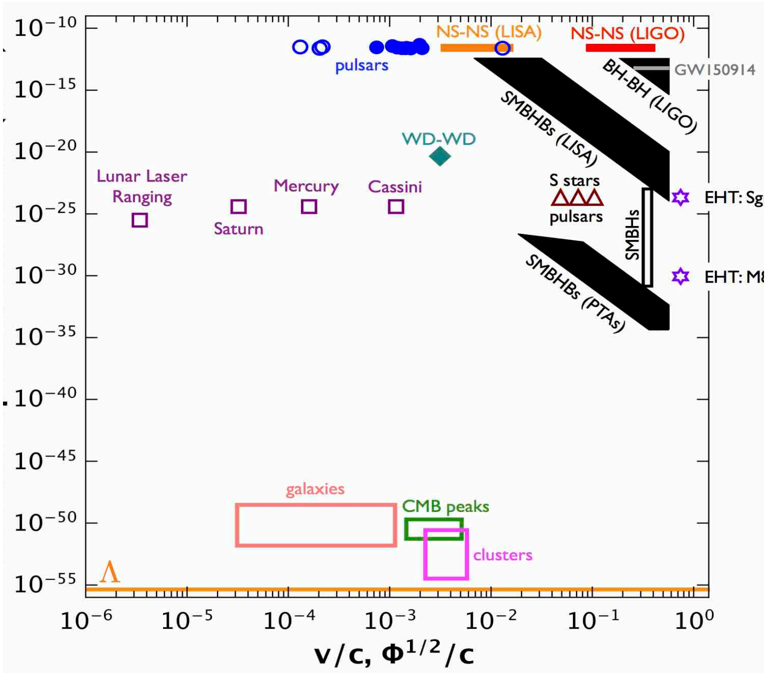

Figure 1: Parameter space of observations and tests of gravity. On the x-axis, v denotes the typical velocity of the system's components while Φ denotes the gravitational potential being probed by photons propagating in the corresponding spacetime. On the y-axis we have the maximum spacetime curvature (taken at the horizon for black holes) in the system as a measure of how much the system deviates from flat spacetime. Filled areas indicate gravitational wave tests, while hollow areas stand for quasi-stationary tests, including accretion onto compact objects. (Wex, priv. comm.)

1.2 Extreme states of matter

A further central fundamental physics question is how matter behaves under extreme conditions. The nuclear equation-of-state (EOS) is highly uncertain and not known. Constraints at low density come from nuclear masses and chiral perturbation theory. This nuclear-physics problem connects accelerator experiments with astrophysics and is as old as neutron stars, but it almost certainly may find a solution through astronomical observations rather than in a lab.

The formation of neutron stars as the densest objects in the observable Universe still needs study. Especially, as supernova explosions are important not only for their cosmological implications, but also for their contributions to chemical evolution. It constitutes a very hard problem that simultaneously involves the EOS, neutrinos, general relativity, High Performance Computing (HPC), magnetic fields, all of which contribute to the explosions. The binary mergers of neutron stars also contribute to chemical abundance in the Universe and the emission from radioactive decay of ejected matter (kilonova) could be missing link between Soft Gamma-ray Bursts and binaries. Indeed, a number of observations point to the association between short gamma-ray bursts and merging binary neutron stars. Nevertheless, despite decades of observations, it is not yet clear what drives these explosions. All of the above topics are closely interlinked, and results – both theoretically and observationally - in one area clearly have an impact in the other areas as well.

2. Key Questions for the Upcoming Decade

The previous decades have been extremely successful. After the first evidence for the existence of gravitational waves using binary pulsars, the first direct detection was achieved in September 2015. General relativity passed this and all other experimental tests with flying colours. However, the also established field of precision cosmology, with PLANCK fulfilling its promises that the community formulated after the WMAP results, supplemented by other results (see Chapter 8 and 9), is studying the impact and nature of Dark Matter and Dark Energy. Some suggest that Dark Matter represents a deviation from general relativity (e.g. Famaey & McGaugh 2012), rather than a massive particle, while Dark Energy's manifestation is even less clear, but it is clearly closely related to gravity. Similarly, understanding the state of super-dense matter relates to nuclear forces, and hence links astrophysics with high-energy and particle physics. It is therefore not surprising that the following key questions are essentially those also and already defined in the ASTRONET Science Vision (de Zeeuw & Molster 2007):

- *How did the Universe begin, how will it evolve?*
- *What are dark matter and dark energy?*
- *Do black holes really exist, and have an event horizon?*
- *If they exist, do black holes host a physical singularity?*
- *Which effects occur in strong-field gravity?*
- *What is the EOS of matter at nuclear density?*
- *How compact are neutron stars?*
- *Is general relativity our last word in our understanding of (macroscopic) gravity?*

In addition to these fundamental questions, the advent of gravitational wave astronomy opens a new window to the cosmos, so that further questions are:

- *What are the properties of the gravitational wave sky across all frequencies?*
- *What is the population of stellar black hole-black hole systems?*
- *How many supermassive binary black hole systems exist and how does that relate to our understanding of galaxy formation and mergers?*
- *What is the population of neutron star-neutron star systems?*
- *What are the properties of black holes, and are they consistent with general relativity?*

3. Key Results from the German Community of the Previous Decade

The last decade has seen a tremendous amount of important key results, from high-precision tests of general relativity using binary pulsars to the ability perform full 3-D simulations of supernova explosions, from the discovery of dark energy to the first direct detections of gravitational waves from a binary black hole merger. We summarize some of these and describe the German contributions below.

