THESIS PROJECTS IN NUMERICAL RELATIVITY AND GRAVITATIONAL WAVES

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This document contains a list of possible thesis projects in the fields of gravitational waves, numerical relativity and computational physics for the MSc in theoretical physics.

Students will be also involved in the activities of the Theoretical Physics Group at Parma (http://www.pr.infn.it/), that include seminars, journal club, and outreach activities.

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Exploring neutron star merger dynamics

The dynamics of colliding (merging) neutron star binaries is a complex process involving nonlinear gravity and hydrodynamics. It is highly depedent on the binary parameters like masses, spins, and the equation of state. As a consequence, it seems extremely difficult, if not impossible, to model such dynamics using computationally expensive numerical relativity simulations in 3+1 dimensions. Surprisingly, however, recent work has shown that it is possible to parametrize such dynamics in a simple way [1]. The goal of this project is to further explore the "universal" parameterization introduced in [1].

[1] "Quasiuniversal properties of neutron star mergers". S. Bernuzzi, A. Nagar, S. Balmelli, T. Dietrich, M. Ujevic Phys. Rev. Lett. 112, 201101 (2014)

Gravitational waveforms from black-hole–neutron star binaries: comparison between numerical and analytical models

Gravitational waves observations by LIGO/Virgo might probe the existance of a class of compact binaries composed of a black hole and a neutron star. Such "mixed binaries" are candidates for gamma-ray-burst and kilonova events engines. Waveforms models are necessary to estimate masses and spins of the objects from the LIGO/Virgo observations.

An analytical model for the gravitational waveform emitted by neutron star binaries has been proposed in [1]. The model can, in principle, also describe mixed binaries. The goal of this project is to test the model's performances against a set of numerical relativity simulation, [2].

[1] "Modeling the dynamics of tidally-interacting binary neutron stars up to merger", S. Bernuzzi, A. Nagar, T. Dietrich, T. Damour Phys. Rev. Lett. 114, 161103 (2015)

[2] "Gravitational waves from spinning black hole-neutron star binaries: dependence on black hole spins and on neutron star equations of state" K. Kyutoku, H. Okawa, M. Shibata, K. Taniguchi Phys. Rev. D84, 064018, (2011)

The final black hole produced by the collision of a black-hole and a neutron star

Gravitational waves observations by LIGO/Virgo might probe the existance of a class of compact binaries composed of a black hole and a neutron star. Such "mixed binaries" are candidates for gamma-ray-burst and kilonova events engines. Waveforms models are necessary to estimate masses and spins of the objects from the LIGO/Virgo observations.

An open problem in the modeling of mixed binaries is the prediction of the properties of the final black hole resulting from the collision [1,2]. The goal of this project is develop such a predictive formula using data from numerical relativity simulations [2,3].

Co-advisor: Francesco Pannarale (Cardiff U).

[1] "The Black Hole Remnant of Black Hole-Neutron Star Coalescing Binaries", F. Pannarale Phys. Rev. D 88, 104025 (2013)

[2] "Hierarchical data-driven approach to fitting numerical relativity data for nonprecessing binary black holes with an application to final spin and radiated energy" Xisco Jiménez-Forteza et al Phys. Rev. D 95, 064024 (2017)

[3] "Gravitational waves from spinning black hole-neutron star binaries: dependence on black hole spins and on neutron star equations of state" K. Kyutoku, H. Okawa, M. Shibata, K. Taniguchi Phys. Rev. D84, 064018, (2011)

Binary black holes with large mass-ratio

The merger of two stellar-mass black hole (BH) has been identified as the source of the first gravitational wave measured on Earth on September 2015. The interpretation (and observation) of the LIGO event was possible thank to the theoretical knowledge of the dynamics and radiation as predicted by first principle calculations in general relativity. A worldwide effort is ongoing to push these calculations to the whole binary black hole parameter space, which is composed of all the possibile values of BH masses and spins, and to produce detailed waveforms and remnant predictions.

Binary black hole configurations with large mass ratio, q=M1/M2>~100, cannot be simulated in numerical relativity due to the enormous computation cost of those simulations. As an alternative approach one can employ black hole perturbation theory.

This project explores the dynamics of such large-mass ratio black hole binaries using an approximate approach that combines time-domain simulations in black hole perturbation theory with analytical methods [1]. Different directions are possibile: development of an analytical radiation reaction guided by perturbative simulations [2,3], study of the final black hole and its quasi normal mode excitation, and a study of the radiation fluxes absorbed by the black hole.

Co-advisor: Alessandro Nagar (Torino U).

