Colliding neutron stars: what do gravitational waves and electromagnetic flashes tell us about physics at the extremes?

Where in the cosmos were the heaviest elements forged?
What are the densest forms of matter in the Universe?
What happens when two neutron stars collide?
What do their observable signals tell us about so-far incompletely understood physics?

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These questions are major motivations behind the ERC Advanced Grant project “INSPIRATION: From inspiral to kilonova”. We aim to achieve consistent modelling of neutron star mergers, from before the collision up to weeks later, to understand the extreme physics (e.g. strong spacetime curvature, high densities, and temperatures) that shape the resulting gravitational wave and electromagnetic emission.

Neutron stars as end products of stellar evolution

Massive stars end their lives as cosmic fireworks that can be observed across vast distances. These ‘supernova’ explosions occur when the inner cores of massive stars, made up of iron nuclei, exhaust their nuclear fuel and begin to collapse. During a collapse, matter becomes denser and hotter until the temperatures are large enough to break up the iron nuclei into neutrons and protons, collectively referred to as nucleons. At the same time, protons are transformed into neutrons by electron capture. The ‘brakes’ are applied to the collapse once the nucleons essentially touch each other, i.e. when the density reaches values found in atomic nuclei. The infalling star compresses the stellar core even further until the matter pressure becomes so large that the core ‘bounces back’ and turns the infall into an explosion. The most massive stars produce black holes in their cores, while lighter ones leave behind neutron stars.

Neutron stars are extreme in every respect. With masses around 1.5 solar masses, they only have radii of ~12 km; therefore, their average densities are several times larger than those found inside atomic nuclei (~3 x 10^{14} g/cm^3). One can thus think of a neutron star as a huge atomic nucleus. As the name suggests, neutron stars are mostly made of neutrons, but not exclusively. Throughout their bulk, they contain a ~10% fraction of protons together with electrons and muons, but in their inner cores, near 10^{15} g/cm^3, they likely contain “exotic” matter phases such as strangeness-bearing baryons, so-called ‘hyperons’, or quark matter. Neutron stars are also endowed with huge magnetic fields that can exceed Earth’s magnetic field by more than 14 orders of magnitude. Last but not least, neutron stars possess enormously strong gravitational fields that curve the spacetime nearly as much as black holes do. In other words, neutron stars are precious laboratories for physics under the most extreme conditions.

Neutron star binaries: why are they relevant?

We know of more than 20 binary systems in our galaxy that contain two neutron stars. Such binaries have undeniably, though indirectly, proven the existence of gravitational waves long before they were finally detected directly in 2015. By emitting gravitational waves, neutron star binary systems continuously lose energy and angular momentum and slowly spiral towards each other. Gravity causes binary systems to speed up as they lose energy. When the orbital separation decreases due to energy loss from gravitational waves, the orbital motion accelerates, increasing the rate of energy loss. As a result, the initially very subtle inspiral becomes faster and faster, finally leading to an extremely violent encounter between the two neutron stars that collide at a good fraction of the speed of light!

While such collisions only occur a few times per 100 000 years in a typical galaxy, they release enormous amounts of energy and, therefore, have the potential to be observable out to cosmological distances. Such collisions produce strong gravitational waves and release huge amounts of neutrinos; they trigger cosmic explosions called ‘gamma-ray bursts’ and, as shown in early work of Rosswog *et al.* (1999) and Freiburghaus, Rosswog and Thielemann (1999), the neutron-rich matter that is ejected into space during the violent collision is a prime cosmic production site for the heaviest elements. Neutron star mergers are, therefore, also crucial for the chemical evolution of the cosmos.

What can we learn from the gravitational wave signal?

The gravitational wave signal from a neutron star merger carries a wealth of information on physics under the most extreme conditions. Apart from allowing us to scrutinise strong gravity (‘Is Einstein’s theory of gravity correct?’), such mergers allow us to probe the properties of dense nuclear matter. When the neutron stars are still far apart from each other (compared to their radii), they can be well described as point masses by means of analytical, ‘post-Newtonian’ methods, which are weak-field approximations to general relativity. When the separation between the stars has reduced to a few times their radii, each neutron star becomes tidally deformed by the gravitational pull of the companion star. This deformation further speeds up the inspiral compared to the point mass limit and leaves a detectable imprint in the gravitational signal. Since the inspiral takes a long time, often several 100 million years, the neutron stars are essentially cold before the merger and well described with temperature $T \approx 0$ K. The properties of cold nuclear matter determine how much the neutron stars become deformed. Therefore, the gravitational wave signal just before merger carries the imprint of cold nuclear matter. Experiments on Earth cannot probe these conditions, neutron star mergers are the only means to explore this matter state!

