Using Waves to Probe Black Hole Collisions

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Abstract

The computational modeling of systems in the strong-gravity regime of General Relativity and the extraction of a coherent physical picture from the numerical data is a crucial step in the process of detecting and recognizing the theory's imprint on our universe. In particular, considerable interest revolves around gravitational collapse, and the nature and behavior of its end products: since gravitational collapse is expected at the end of the thermonuclear lifetime of the more massive stars, collapsed objects (i.e., black holes) should constitute an appreciable component of the cosmological environment, as confirmed by a growing collection of astrophysical evidence. The encounter of compact objects is also one of the premium candidates for the emission of substantial gravitational radiation, thereby possessing a direct detection channel through the gravitational wave observatories currently in operation worldwide. The collection and analysis of gravitational emission from celestial events, known as gravitational wave astronomy, has the potential to disclose details of our universe which are invisible to electromagnetic and neutrino-based observations, providing an opportunity to observe our cosmic surroundings under a new lens. As one of the first steps in this direction, full 3D simulations of the encounter of two black holes in vacuum are now a reality, based on the synergy of theoretical modeling, numerical analysis and computer science efforts. The emerging physical picture indicates that, after an interval spent orbiting around each other much like planets, the two black holes plunge towards each other and enter a violent stage where extreme, non-classical effects take place. The simulations give us a controlled laboratory where we can experiment with the physics of the collision: here I present how the properties of the two-black-hole system can be captured by letting waves propagate around it and be reflected and diffracted by it. The features of the system leave an imprint on the waves, much like objects floating on a lake will alter the propagation of ripples on its surface.

Waves and Shapes

Wave scattering techniques have been a traditional tool used to probe the structure of complex systems. While the concept of scattering from black holes has been extensively explored in the past, recent numerical simulations provide the brand new opportunity to extend the range of previous experiments to binary systems.