[3] Harms, E et al "Spinning test-body orbiting around Schwarzschild black hole: circular dynamics and gravitational-wave fluxes" Phys. Rev. D 94, 104010 (2016)

[2] Bernuzzi, S and Nagar, A and Zenginoglu, A "Binary black hole coalescence in the extreme-mass-ratio limit: testing and improving the effective-one-body multipolar waveform" Phys. Rev. D83 064010 (2011)

[1] Bernuzzi, S and Nagar, A "Binary black hole merger in the extreme-mass-ratio limit: a multipolar analysis" Phys. Rev. D81 084056 (2010)

Binary neutron star post-merger gravitational-wave models

The high-frequencies (>~kHz) gravitational-wave emitted by a binary neutron star merger remnant contains information about the stiffness of the matter's equation of state at supranuclear densities e.g. [1,2]. Although the observation of kHz signals is challening for current interferometric experiments [3], theoretical models based on numerical relativity simulations are essential to link the spectrum to the source properties. The goal of this project is to construct a model based on numerical data and ideas proposed in [4].

Co-advisor: Walter Del Pozzo (Pisa U).

[1] "Measuring neutron-star properties via gravitational waves from binary mergers" A. Bauswein, H.-Th. Janka Phys.Rev.Lett. 108 (2012) 011101

[2] “Prompt merger collapse and the maximum mass of neutron stars” A. Bauswein, T. W. Baumgarte, H.-T. Janka Phys.Rev.Lett. 111 (2013) no.13, 131101

[3] “Observing Gravitational Waves From The Post-Merger Phase Of Binary Neutron Star Coalescence” J. A. Clark, A. Bauswein, N. Stergioulas, D. Shoemaker Class.Quant.Grav. 33 (2016) no.8, 085003

[4] “Modeling the complete gravitational wave spectrum of neutron star mergers”, S. Bernuzzi, T. Dietrich, A. Nagar Phys. Rev. Lett. 115, 091101 (2015)

Efficient representation of gravitational waveforms from compact binaries

Measuring the parameters of compact binaries from gravitational waves observations requires waveform models that are both fast, to account for 10^6 - 10^7 waveform evaluations, and accurate, to minimize systematic errors in the recovered parameters. Some of the most accurate waveform models are, however, not sufficiently fast for data analysis. Reduced-order modeling (ROM) techniques provide a framework for reducing large data sets that can be used to build lightweight models that are rapidly evaluated as a substitute, or surrogate, in place of the slow waveform generation code.

The goal of this project is to use ROM techniques for the representation of gravitational waveforms from compact binaries.

[1] “Fast prediction and evaluation of gravitational waveforms using surrogate models”, Scott E. Field, Chad R. Galley, Jan S. Hesthaven, Jason Kaye, Manuel Tiglio, Phys. Rev. X 4, 031006 (2014)

[2] “Fast and accurate prediction of numerical relativity waveforms from binary black hole coalescences using surrogate models”, Jonathan Blackman, Scott E. Field, Chad R. Galley, Bela Szilagyi, Mark A. Scheel, Manuel Tiglio, Daniel A. Hemberger, Phys. Rev. Lett. 115, 121102 (2015)

[3] “Effective-one-body waveforms for binary neutron stars using surrogate models”, B. D. Lackey, S. Bernuzzi, C.R. Galley, J. Meidam, C. Van Den Broeck Phys. Rev. D 95, 104036 (2017)

Black hole formation via the collapsar scenario

The cores of a large fraction of the most massive stars (i.e., stars starting their life with more than ~15 Msun) are expected to collapse at the end of their life and to form a black hole (BH). Beside giving rise to a population of stellar BH (which is now partially accessible via GW observations of compact binary mergers), this process is expected to play a significant role in the so-called collapsar model for failed supernovae and gamma-ray bursts. The quantitative modelling of the BH formation and its subsequent growth due to the accretion of the stellar envelope is numerically challenging.

In this project, we will study the BH formation process and the accretion of matter inside the horizon in the context of general relativistic hydrodynamics, including realistic and detailed models of stellar collapse.

Co-advisor: Albino Perego.

[1] “Very Low Energy Supernovae from Neutrino Mass Loss” Lovegrove E., Woosley S.E., The Astrophysical Journal, 769, 2, 109 (2013)

[2] “Black Hole Formation in Failing Core-Collapse Supernovae” O’Connor E.P., Ott C.D., The Astrophysical Journal, 730, 2, 70 (2011)

Evolution and fate of the Thorne-Zytkow objects (TZOs)

In many cases, a binary system formed by a neutron star (NS) and an evolved massive star (red supergiant) is expected to end up in a Thorne-Zytkow object (TZO): the NS sits in the center of the evolved star, which continues to evolve up to the point where gravitational instability is reached. However, the details of the structure and of the fate of the TZOs are still unclear and largely unexplored.

