Multi-messenger signals of gravitational wave sources (MINOTAUR)

Stephan Rosswog

January 22, 2023

Introduction

Stars with more than eight solar masses end their lives in cataclysmic fireworks called supernovae. The luminosities of these explosions rivals those of whole galaxies. Supernovae eject most of their mass into space where it forms the basis for the next generation of stars. The core of the stars, however, become enormously compressed and –if the star was not too massive– the explosion produces a neutron star, or otherwise a black hole of a few solar masses will form. Neutron stars can be thought of as gigantic atomic nuclei: with a mass of about 1.4 solar masses and radii of only 12 km their central densities substantially exceed the density in atomic nuclei ($\rho_{\rm nuc} = 2.7 \times 10^{14}$ g/cm^3).

In some cases two such exotic stars orbit as a binary system around their common centre of mass. Due to their enormous compactness, such stars can revolve around each other at very small separations and therefore extremely large speeds. In such systems strong-field gravity effects become important, making them excellent laboratories to test gravitational theories such as Einstein's theory of General Relativity. In fact, the first –though indirect– evidence for the existence of gravitational waves came from such a neutron star binary system and it earned its discoverers, Russel Hulse and Joseph Taylor, the Nobel Prize for Physics in 1993. One implication of the emission of gravitational waves is that the binary orbit shrinks further until the stars finally merge. This releases gigantic amounts of gravitational energy, more than the Sun could radiate away during the whole lifetime of the Universe. On August 17, 2017 such a neutron star merger has been detected for the first time: the LIGO detectors recorded the "chirping" (i.e. increasing in frequency and amplitude) gravitational wave signal for about one minute and 1.7 seconds later a short gamma-ray burst was detected. During the following weeks fireworks all across the electromagnetic spectrum were observed. This watershed event marks the beginning of the era of multi-messenger astrophysics where events are observed via several different messengers (e.g. photons and gravitons) that convey complementary information. Already the first such event revealed that a) mergers of neutron stars emit gravitational waves in agreement

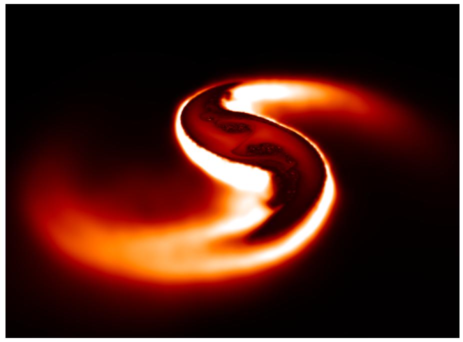

Figure 1: HLRN simulation of the merger of two neutron stars. Shown is a volume rendering of the density. To allow a view inside, only the lower part of the matter distribution is visualized.

with Einstein's General Relativity, b) they cause bright cosmic explosions called gamma-ray bursts, c) they forge the heaviest elements in the Universe (such as gold or platinum). Moreover, the delay between the gravitational wave peak and the gamma-ray burst has been used to constrain the speed at which gravitational waves travel: it is equal to the speed of light to within one part in 10^{15}! For these reasons this detection was elected by the Science Magazine as the "Breakthrough of the year 2017".

While this event was a major breakthrough for the physics of 21st century and has brought major leaps forward on many fronts, it left many questions unanswered and triggered new ones, respectively. There is much we hope to learn from the observations of the expanding worldwide network of gravitational wave detectors combined with astronomical telescopes. To interpret such observations and to connect them to the physics of the emitting sources, however, one needs simulations such as those performed within this project. An example of a neutron star merger simulation that has been performed on HLRN resources is shown in Fig. 1.

The power of Multi-Messenger Astrophysics

By receiving information from different messengers, say gravitational waves and light, one may discover entirely new sides of an astrophysical event. For example, in the first multi-messenger detection of a merging neutron star binary the gravitational waves conveyed the physics of the merging binary (e.g. its mass and tidal deformability) while the electromagnetic radiation allowed to place the merger in an astrophysical context: it revealed the location in the sky and allowed to identify the "host galaxy" (including its cosmological redshift) in which the merger took place. Taking the two sides of the story together provides a host of information, both on the past of the observed binary system, its stellar evolution path, and on the involved physics such as nuclear matter properties or the formation of heavy elements.