3.1 Precision tests of gravity with pulsars

The foundation of General Relativity is summarized in the Equivalence Principle. German teams are leading experiments aimed at testing the Local Lorentz Invariance (Schlippert et al. 2014). Germany is also strongly contributing to an ongoing space mission aiming at a largely improved test of the universality of free fall (Hagedorn et al. 2013). The German community is also world leading in the experimental exploration of the interplay between quantum mechanics and gravity – an issue which might be of importance for the interpretation of astronomical data. The numerically most precise test of the validity of the Einstein field equations has been so far achieved by studying the propagation of signals from the Cassini spacecraft in the weak-field gravitational potential of the solar system, achieving a precision of 10^{-5} (Bertotti et al. 2003).

However, as these tests have only been performed in the weak gravitational field of the Solar system, testing the strong-field regime is essential. Testing strong-field effects of strongly self-gravitating bodies has been possible by binary pulsar observations, with the Double Pulsar providing the most precise tests so far (Kramer et al. in prep., see Figure 2). The Bonn group at MPIfR is a world leader in these tests, conducted not only the best tests for general relativity (e.g. Kramer 2016; Kramer et al. in prep.) but also for tests of alternative theories of gravity, in particular scalar-tensor gravity (e.g. Freire et al. 2012, Antoniadis et al. 2013, Wex 2014). Furthermore, important phenomena like geodetic precession have been first discovered in pulsars with the Effelsberg telescope (e.g. Kramer 1998, 2012; Desvignes et al. 2016), while other work of the group has produced new recipes for the tests of the University of Free Fall (Freire et al. 2012) and provided tests for gravitational Lorentz invariance and other fundamental symmetries of gravity (Shao & Wex 2012, Shao et al. 2013, Shao & Wex 2016). This observational effort is matched by an intense theoretical research carried out in Tübingen, where the impact of alternative theories of gravity on the equilibria of neutron stars has been explored systematically (Doneva et al. 2014, Yazadijev et al. 2015).

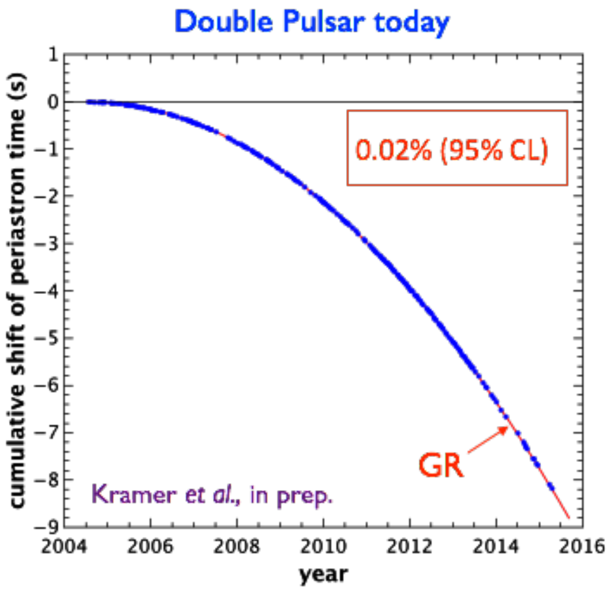

Figure 2: Effects of the orbital period decay due to gravitational wave emission as observed in the Double Pulsar. The back-reaction of gravitational-wave emission leads to a continuous change in the orbital period and consequently to an acceleration in the orbital phase evolution, leading to a cumulative advance in the time of periastron passage. The observed change in periastron passage (blue dots) is in perfect agreement with the theoretical predictions by GR's quadrupole formula (red curve). (Kramer et al. in prep.)

3.2 Indirect and direct gravitational wave detection

The MPIfR leads the exploitation of the Double Pulsar system, a unique system that provides the most precise tests for GR's quadrupole formula for gravitational wave emission to date (e.g. Figure 2). With this evidence for gravitational waves from binary pulsars, the community had eagerly expected the first direct detection with ground-based detectors. This was finally achieved in 2015, when the upgraded Advanced LIGO detectors measured with the event GW150914 (Abbott et al. 2016a), the signal of a merger of two stellar-mass black holes. German colleagues were the first to recognize the signals and continue to play a leading role in the data analysis of LIGO data, both computationally as well as theoretically. Indeed, over the last few years a great development effort has been made in Germany to obtain a computational infrastructure that is able to provide a seam-less description of the evolution of binary systems containing compact objects such as black holes or neutron stars. These calculations, which have played a key role in the recent detection of the gravitational wave signal from GW150914 and the other signals that have been detected so far, e.g. GW151226 (Abbott et al. 2016b).

As explained further below, it has been the technology developed by the German community and successfully deployed to the German/UK gravitational wave detector GEO600 that made the era of gravitational wave astronomy a reality. Indeed, this discovery (Figure 3) heralds the begin of a new era, which will not only allow tests of gravity in the highly dynamical strong-field regime that was not accessible before with pulsars (see Figure 1), but it also opens up a new window to the Universe. This window already provides a first direct view onto a population of black holes, whose numbers and properties were essentially unknown before the LIGO result. Furthermore, as we discuss in more detail later on, when the information contained in the gravitational waves from merging binary neutron stars will be combined with the electromagnetic emission that is expected from this process, we will also obtain very important clues on the central engine of short gamma-ray bursts and on the status of matter at nuclear densities.

While the ground-based detectors like LIGO and GEO are sensitive to the frequencies above 10 Hz, one has to move to space to access the gravitational wave sky at lower frequencies. The German community, especially the colleagues at Hannover, are leading the global efforts in developing the first space-based detector. Consequently, they played a crucial role in the success of the LISA Pathfinder probe launched in 2015 (Armano et al. 2016).