In many cases, a merger results in the formation of a hot central remnant that does not (immediately) collapse to form a black hole. Such remnants harbour the most extreme matter states since the Big Bang: the densities reach values of ~10^{15} g/cm^3, and the temperatures exceed 10^{11} K, i.e. 10 000 times the central temperature of our Sun. Such remnants emit gravitational waves with frequencies of several kHz, and such post-merger signals are major science targets of the next generation of gravitational wave detectors, such as the European Einstein Telescope.

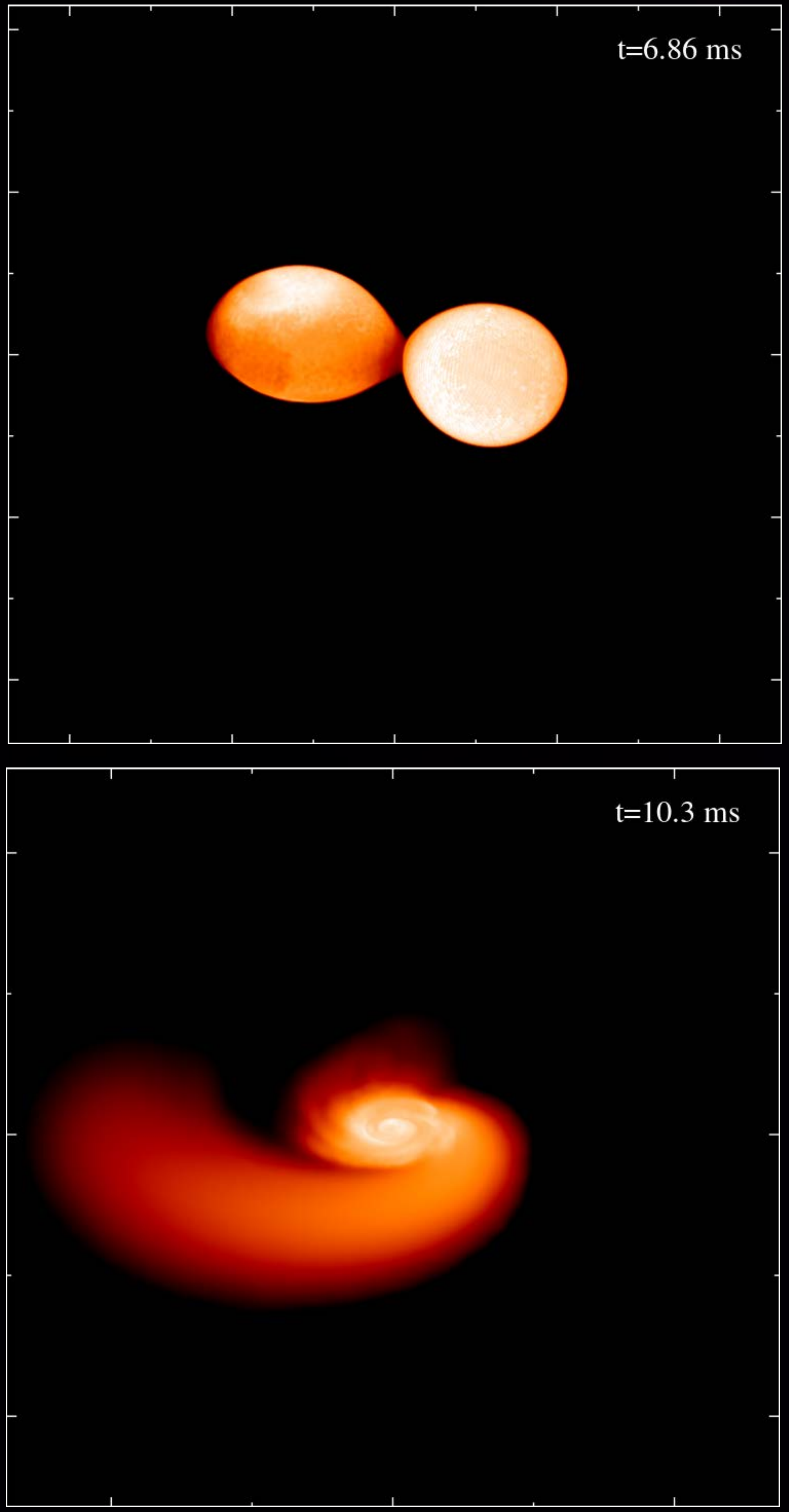

Figure 1: A SPHINCS_BSSN simulation of a neutron star merger where both stars have 1.3 solar masses.

