Connecting numerical simulations of black holes with experiment and observations

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Scientific Background

Compact objects and black holes (BHs) in particular have acquired an increasingly centre-stage role in many areas of contemporary physics. For example, compact objects are one of the most important source of gravitational waves (GWs) whose direct observation with laser interferometers (such as LIGO, VIRGO, KAGRA or the future space based eLISA mission) is expected to provide us with unprecedented views of the universe. The possible formation of BHs in particle collisions is one of the avenues pursued in high-energy physics experiments at the LHC to probe physics beyond the standard model of particles. A quite remarkable application of BH spacetimes arises through the so-called gauge-gravity duality which has established an analogy between a certain class of BH spacetimes and various types of non-gravitational physical systems including, for example, super conductors or heavy-ion collisions. The theoretical modelling BHs is mandatory in all these relatively new directions of physics, and the connection of this modelling with experiment and observation in the above mentioned fields has been the main focus of this CIG project.

Gravitational wave physics

Gravitational waves are ripples in spacetime created by compact astrophysical objects analogous to the generation of waves when a stone is thrown into a pond of water. These waves propagate from their source, say two BHs orbiting each other, across the universe and eventually can reach our observatories on planet earth. GWs manifest themselves in a manner rather different from light or other electromagnetic waves. Their effect is a periodic squeezing and stretching of objects albeit with the tiniest of amplitudes; under passage of a GW, a one-kilometre bar oscillates in length by a fraction of an atomic nucleus. This effect is measurable only using the most modern laser technology and even then realistic signals are buried in comparatively large levels of instrumental and environmental noise. Digging out a signal from the noise-dominated data streams is therefore a highly non-trivial exercise and often employs a method dubbed "matched filtering". This resembles in many ways the identification of finger prints collected on a scene of crime using a large data bank of known finger prints. In GW physics, the analog of the data bank is a *gravitational waveform catalogue*, a large set of theoretically predicted waveforms that is searched for in the analysis of observational data in order to indentify the template matching best the observed data stream. In line with the objectives of the project, we have advanced the generation of such template banks and explored the GW signals encoding of the sources physics as follows.

1) One of the strongest source of GWs are binaries consisting of two spinning BHs. We have discovered a new classification scheme of these binaries into three *morphologies* or *phases* determined by the precession properties of their spins. Under the emission of GWs, the binaries can undergo phase transitions and the specific morphologies carry an imprint or memory of the binary's formation history. Identification of a binary's morphology in GW observations will thus reveal valuable information about how the system was formed millions or even billions of years ago.

2) The formalism developed for this purpose employs an averaging technique over the precession timescale that vastly increases the computational efficiency of its modelling by orders of magnitude

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compared with previous methods

3) The eventual coalescence of BH binaries into a single hole can only be described with fully non-linear numerical relativity simulations. Large numbers of numerical waveforms have been generated, studied in GW data analysis and used to demonstrate their suitability for identifying GW signals in noisy data streams and provide good estimates of source parameters such as BH masses.

4) In preparation for observational tests of Einstein's theory of relativity against modified theories of gravity, we have identified a type of scalar waves distinguishing Einstein's theory from so-called scalar-tensor theories of gravity. We have also explored the behaviour of static neutron stars in this class of theories and identified differences in their properties from the general relativity predictions.

5) A special type of interaction of rotating BHs with surrounding matter fields is called *superradiance*, an effect also dubbed as the *BH bomb* where rotational energy is extracted from the BH to amplify the oscillation of the surrounding matter fields. We performed the first numerical simulations of this effect in 3 spatial dimensions confirming the growth of the matter fields in these scenarios.

High-energy collisions and higher-dimensional black holes

In comparison with the other forces (electromagnetic, weak and strong nuclear forces), gravity is extraordinarily weak, about 40 orders of magnitude below electromagnetic forces. Physicists, notoriously puzzled by such discrepancies, have conjectured intriguing scenarios to explain the weakness of gravity which involve extra dimensions. In these so-called TeV gravity scenarios, gravity would become the dominant interaction at microscopic distances and one of the most dramatic predictions of these theories is the possibility of generating black holes in particle collisions at the LHC. The second main goal of this project was the theoretical modelling of these processes in terms of high-energy collisions of BHs. We have completed this study in four dimensions and developed a framework that overcomes numerical difficulties in extending these studies higher-dimensional spacetimes.

1) Ultra-relativistic collisions in four dimensions generate enormous amounts of gravitational waves but not in excess of about 50 %. This supports a main assumption in the interpretation of experimental data, namely that a fraction of order unity of the total energy remains available for the formation of a BH that can then evaporate through Hawking radiation.

2) This upper limit of energy loss in GWs is due to absorption of about half of the kinetic energy by the BH formed.

3) A further assumption underlying these collision experiments is that the inner structure of the colliding particles becomes irrelevant at high velocities. We have tested this in the form of giving the colliding objects a spin of some magnitude and indeed find any impact of the spin magnitude on the collision dynamics to be washed out at speeds above ~ 90 % of the speed of light.

4) Simulations in higher-dimensional spacetimes are made difficult by numerical instabilities. By extending literature studies, we have developed a formalism that enables us to collide BHs in up to 10 spacetime dimensions which covers the relevant range for the application to TeV theories. We have furthermore generated a code for calculating initial data for these processes and are now able to combine these tools to systematically explore the collisions in higher dimensions.

The socio-economic impact of fundamental science is often of long-term nature; it took number theory centuries if not milennia to provide data security in modern-day internet commerce. We dare not predict here how a reassessment of our position in the universe through GW observations or the discovery of dimensions beyond those familiar from daily experience may change our lives but merely conclude with noting that similarly revolutionary discoveries by Copernicus, Kepler and Galilei had long-lasting and presumably liberating effects on societal structure in the past.