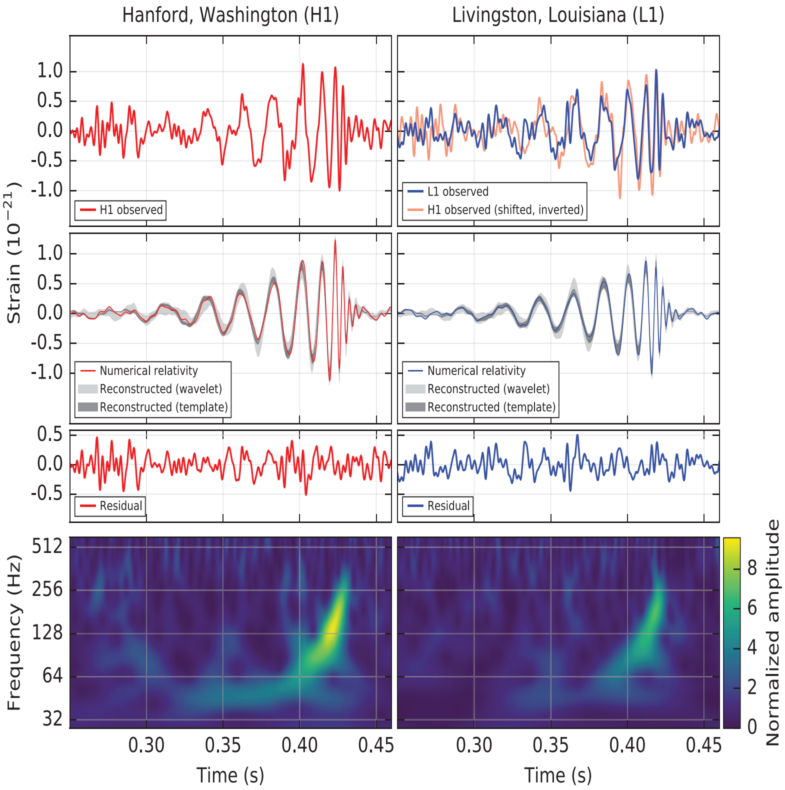

Figure 3: First direct detection of gravitational waves from a binary black-hole merger GW150914. (Abbott et al. 2016a).

Going to even lower frequencies, one expects to see the gravitational wave signals of supermassive binary black holes. According to the standard scenario of galaxy formation, they are produced during the merger of galaxies in the early Universe. Emitting signals at nano-Hertz frequencies, these systems can be detected using a "Pulsar Timing Array" (PTA) – a network of fast rotating millisecond pulsars that act as the end points of a Galactic-sized gravitational wave detector. High precision timing of the pulsars allows to pick up tiny variations in the expected arrival time of the detected pulses as the local spacetime is modified by low-frequency gravitational waves, both at Earth as well as the pulsars. This experiment is conducted in Europe as the European Pulsar Timing Array (EPTA; Kramer & Champion 2013), with scientists in Bielefeld, Bonn, Golm and Potsdam co-leading the efforts. The first complete official data release with the precision timing of 42 millisecond of the EPTA was led by the Bonn group (Desvignes et al. 2016). The data set was used by Caballero et al. (2016) for a sophisticated noise-analysis which is essential to reveal the signal of the expected stochastic gravitational wave background in the presence of competing red-noise processes, again led in Bonn. Already earlier, colleagues in Golm led an EPTA publication, which sets the currently best limit on the continuous gravitational waves from individual supermassive black hole binaries, using the Desvignes EPTA data set (Babak et al. 2016). This limit was derived using frequentist and Bayesian detection algorithms to search both for monochromatic and frequency-evolving systems for the first time.
Effelsberg, as the most sensitive telescope in Europe, acts as the back-bone of the EPTA and also serves as the reference telescope in the "Large European Array for Pulsars" (LEAP, PI Kramer; Kramer & Champion 2013), which forms a synthetic 200-m dish for low-frequency gravitational wave detection. Both EPTA and LEAP are therefore crucial contributors to the "International Timing Array" (IPTA) which coordinates the efforts of the EPTA with the experiments in North-America (NANOGrav)

and Australia (PPTA). The importance of the German community if signalled by the fact that the first official IPTA data is led by Joris Verbiest at the University of Bielefeld (Verbiest et al. 2016), while Kramer championed the PTA experiment as one of the Key Science Projects for the Square Kilometre Array (SKA) for more than a decade (Kramer et al. 2004, Kramer & Stappers 2015).

3.3 Super-dense matter

Clearly, one of the most important results of the last decade for the study of super-dense matter was the precision measurement of the highest neutron star mass in PSR J0348+0432 of $2M_{\odot}$. This work by the Bonn group (Antoniadis et al. 2013) is already the most cited German radio astronomy paper in the last decade with well over 750 citations (as by ADS in July 2016). The importance of the result is given by the impact of this large mass for the validity of proposed equations-of-state of super-dense matter, which have to be stiff enough to sustain such a large mass (see Figure 4). In fact, most of the mass measurements of neutron stars have come from the Bonn group (see Özel & Freire 2016 for a list with references), and especially the study of the important Double Neutron Star systems is dominated by results from Bonn (see Martinez et al. 2015 and references therein).