In this project, we would like to study quantitatively the innermost structure of the TZO, and to address the problem of its gravitational stability and of its fate through numerical solution of the TOV equations and numerical models of the stellar collapse.

Co-advisor: Albino Perego.

[1] Thorne, K. S.; Zytkow, A. N, "Red giants and supergiants with degenerate neutron cores" ApJ, vol. 199, July 1, 1975, pt. 2, p. L19-L24

[2] Thorne-Zytkow objects (TZOs), "Stars with degenerate neutron cores. I - Structure of equilibrium models" Astrophysical Journal, Part 1, vol. 212, Mar. 15, 1977, p. 832-858

Neutrino annihilation above binary merger remnants

The annihilation of neutrino-antineutrino pairs is considered one of the viable machanisms powering gamma-ray burst and a relevant process in the evolution of binary neutron star merger remnants. Calculations of the annihilation rates are computationally expensive and require large computatinal resources.

In this project, we would like to perform a detailed study of the properties of neutrino pair annihilation based on the outcome of full GR binary NS merger simulations. We will use advanced computational methods to compute the annihilation rates and to study their variability with respect to the properties of the merging system and of the remnant.

Co-advisor: Albino Perego.

[1] Perego A, Yasin H, Arcones A, "Neutrino pair annihilation above merger remnants: implications of a long-lived massive neutron star" Submitted to Journal of Physics G, 2017

Systematics of neutrino-driven winds from binary mergers

The interaction between neutrinos and matter in the remnant of binary neutron star mergers drives the ejection of matter from the remnant inside the so-called neutrino-driven winds. The amount of matter ejected andits properties makes this ejection channel unique and peculiar.

Up to now, neutrino-driven wind studies focused on a limited set of models. In this project, we would like to extend the present analysis to several different models, differing mainly by the mass of the merging neutron stars. This study will allow to explore how the properties of the wind correlates with the properties of the emitted neutrino radiation and, ultimately, with the properties of the merging system.

Co-advisor: Albino Perego.

[1] Perego, A.; Rosswog, S.; Cabezón, R. M.; Korobkin, O.; Käppeli, R.; Arcones, A.; Liebendörfer, M., "Neutrino-driven winds from neutron star merger remnants", MNRAS, Volume 443, Issue 4, p.3134-3156

[2] Martin, D.; Perego, A.; Arcones, A.; Thielemann, F.-K.; Korobkin, O.; Rosswog, S., "Neutrino-driven Winds in the Aftermath of a Neutron Star Merger: Nucleosynthesis and Electromagnetic Transients", ApJ, Volume 813, Issue 1, article id. 2, 14 pp. (2015)

Parametric study of the properties of matter ejected by neutrinos in binary mergers

The interaction between neutrinos and matter in the remnant of binary neutron star mergers drives the ejection of matter from the remnant inside the so-called neutrino-driven winds. The amount of matter ejected and its properties makes this ejection channel unique and peculiar. Detailed hydrodynamical models allows to study the evolution of fluid elements inside the wind. However, large uncertainties in the neutrino and nuclear physics are still present and deserve a deeper analysis. These information are crucial to predict the properties of the ejecta and their impact on the electromagnetic counter parts of binary NS mergers.

In this project, we would like to perform parametric studies of the properties of the ejecta, starting from results of the detailed simulations. More specifically, we would like to study the sensitivity of the fluid element evolution with respect to the neutrino fluxes, to the neutrino interactions and to a more detailed treatment of the formation of nuclei.

Co-advisor: Albino Perego.

[1] Perego, A.; Rosswog, S.; Cabezón, R. M.; Korobkin, O.; Käppeli, R.; Arcones, A.; Liebendörfer, M., “Neutrino-driven winds from neutron star merger remnants”, MNRAS, Volume 443, Issue 4, p.3134-3156

[2] Martin, D.; Perego, A.; Arcones, A.; Thielemann, F.-K.; Korobkin, O.; Rosswog, S., “Neutrino-driven Winds in the Aftermath of a Neutron Star Merger: Nucleosynthesis and Electromagnetic Transients”, ApJ, Volume 813, Issue 1, article id. 2, 14 pp. (2015)

[3] Rosswog, S.; Feindt, U.; Korobkin, O.; Wu, M.-R.; Sollerman, J.; Goobar, A.; Martinez-Pinedo, G. “Detectability of compact binary merger macronovae” Classical and Quantum Gravity, Volume 34, Issue 10, article id. 104001 (2017)

New computational strategies for numerical relativity

Numerical relativity simulations are multiscale and multiphysics applications that require high-performance-computing. Simulations typically use Adaptive Mesh Refinement (AMR) methods that allows one to efficiently resolve the different scales of the problem. A second, key ingredient is the use of high-order accurate discrete algorithms characterized by fast convergence properties with the grid spacing. Finally, those methods have to be implemented for efficient parallel computations, using distributed and shared memory paradigmas and vectorization.