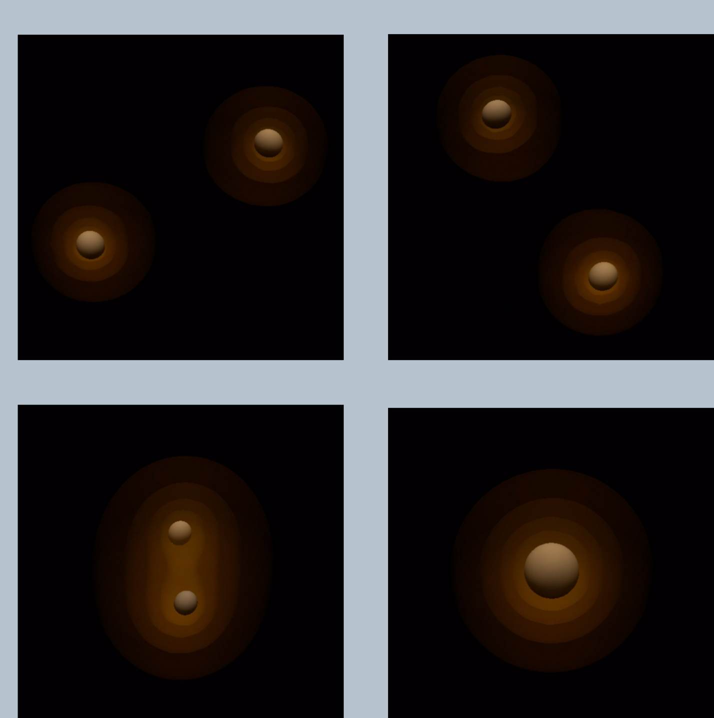
Credit: jitZul.com

Numerical Relativity: a Black Hole Lab that Fits in a Room

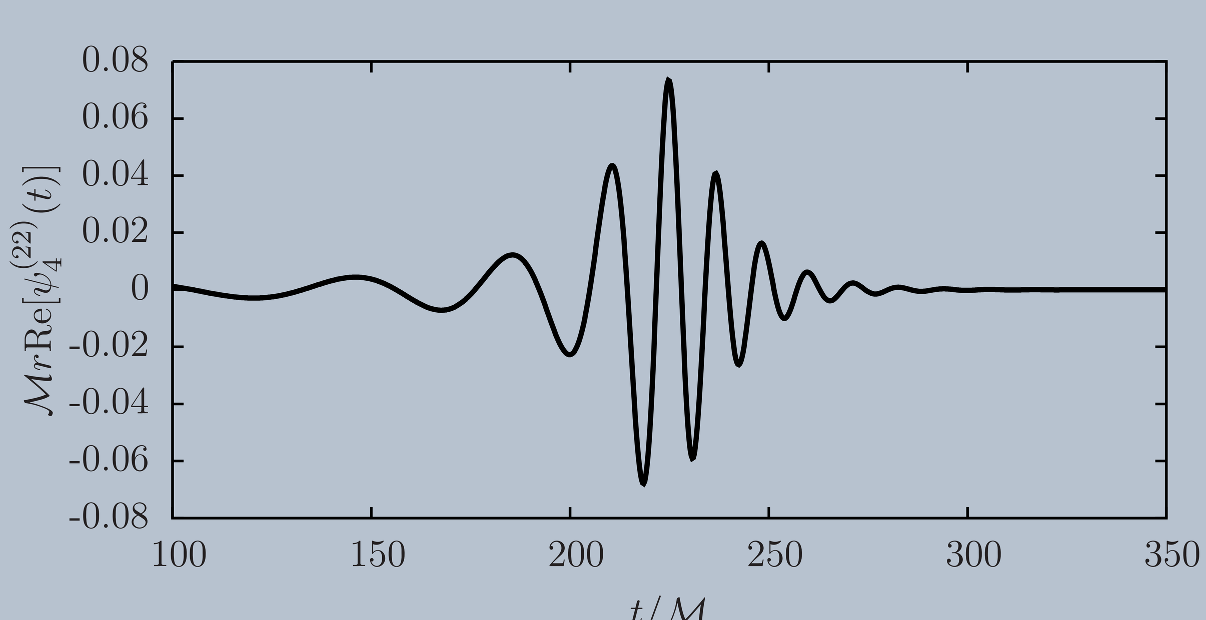
Far from being an offspring of Einstein's General Relativity alone, the idea of a gravitational system, so massive that not even light is able to escape from it, has been the object of scientific speculations for over two centuries. In the simple Newtonian framework, for instance, all bodies with an escape velocity greater or equal to the speed of light are, literally, "black".
However, the modern notion of a black hole has only emerged after General Relativity's formulation of the gravitational interaction, along with its description of horizons and mass-energy equivalence which were absent in Newtonian gravity. Since the introduction of the first black hole solution by Schwarzschild in 1917, this notion has evolved and developed into one of the most polyhedric objects of twentieth century physics.
The study of systems of two black holes relies entirely on accurate numerical modeling of the black holes and their surroundings, which has generated a whole new perspective on the black hole concept, centered around its *evolution* along some predefined time direction.

Follow their trajectories...

Find their horizons...



Measure the emitted radiation...