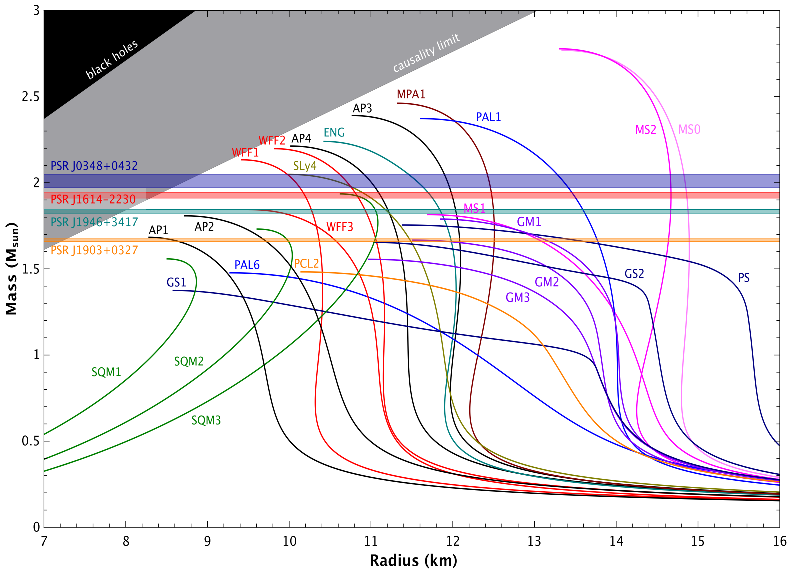

Figure 4: Radius-mass relations of neutron stars for different EOSs (Lattimer & Prakash 2001). High mass pulsars provide important constraints by ruling out those equations of state that cannot support two solar mass neutron stars.

4. Particular Role/Strengths of Research Groups in Germany

Many of the key results obtained in this research field have been obtained under the leadership and/or collaboration of German institutions and scientists.

4.1 Pulsar and neutron star observations

Research groups at Bonn (MPIfR) and now also Bielefeld (university), have established themselves as word leaders in the discovery and exploitation of pulsars for studies of fundamental physics. These German scientists combine expertise from wide areas in neutron star and gravitation research, from mass measurements and equation-of-state studies to low-frequency gravitational wave detection, from radio pulsar searching and precision tests of general relativity to gamma-ray observations. An ambitious observing program using the 100-m Effelsberg telescope and others with deep involvements in international projects such as the European Pulsar Timing Array, are matched by rigorous efforts in a theoretical interpretation of the data. Indeed, the combination of such strong theory and observational efforts are unmatched in the world of neutron star and pulsar research, positioning the group at the forefront of this exciting research field. Most of the best constraints on, or measurements of, parameters describing relativistic gravitational theories or the rotation of fast-rotating pulsars have been achieved by experiments led by these colleagues. This goes in hand with the development and exploitation of instrumentation developed for pulsar observations installed at various telescopes around the world. The group in Bonn is also at the centre of the SKA gravitational physics Key Science Project. With access to the LOFAR station in Effelsberg, scientists in Bielefeld and Bonn are being intimately involved in the exploitation of the International LOFAR Telescope, and the early engagement and MeerKAT science. Current projects include an all-sky survey of the dynamic radio sky in the Northern and Southern hemisphere producing the defining data set to be studied and explored before the SKA comes on-line and the ERC-funded Large European Array for Pulsars (LEAP) that has a good chance in directly detection low-frequency gravitational waves.

4.2 Gravitational-wave Astronomy

4.2.1 Instrumentation and Data analysis

Already in the 1970s, German researches began to develop the technology of interferometers to detect gravitational waves directly, leading eventually to the construction of GEO600 and the development of innovative technology that was used for critical components (e.g. high-powered lasers) at the LIGO detectors and its upgrades. Scientists from the AEI have therefore played a leading role developing the instruments that led finally to the successful direct first detection of gravitational waves. The AEI is also the driving force behind the development of technology for the space-based detector LISA and has been a key player in the development of LISA Pathfinder, which was launched on December 3rd, 2015, and is now in its science mission. The first results published in July 2016 show that the design specifications are vastly exceeded, achieving already a performance that is required for LISA itself.

These hardware efforts are paired with work on the data analysis side, where AEI scientists are leading the development and implementation of mathematical methods (data analysis algorithms) to search for the different expected gravitational wave signatures of possible cosmic sources. In fact, it has been colleagues in Hannover who detected the signals of GW150914 for the first time. In addition to HPC clusters, a data analysis project known throughout the world is Einstein@Home., which is also used to discover radio pulsars in collaboration with colleagues in Bonn. The scientists at the AEI take a leading role in developing and running this global project.

4.2.2 Theory

As mentioned above, the last decade has seen the development of new approaches to the study of compact objects that are either based on analytical techniques that provide more and more accurate approximations to the dynamics or full-scale nonlinear numerical simulations. Colleagues at the AEI in Potsdam are leading experts in the development of accurate analytical models of gravitational-wave mergers that involve pairs of black holes, while colleagues in Jena and Potsdam have developed advanced and accurate codes for the numerical solution of this problem and the full calculation of the gravitational-wave signal.

Analytical and numerical models for black hole mergers (and other sources) play a crucial role for gravitational wave astronomy. Concretely, the work on post-Newtonian and numerical models done in Germany played an important role in the interpretation of the first signals as black hole merger signals and the derivation of the astrophysical parameters of the observed binaries (Abbott et al. 2016c).

In the case in which the binary contains at least one neutron star, numerical simulations of colleagues in Frankfurt, Jena and Munich are able to provide an accurate and realistic description of the various stages of the final dynamics of the binary, going from the inspiral stage, over to the creation of a hyper-massive neutron star (HMNS) and, ultimately, to the formation of a black hole surrounded by a hot and dense torus (Baiotti, Giacomazzo & Rezzolla 2008). Recently, a very accurate description of the inspiral and merger of binary neutron stars has been obtained using high-order finite-difference techniques for the solution of both the Einstein and the relativistic hydrodynamics equations. A newly developed code has been shown to achieve among the highest convergence rates demonstrated for this type of simulation, thus providing the high accuracy required to model even the tiny changes introduced by the tidal deformation of the stars in the evolution of the gravitational-wave phase (Radice, Rezzolla & Galeazzi, 2013). In addition, work has also been done to include radiative losses via neutrinos, which can be very useful to understand the relationship between the matter dynamics and the neutrino emission, which is essential to model the neutrino signals from mergers of compact-star binaries.