The goal of this project is to explore new solutions for AMR, high-order methods and parallelization strategies using a toy problem for numerical relativity. The project can be focused on a single or multiple aspects of the problem. It has a strong computational component, including the implementation of parallel codes.

Dual foliation implementation of the wave equation on hyperboloidal slices

An open problem in numerical relativity is the implementation of a 3+1 decomposition of Einsteins equations on hyperboloidal slices. Hyperboloidal foliations allow one to incorporate null-infinity in the simulation domain, with two main advantages: the treatment of the outer boundary becomes trivial and the radiation fields can be computed accurately and unambiguously. A possible approach to hyperboloidal evolutions is the dual foliation formulation of general relativity, which relates the geometries of two foliations of the spacetime [1]. The dual foliation formalism, however, can be applied to first order formulations of Einstein equation [2], but not yet to second order ones like for example the popular BSSN or Z4c. The goal of the project is to investigate an implementation of the second-order wave equation on hyperboloidal slices using the dual foliation formalism.

Co-advisor: David Hilditch (CENTRA, Lisbon).

[2] “The evolution of hyperboloidal data with the dual foliation formalism: Mathematical analysis and wave equation tests” David Hilditch, Enno Harms, Marcus Bugner, Hannes Rueter, Bernd Bruegmann, https://arxiv.org/abs/1609.08949

[1] “Dual Foliation Formulations of General Relativity” David Hilditch, https://arxiv.org/abs/1509.02071

Yin-Yang grids for numerical relativity

Spherical coordinates are ideal for many astrophysical problems, including isolated stars and black holes, accretion disks and supernovae explosions. However, the coordinate singularities at the poles and the convergence of the spherical grid lines near the poles pose serious problems for the use of these coordinate in numerical applications. An approach that retains such coordinates but allows one efficient computations, is the use of multiple patches (hence grids) to cover the sphere. The Yin-Yang grid design, in particular, has several interesting features: it uses the minimum number of patches (two); the two component grids are the same size and shape; the component grid is nothing but a low latitude part of the usual spherical polar coordinate (latitude-longitude) grid, which is orthogonal and has the well-known simple metric. This project aims at exploring the use of Yin-Yang grids for their use in numerical general relativity.

[1] "Yin-Yang grid"': An overset grid in spherical geometry,
Kageyama, A. and Sato, T., Geochemistry Geophysics Geosystems, 2004, Vol 5, Number 9.

[2] YinZhong grid: An overset grid system for a sphere, H. Hayashi and A. Kageyama Journal of Computational Physics, 305, 2016

[3] An axis-free overset grid in spherical polar coordinates for simulating 3D self-gravitating flows, Wongwathanarat, A., Hammer, N J. and Müller, E., Astronomy and Astrophysics, 2010, 514.

[4] http://www.research.kobe-u.ac.jp/csi-viz/members/kageyama/yin_yang_grid/index.html

Neutrino treatment for astrophysical simulations with detailed muon flavor physics

Recent studies suggest that muons play a significant role in the core of an exploding supernova, as well as in the merger of two neutron stars. Most of the present neutrino treatments and thermodynamical equation of states for dense and hot matter do not take into account detailed muon physics. In this project, we want to couple a microphysical EOS that includes consistently and explicitly muons, and to couple it to an efficient neutrino treatment that takes into account the weak reactions related to the presence of muons. The project will also explore the impact of these imporvementes on the dynamics of core collapse supernovae and binary compact mergers.

Co-advisor: Albino Perego.

[1] "An Advanced Leakage Scheme for Neutrino Treatment in Astrophysical Simulations", Perego A, Ruben C., Kaeppeli R., The Journal of astrophysics Supplement Series, 223, 2, 22 (2016)

[2] "Charged Current Interactions of numu Neutrinos in Supernova" Lohs A, Martinez=Pinedo G., Fischer T. Proceedings of XIII Nuclei in the Cosmos (NIC XIII). 7-11 July, 2014. Debrecen, Hungary.

Ringdown models for supermassive black holes

The Laser Space Interferometric Antenna (LISA) will observe hundreds of mergers of supermassive black hole binaries with signal-to-noise ratios up to thousands. Many systems will be so massive that only the final phases of the coalescence (the merger and ringdown) will be in the LISA sensitive band. At such high signal-to-noise ratios, it is paramount to properly model the expected gravitational wave signal. This project will explore the feasibility of constructing accurate models of the ringdown for use in a realistic analysis setting of LISA sources.

Co-advisor: Walter Del Pozzo