Il Colle di Galileo

Gravitational scattering, inspiral, and radiation

Florence, 19/04 - 21/05 2021
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Abstract. The workshop gathered theorists working on different though connected areas concerning the recent discovery of gravitational waves. It fostered new collaborations between the quantum gravitational scattering amplitude and the general relativity community, leading to the calculation of new, high-order, terms in the post-Newtonian and post-Minkowskian perturbative approaches to the physics of binary systems, at both analytical and numerical level, in order to construct the waveform templates necessary for the analysis of LIGO/Virgo data. The use of recent progress on gravitational scattering and radiation in ultra-relativistic collisions of elementary particles or strings improved the determination of parameters appearing in the effective-one-body approach to the relativistic two-body problem. Various consequences of modified gravity theories for the LIGO/Virgo discoveries were also explored.

Keywords. Gravitational waves, numerical relativity, perturbative calculations, string theory, modified theories of gravity.

Topic and context

The remarkable recent detection of gravitational waves from the coalescence of two black holes or of two neutron stars, as well as of the electromagnetic radiation in the latter case, began a new era in astrophysics. Prospects for the future are very bright: after the upgrade of LIGO and VIRGO, and with the addition of other earth-based interferometers such as KAGRA by the end of 2019, gravitational wave astronomy will enter a precision era. In the more distant future, LISA will detect many more sources in a very interesting lower-frequency range.

The interplay between theory and observations, which has already had a major impact on gravitational wave theory and on the proper interpretation of gravitational wave data, is very important to this end. Interpretation rests on the construction of accurate gravitational waveform models for coalescing relativistic binaries. This construction was enabled by foundational progress in numerical

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relativity and in analytical general relativity, with particular regard to perturbative approximations and the effective-one-body formalism, which mutually enrich one another.

Motivations

The discoveries stemming from the observation and interpretation of gravitational waves will have a profound impact on fundamental theoretical physics. As with the standard model of particle physics, precision future observations demand similarly precise theoretical predictions. So we believe that the theory community will increasingly turn to the problem of calculating detailed predictions of general relativity, and to test it against alternative theories.

The aim of the workshop was to bring together theorists working in different – yet related – areas of theoretical gravitational physics. In particular, we aimed to:

- deepen links and foster new collaborations between the quantum gravitational scattering amplitude and the classical general relativity communities, that will lead to the calculation of new terms in the post-Newtonian and post-Minkowskian perturbative approaches to the physics of binary systems;
- identify new synergies between the general relativity analytical and numerical communities, which have already proved crucial in providing the reliable waveform templates needed for the analysis of LIGO/VIRGO data;
- use recent progress on gravitational scattering and radiation in ultra-relativistic collisions of elementary particles or strings to improve the determination of parameters appearing in the effective-one-body approach to the relativistic two-body problem;
- connect properties of the gravitational wave spectrum at low frequencies to recent developments in soft-graviton theorems at sub- and sub-sub-leading level, including predictions for gravitational memory, Bondi-Metzner-Sachs asymptotic symmetries, and logarithmic enhancements;
- explore various consequences of modified gravity theories for the LIGO/VIRGO present and future observations.

Results

The first part of the event was a "training week", in which several experts provided a pedagogical introduction to the main topics addressed during the workshop, for the benefit of students, young researchers and those working in different fields. An average 30 participants attended each training lecture.

The second part of the event hosted the "Conference week", with the delivery of 20 talks by eminent scientists. The conference was opened by the three recipients of the 2021 Galileo Medal, Alessandra Buonanno, Thibault Damour and Frans

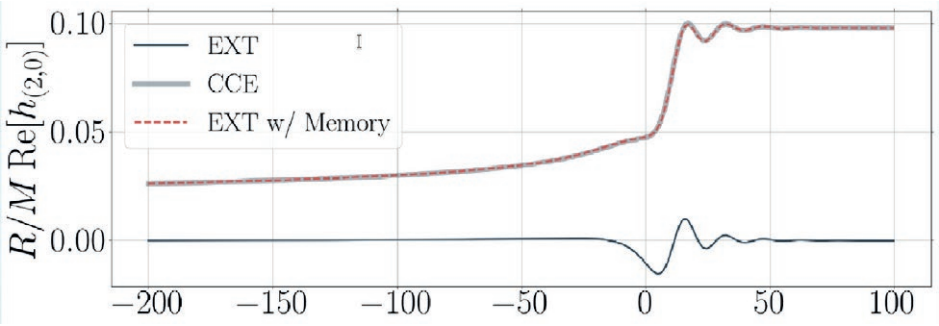

Figure 1. Gravitational waves produced by the coalescence of two black holes: the black curve represents the wave without memory effect. The red-dashed curve includes the memory effect, which amounts in a residual offset of the metric coefficients.