At the same time, great progress has also been made in improving the description of the EOS for merging neutron stars, also exploiting in part the constraints coming from astronomical observations. The calculation of the EOS for astrophysical simulations poses significant challenges. In particular, special care has to be taken because of the extremely high neutron densities and the nearly vanishing electron fractions. Hence, in addition to extending the EOS to non-vanishing temperatures, weak equilibrium and a fixed charge-to-baryon ratio have to be implemented for a large range of temperatures and baryon densities. A thermodynamically consistent framework has been developed recently for a large variety of modern nuclear EOSs for core-collapse supernova simulations within microscopic models, such as Skyrme-Hartree-Fock, relativistic mean-field models and more general density-functional approaches. In this way, it was possible to obtain a smooth matching between the neutron matter EOS and the high-density limit from perturbative QCD.

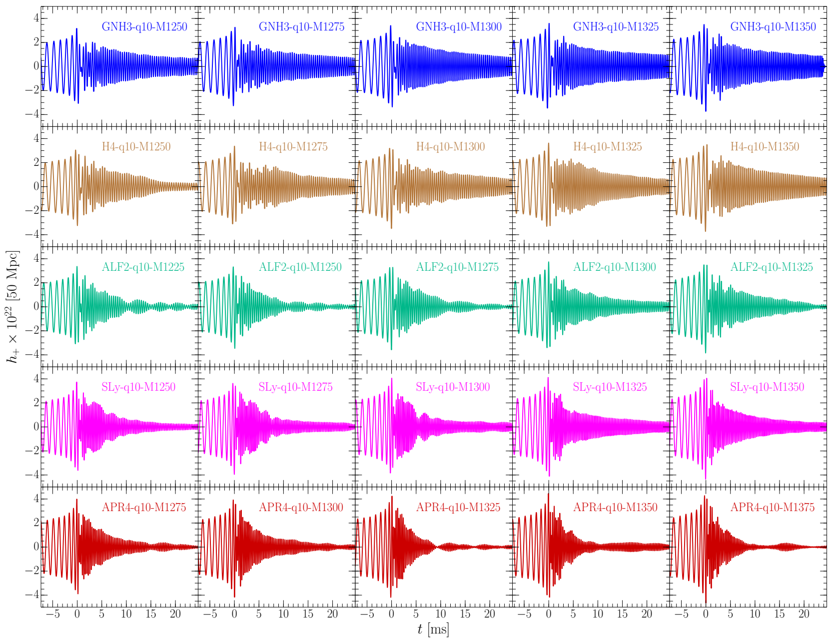

Figure 5 Gravitational waveforms for equal-mass neutron star binaries. Each row refers to a given EOS, while each column concentrates on a given initial mass. The different EOSs are distinguished by different colors.

An example of this ability to model the gravitational dynamics of binary neutron stars in full general relativity is shown in the figure below, which reports the gravitational waveforms for a number of binaries spanning five EOSs and five different mass ranges.

Groups in Frankfurt, Jena, MPI Garching, MPI Hannover, and MPI Potsdam have a long track record of excellent results in this area and over the last decade have imposed themselves as reference points worldwide for the *numerical modeling of compact binaries* and the accurate calculation of the gravitational-wave emission that is produced in the process, as well as the *development of technologies* in use in the advanced interferometric detectors.

Regarding the analytical description of the motion of stars and the propagation of light around black holes, new methods have been developed at the Universities of Bremen and Oldenburg. These methods can be applied to pulsar and star motion around Sgr A* (Hackmann & Lämmerzahl 2008) and also to the calculation of light effects in black hole spacetimes, like lensing and shadows of black holes (Grenzebach, Perlick & Lämmerzahl 2014), even in the case of black holes surrounded by plasma as needed for the EHT.

4.3 Relativistic Astrophysics Supernovae and Gamma-ray Bursts

Short GRBs are flashes of gamma rays releasing amounts of energy of the order of 10^{48} – 10^{51} erg, which suggests that the "central engines" are highly relativistic objects. These are among the most energetic events in the Universe and yet it is not entirely clear what their cause and nature is. The standard model envisages short GRBs as the outcome of the merger of a binary neutron star system leading to the formation of a HMNS, which eventually collapses to produce a rotating black hole surrounded by a massive and hot accretion torus. This scenario is also favoured by arguments based on stellar population synthesis and on stellar evolutionary models. Given the initial mass function and the rate of binary formation among massive stars, it is possible to estimate the number of binary neutron stars that form following normal stellar evolution and hence the rate of such systems that are about to merge. Such information can be exploited to relate binary mergers with short GRBs. It should be noted that both the HMNS and the black hole-torus systems could supply the required energy via neutrino emission or by extracting the rotational energy of the black hole via magnetic fields.