‘Kilonovae’: electromagnetic flashes powered by radioactive decay

A neutron star merger ejects ~1% of the binary mass as extremely neutron-rich matter into space (Rosswog *et al.*, 1999). With many more neutrons than protons, this matter provides ideal conditions for producing heavy elements via the ‘rapid neutron capture’, or r-process (Freiburghaus *et al.*, 1999; Cowan *et al.*, 2021). The neutron captures are over after ~1 second and lead to very heavy and initially extremely neutron-rich nuclei that decay over time into stable isotopes. Thus, the merger ejects about 1% of its mass as a gas cloud heated by the radioactive decay of freshly synthesised heavy elements. As the cloud expands, its density drops rapidly until the photons can escape and produce an electromagnetic flash that is often called a ‘kilonova’ (Metzger *et al.*, 2010) because it is about 1000 times brighter than an astronomical ‘nova’ explosion. Kilonovae were studied theoretically for nearly two decades before the first event was finally unambiguously observed in 2017 in the aftermath of the first neutron star merger gravitational wave detection (Abbott *et al.*, 2017). Although information about individual elements has remained very meagre, this event proved conclusively that neutron star mergers are major production sites for heavy elements.

The project: From inspiral to kilonova (INSPIRATION)

Neutron star mergers involve a broad range of physics, from strong gravity to dense matter and neutrino physics, to the nuclear reactions in the r-process and finally, the interaction of photons with ionised heavy elements. In addition, the range of length and time scales is mind-boggling: the orbital periods of the binary before merger (at orbital separation ~50 km) are only ~1 millisecond, while the resulting kilonova reaches its peak brightness after ~1 day when the ejecta have expanded to ~10^{10} km! This breadth of physical processes and length and time scales makes consistent modelling of the multi-messenger signals of neutron star mergers a formidable computational physics challenge.

This is the challenge that we are tackling in the INSPIRATION project. To this end, the project’s PI has developed a worldwide unique numerical relativity code, SPHINCS_BSSN (Rosswog and Diener 2021; Rosswog *et al.*, 2023), that solves the full set of Einstein equations while the neutron star matter is modelled with freely moving particles. Compared to more conventional, grid-based numerical relativity codes, this new methodology has major advantages for evolving the ejecta that produce the electromagnetic emission of a neutron star merger, while it has the same capabilities as grid-based methods when it comes to predicting the gravitational waves. A major goal of the project is the consistent modelling of observable signatures, starting with numerical relativity simulations before the merger and evolving the ejecta up to and beyond the peak kilonova emission. In particular, we want to explore how incompletely understood physics, such as supra-nuclear matter properties and neutrino processes, leaves imprints on observable gravitational waves, neutrino and electromagnetic signals.

Figure 1 shows an example of a SPHINCS_BSSN simulation of a neutron star merger where both stars have 1.3 solar masses, but only one of the stars is rapidly spinning (Rosswog *et al.*, 2024). Such binaries can form in dense stellar regions such as globular clusters, where most neutron stars are spinning with millisecond periods. Compared to the traditionally considered case where both stars have negligible spins, such single-spin binaries are significantly different in many respects. Their gravitational wave emission, for example, is less efficient; therefore, the merger remnants will survive for longer before collapsing into black holes. Such surviving remnants may be related to a puzzling class of gamma-ray bursts that produce kilonovae but last much longer than typical gamma-ray bursts from neutron star mergers (Levan *et al.*, 2024). Such single-spin systems also eject substantially more neutron-rich matter and, therefore, cause particularly bright kilonovae.

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PROJECT NAME

From inspiral to kilonova (INSPIRATION)

PROJECT SUMMARY

Mergers of two neutron stars are related to many timely astrophysical questions, such as the production of gravitational waves, the densest forms of matter in the Universe and the cosmic origin of heavy elements. This project applies a novel computational methodology to strive for consistent numerical modelling involving a broad range of both physical processes and length/time scales.

PROJECT LEAD PROFILE

Stephan Rosswog is a Professor for the Theoretical Astrophysics of Compact Objects at the University of Hamburg. He earned his PhD in theoretical physics at the University of Basel, Switzerland and held professorships in Bremen, Germany and Stockholm, Sweden. In 2022 he was awarded an ERC Advanced Grant for the project INSPIRATION. He is interested in the multi-messenger astrophysics of compact objects, with particular emphasis on their fluid dynamics, gravitational waves, nucleosynthesis, and electromagnetic transients.

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