Pretorius, who gave their own appreciation of the state of the art and challenges in their respective domains. The average attendance during the conference was of about 70 participants.

The workshop took place over the last three weeks. It was attended by over 110 scientists from numerous countries around the world. Every day ended with a lively and often long discussion.

Much of the first week was devoted to analysing the connection of the so-called "infrared triangle", which relates asymptotic symmetries, soft theorems and memory effects in gravity. Advances in this field were the extension of the concept of asymptotic symmetries to time-like infinity and its role in the definition of angular momentum in general relativity, as well as the extension of the concept of gravitational memory to string-string interactions. The second week focused on the relativistic two-body problem. An important relationship between the scattering (i.e.: unbound or hyperbolic) and the inspiral (i.e.: bound or elliptic) problem was presented. Another central topic was the connection between scattering amplitudes and classical general relativity methods. In the approximation that neglects the radiation of waves, the effective Hamiltonians were derived at high perturbative levels both in the post-Newtonian and post-Minkowskian expansion. This allows accurate determination of the orbit when gravity is strong. Some studies took into account the radiation process, regarding the contributions of radiation reaction to elastic processes, as well as describing the calculation of the gravitational wave-forms emitted in inspiralling orbits.

In the last week, various efficient loop techniques were presented, in order to calculate gravitational observables both at conservative (without radiation) and dissipative (with gravitational waves) levels. Some of these studies also involved the connection between gauge theories and gravity, with emphasis on particle scattering off a large black hole at small impact parameters; lastly, very recent work on tidal deformations and dissipation of rotating black holes was present-

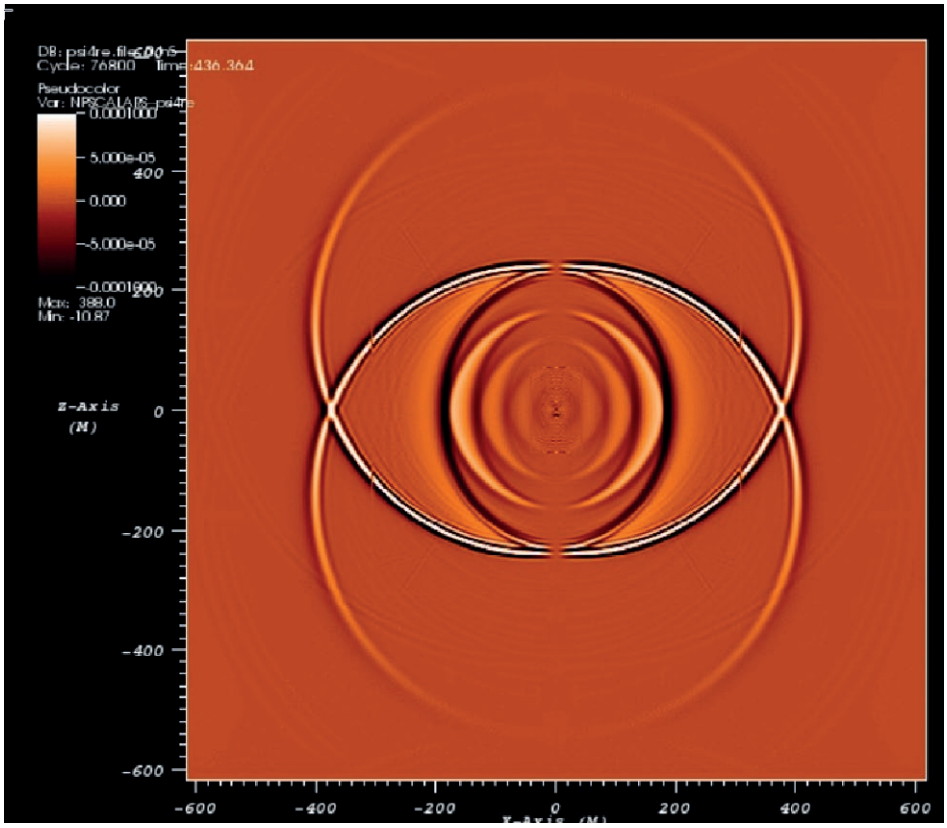

Figure 2. Numerical simulation of the metric deformation following a head-on black hole collision. In the central region, the event horizon of the resulting black hole is visible. On the edges, the expanding shock-wave originated from the collision.

ed. Most of the analyses were performed in "conventional" general relativity and quantum-field theory. However, many aspects were also considered in alternative theories of gravity, trying to identify observational signatures of deviation from the standard predictions.

The workshop ended with a long, lively and informative discussion entitled "Inspiralling Discussion Around the Two-Body problem". At the end, the suggestion was made – given the vitality of this rapidly developing subject – to update the situation with a new edition of the workshop in a couple of years. A year after the end of the workshop, dozens of papers originating (or benefiting greatly) from it have already appeared. We expect many more to follow.