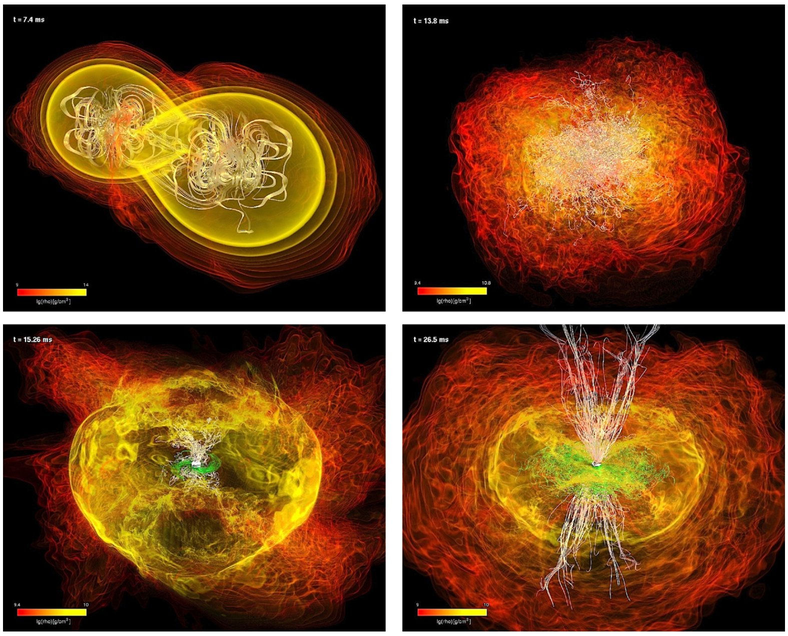

Figure 6 Snapshots at representative times of the evolution of magnetised binary of neutron stars and of the formation of a large-scale ordered magnetic field (Rezzolla et al. 2011)

Over the last few years it has become clear that the corrections to the gravitational wave signal during the inspiral and due to magnetic fields are too small to be detected by present and future detectors, but that magnetic fields do have an impact after the merger. They can influence the stability of the HMNS, and they could be subject to the magnetorotational instability (MRI), which leads to the exponential growth of the magnetic field even from very weak seeds. Furthermore, they can launch a quasi-isotropic, baryon-loaded and mildly relativistic wind, which could be used to explain the X-ray afterglows observed in a large fraction of short GRBs.
The material ejected during these events can yield to the nucleosynthesis of heavy elements via rapid neutron-capture processes (r- processes), but also to a radioactive decay which could explain the infrared excess in the afterglow (kilonovae). Finally, magnetic fields provide the link between inspiralling binaries and the generation of a large-scale jet that could power short GRBs.
Groups in Frankfurt, MPI Garching, and Tübingen are now playing a leading role in the modeling of these processes that are perfect examples of a novel approach to astronomy based on multimessenger observations.

4.4 Nuclear Astrophysics

We are entering a new era with multi-messenger observations (electromagnetic, neutrinos, gravitational waves) and new nuclear physics facilities. The combined efforts of astrophysics simulations, observations, nucleosynthesis calculations and nuclear physics (theory and experiment) will allow us to understand the origin of heavy elements in the Universe. The work proposed here focuses on the two main processes producing heavy elements and their contribution to the Solar System abundances: the slow and the rapid neutron capture processes (s- and r-process). The r-process produces half of the heavy elements but it is still a nuclear physics and astrophysics challenge.
Germany has a long history of nuclear physics and the largest experimental facility in Europe is in construction in Darmstadt (Facility for Antiproton and Ion Research, FAIR). Yet, the extreme neutron-rich nuclei involved in astrophysical conditions such as the merger of binary neutron stars cannot be produced in the laboratory and their properties are loosely constrained by theoretical models. The astrophysical sites involve neutron stars and explosive conditions that allow the rapid capture of abundant neutrons. We will investigate the nucleosynthesis in compact binary mergers that are an excellent candidate to explain the origin of heavy elements in the Universe. This is further supported by the potential observation of the radioactive decay of r-process material in a kilonova after the short GRB 130603. Even if they are rare, the amount of matter ejected is enough to account for the r-process elements in our solar system.

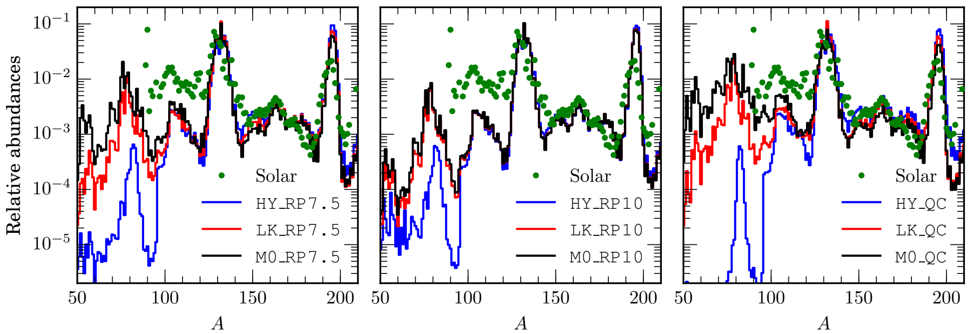

Figure 7 Final abundances in the ejecta for the merger of binary neutron stars. For each configuration we consider three different levels of microphysical description. The abundance pattern for elements with A > 120 is very robust and in overall good agreement with the Solar r-process abundances

Groups in Bonn, Darmstadt, Frankfurt, Heidelberg and MPI Garching have now built a large and robust framework for the exploration of the microphysics of nuclear process in astrophysics. Such a framework is built on a novel and collaborative effort in which traditionally independent scientific communities are brought together to analyse the different phenomena that take place in nuclear astrophysics.

4.5 Exploring the Galactic Centre

The centre of our Galaxy is a particularly interesting location to probe gravity. Colleagues at Garching and also Cologne have been world leaders in the observational efforts to detect and exploit stars orbiting the central supermassive black hole for a long time (Gillessen et al. 2009). This and future observations of stars to probe the gravitational field of the black hole are described elsewhere. These efforts are matched by efforts including colleagues in Bonn and Frankfurt to obtain an image of the “shadow” of the event horizon using mm-VLBI, a technique where the German community is traditionally world-leading (described elsewhere), and to combine these images also with insight from pulsars observations and theoretical studies. The idea to obtain an image itself originated in Bonn and is now being explored globally within the Event Horizon Telescope (EHT) project under co-leadership of German colleagues with strong theoretical work by colleagues in Frankfurt.