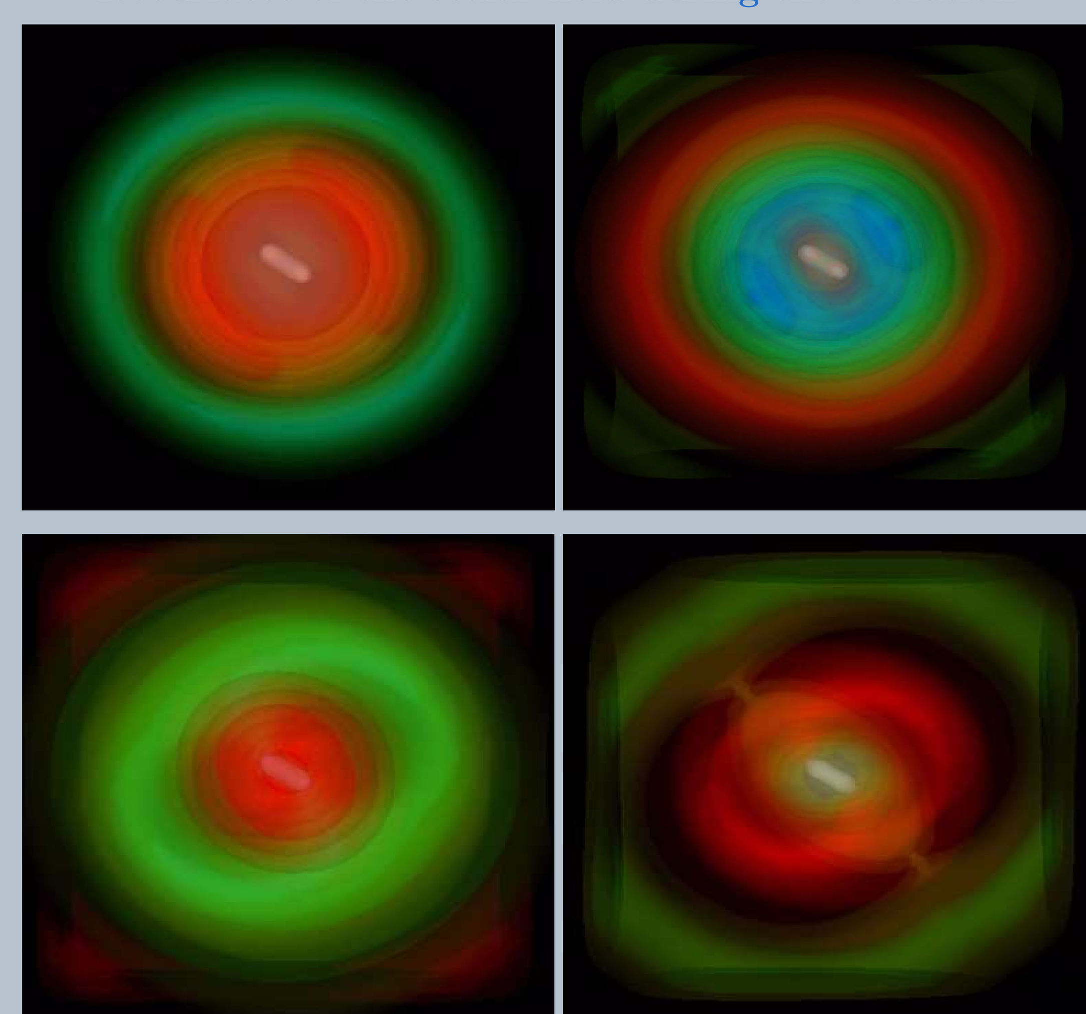
Waves on a Two-Black-Hole Background

The behavior of a massless scalar field Φ on a curved background is governed by the source-free scalar wave equation:

$$\Box\Phi := g_{ab}\nabla^a\nabla^b\Phi = 0\,.$$

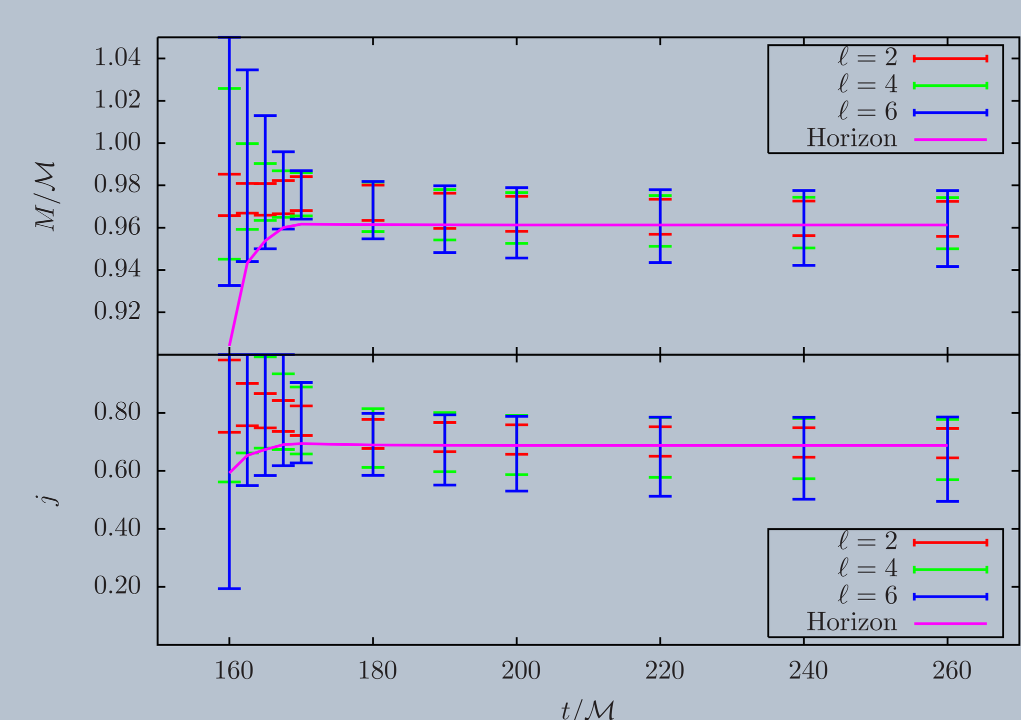
When the metric tensor g_{ab} is that of a black hole spacetime, Φ will exhibit a damped, oscillatory behavior with a frequency that depends on the mass and on the spin of the black hole.

Isosurfaces of the scalar field during the evolution



During the coalescence of two black holes, from the waves we can read off the two-body system properties and observe their evolution as the two black holes merge into one.

Mass and spin of the merged system



Acknowledgements

I acknowledge the Numerical Relativity group (Tanja Bode, Frank Herrmann, Ian Hinder, Andrew Knapp, Pablo Laguna, Deirdre Shoemaker, Shaun Wood) for discussions, suggestions and contributed code. I also acknowledge the support of the Center for Gravitational Wave Physics and the NSF grants PHY-0555436 and PHY-0653443. The Center for Gravitational Wave Physics is supported by the George A. and Margaret M. Downsbrough Endowment and the National Science Foundation under cooperative agreement PHY 01-14375. The simulations presented in this poster were carried out under allocation TG-PHY060013N at NCSA.

References

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