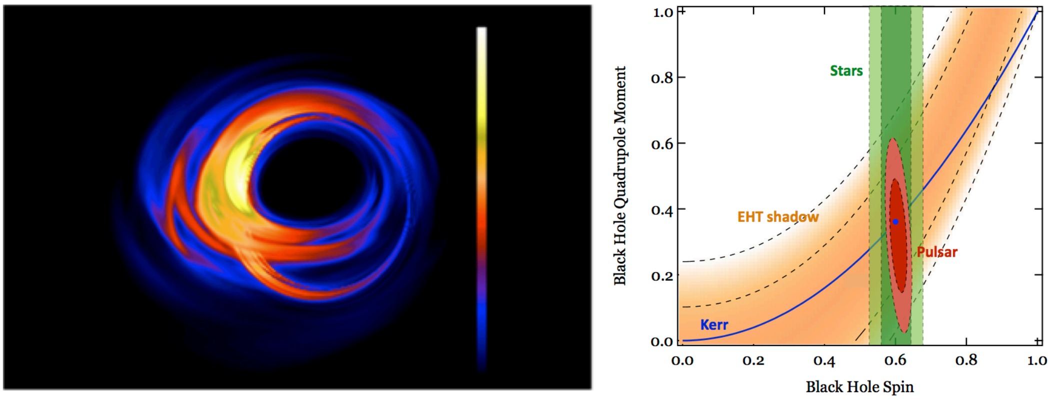

Figure 8: Computations by Dexter et al. (2010) of the underlying structure of an image project of the Galactic Centre black hole to be taken by mm-VLBI in the Event Horizon Telescope (left). The results of these images of the event horizon can be combined with future observations of pulsars and stars providing complementary information to determine the black hole properties like mass, spin and quadrupole moment, providing a test of the no-hair theorem when combined with the theoretical insight as in the black hole Cam project (right; see Psaltis et al. 2016).

5. Key Infrastructures Needed and Relevant for Researchers in Germany

In order to exploit and further enhance the leadership position of the German community in this research field, it is important that German scientists gain access to the number of key infrastructures that are being constructed, designed, in preparation or planned. It is clear that true advances will rely on a multi-messenger approach that includes a number of observational windows combined with facilities for data analysis and interpretation. Figure 8 highlights important aspects of this approach. In order to increase the sensitivity of ground-based detectors, cryogenically-cooled underground detectors of a 3rd generation of gravitational wave detectors are needed in the long-term after Advanced LIGO and Advanced Virgo. The LCGT/KAGRA facility is a start in this direction, but access to a 10-times longer *Einstein Telescope* (ET) detector is clearly required for German scientist in the future, as this would improve on existing detectors in sensitivity by another order of magnitude. ET will observe hundreds of binary neutron stars and Gamma Ray Burst associations each year.

The early results from LISA Pathfinder show that a space-based detector *LISA* can be built, providing access to lower frequencies and different sources with a sensitivity that would make LISA the perfect facility for fundamental physics, cosmology and astrophysics at the same time. Questions to be address are the nature, population and physics of massive black holes (10^4 to 10^8 $M_\odot$), the study of Extreme Mass Ratio Inspirals (EMRIs, 1 to 10 $M_\odot$ into 10^4 to 5 x 10^6 $M_\odot$), the observations of ultra-compact binaries in the Milky Way, and cosmological signals of stochastic nature (e.g. probing phase transitions, Higgs-field self-coupling, supersymmetry).

LISA will be perfectly complementary to the *Square Kilometre Array (SKA)*. As the world's largest and most sensitive radio telescope, the SKA will improve the sensitivity of Pulsar Timing Arrays (PTAs) such that not only the stochastic background of merging super-massive black-hole binaries in early galaxy evolution can be observed, but it will also be able to detect and potentially localize single sources emitting continuous gravitational waves. SKA will probe BHs on mass-scale larger than those observed by LISA and/or studies LISA sources at different evolutionary times. Combined with other EM-observations at optical and x-ray frequencies, the combination of SKA, LISA and ET will mark the beginning of a "black hole astrophysics" era. SKA observations will also allow to study the polarization properties of gravitational waves and to put stringent constraints on the graviton mass. At the same time, the SKA will discover and exploit compact relativistic binaries that will further improve on precision tests of gravity; it will also provide a complete sample of Galactic radio pulsars, firmly establishing the mass scale of neutron stars, the limits on spin-period, and the moment-of-inertia of neutron stars – all essential information to identify the EOS of super-dense matter. Access to pathfinder instruments like MeerKAT will prepare the German community for the SKA.

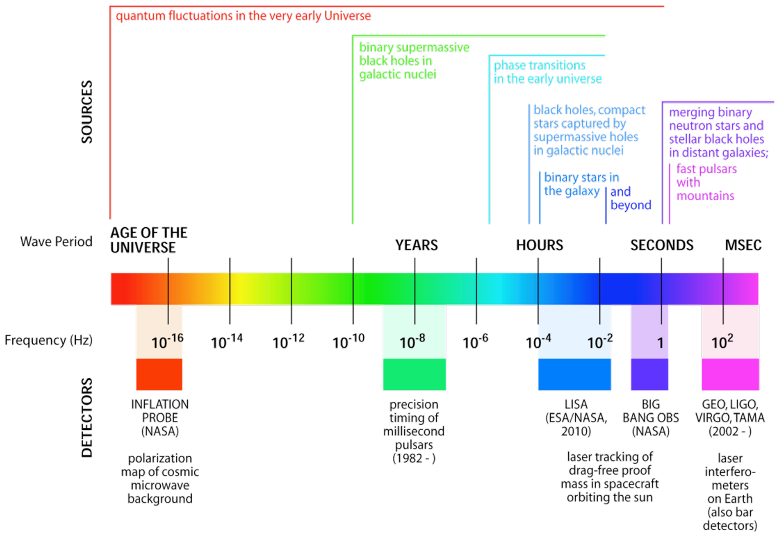

Figure 9: Gravitational wave spectrum demonstrating the need for different complementary instruments.

Access to instruments probing the cosmic microwave background and its polarisation will be needed to study the properties of gravitational waves from the era of inflation, while space-probes will complement the SKA efforts to study the properties of Dark Energy. These are described elsewhere.

The observational efforts have to be matched by access to adequate *High Performance Computing* (HPC) facilities, as the development and testing of new codes is integral part of the basic research activity. Indeed, in many respects the development of computational facilities dedicated to HPC in Astronomy, Astrophysics and Cosmology is as important as the development of new observational facilities.

We are now witnessing a first migration of the astronomical community as a whole towards the use of complex, large-scale, three-dimensional and fully nonlinear simulations for the interpretation of the observations. This migration will only increase in the future and so will the need for dedicated computationally intensive supercomputing facilities. Hence, the time has come for a serious planning and for the creation of an infrastructure that will give German scientists the much needed resources that are needed for self-consistent and informative interpretation of the observations from astrophysical objects exploring the extreme states of matter.

6. Summary and Conclusions

The German community is extremely strong and very well positioned in the area of fundamental physics and its study via astronomical techniques. This world-leadership position can only be maintained if access to the world's best facility is available. In many cases, the best advances and most important insights are only guaranteed by engaging in long-term efforts, the participation in large international projects, and the access to sufficiently powerful computational resources. Reflecting on the important results so far, the German community has succeeded to lead many efforts and to be visible as such. With the appropriate action this success story can continue, as it is clear clearer that a golden era in fundamental physics research has truly just begun.

References

Abbott, B. P., et al., Phys. Rev. Lett., 116:061102 (2016a)
Abbott, B. P., et al., Phys. Rev. Lett., 116:241103 (2016b)
Abbott, B. P., et al., Phys. Rev. Lett. 116:241102 (2016c)
Antoniadis, J., et al., Science, 340:1233232 (2013)
Armano, M., et al., Phys. Rev. Lett., 116:2311101 (2016)
Babak, S., et al., Mon. Not. R. Astron. Soc. 455:1665 (2016)
Baiotti, L., Giacomazzo, B., Rezzolla, L., Phys. Rev. D, 78:084033 (2008)
Bertotti, B., Iess, L. & Tortora, P., Nature, 425:374 (2003)
Breton, R. P., et al., Science, 321:104 (2008)

Desvignes, G. et al., Mon. Not. R. Astron. Soc. 458:3341 (2016)
Dexter, J., et al., Astrophys. J, 717:1092 (2010)
De Zeeuw, P. T., Molster, F. J. (eds), A Science Vision for European Astronomy, ASTRONET (2007)
Doneva, D. et al., Phys. Rev. D 90, 104021 (2014)
Famaey, B. & McGaugh, S. S., Living Rev. Relativity, 15 (2012),
Freire, P. C. C., et al., Mon. Not. R. Astron. Soc., 423:3328 (2012)
Gillessen, S., et al., Astrophys. J., 692:1075 (2009)
Grenzebach, A., Perlick, V., & Lämmerzahl, C., Phys. Rev. D, 89:124004 (2014)
Hackmann, E., & Lämmerzahl, C., Phys. Rev. Lett. 100:171101 (2008)
Hagedorn, D. et al., Annalen Phys. 525 (2013), 720
Kramer, M., & Champion, D., Class. Quatum Gravity 30:224009 (2013)
Kramer, M., et al., New Astron. Rev. 48:993 (2004)
Kramer, M. & Stappers, B., Proceedings of Advancing Astrophysics with the Square Kilometre Array (AASKA14). 9 -13 June, 2014. Giardini Naxos, Italy
Kramer, M., ArXiv e-prints: 1606.03843 (2016)
Lattimer, J. M. & Prakash, M., Astrophys. J, 550:426 (2001)
Martinez, J.G. et al., Astrophys. J,812:143 (2015)
Özel, F. & Freire, P., ArXiv e-prints:1603.02698 (2016)
Planck Collaboration 2013, Astron. & Astrophys., 571:A1 (2013)
Psaltis, D., Wex, N. & Kramer, M., Astrophys. J. 818:121 (2016)
Radice, D., Rezzolla, L. & Galeazzi, F., Mon. Not. R. Astron. Soc., 437:L42 (2013)
Rezzolla, L., et al., Astrophys. J., 732:L6 (2011)
D. Schlippert D. et al., Phys. Rev. Lett. 112 (2014) 203002
Shao, L. & Wex, N., Class. Quantum Gravity 29:215018 (2012)
Shao, L. et al., Class. Quantum Gravity 30:165019 (2013)
Shao, L. & Wex, N., SCPMA 699501:23 (2016)
Verbiest, J. P. W., et al., Mon. Not. R. Astron. Soc. 458:1267 (2016)
Wex, N., ArXiv e-prints:1402.5594 (2014)
Will, C. M., Living Rev. Relativ., 17 (2014)
Yazadjiev, S. et al. Phys. Rev. D 91, 084018 (2015)