EOB@Work25: 10 years of gravitational wave detections

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Book of Abstracts

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Highly accurate simulations of asymmetric black-hole scattering and cross validation of effective-one-body models

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The study of unbound binary-black-hole encounters provides a gauge-invariant approach to exploring strong-field gravitational interactions in two-body systems, which can subsequently inform waveform models for bound orbits. In this talk, we compare our NR scattering angle results from the Spectral Einstein Code (SpEC) to the post-Minkowskian PM-based effective-one-body (EOB) closed-form models SEOB-PM and wEOB and the post-Newtonian-based EOB evolution models SEOBNRv5 and TEOBResumS-Dalí.

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Kerr-fully peaking into the abyss: characterizing the merger of equatorial-eccentric-geodesic plunges in rotating black holes

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In this talk, I will show and describe gravitational waveforms generated by critical, equatorial plunging geodesics of the Kerr metric that start from an unstable-circular-orbit, which describe the test-mass limit of spin-aligned eccentric black-hole mergers. The waveforms are generated employing a time-domain Teukolsky code. We span different values of the Kerr spin $-0.99 \le a \le 0.99$ and of the critical eccentricity, for bound ($0 \le ec < 1$) and unbound plunges ($ec \ge 1$). We find that, contrary to expectations, the waveform modes hℓm do not always manifest a peak for high eccentricities or spins. In case of the dominant h22 mode, we determine the precise region of the parameter space in which its peak exists. In this region, we provide a characterization of the merger quantities of the h22 mode and of the higher-order modes, providing the merger structure of the equatorial eccentric plunges of the Kerr spacetime in the test-mass limit. This model-independent work provides valuable numerical information to extend current merger-ringdown EOB models in the small-mass limit, looking forward to the next generation of EOB models for the IMRI regimes. The aim of the talk is also to open a discussion of how to extend the future attachment procedures of the MR EOB models to the analytically derived inspiral part of the waveforms.

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Covariant and Gauge-invariant Metric-based Gravitational-waves Extraction in Numerical Relativity

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In this talk I'm going to revisit the problem of gravitational-wave extraction in numerical relativity with gauge- invariant metric perturbation theory of spherical spacetimes. We present our extraction algorithm which allows the computation of even-parity (Zerilli-Moncrief) and odd-parity (Regge-Wheeler) multipoles of the strain from a (3+1) metric without the assumption that the spherical background is in Schwarzschild coordinates. The algorithm is validated with a comprehensive suite of 3D problems including fluid (f-modes) and spacetime (w-modes) perturbations of neutron stars, gravitational collapse of rotating neutron stars, circular binary black holes mergers and black hole dynamical captures and binary neutron star mergers. We find that metric extraction is robust in all the considered scenarios and delivers waveforms of overall quality similar to curvature (Weyl) extraction. Metric extraction is particularly valuable in identifying waveform systematics for problems in which the reconstruction of the strain from the Weyl multipoles is ambiguous. Direct comparison of different choices for the gauge-invariant master functions show very good agreement in the even-parity sector. Instead, in the odd-parity sector, assuming the background in Schwarzschild coordinates can minimize gauge effects related to the use of the Γ-driver shift. Moreover, for optimal choices of the extraction radius, a simple extrapolation to null infinity can deliver waveforms compatible to Cauchy-characteristic extrapolated waveforms.

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Biases from Quasi-Circular Templates in Eccentric BInary Neutron Stars Gravitational Wave Analysis

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The use of quasi-circular effective-one-body waveforms in Bayesian mock analyses of signals from eccentric binary neutron star mergers can lead to signal-to-noise losses and to significant deviations in the inference of the chirp mass, the mass ratio and the effective spin, yielding incorrect and ambiguous source identification. The inclusion of spin precession in the quasi-circular waveform also fails to capture eccentricity effects.

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Spin precession across timescales

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The dynamics of precessing black-hole binaries in the post-Newtonian regime is deeply characterized by a timescale hierarchy: the orbital timescale is short compared to the spin-precession timescale which, in turn, is shorter than the radiation-reaction timescale on which the orbit is shrinking due to gravitational-wave emission. I present the development of a generic multi-timescale analysis that averages the dynamics over both the orbital and the precessional motions. Spin-precession cones can be treated "as a whole", without tracking the spin's secular motion. These solutions improve our understanding of spin precession in much the same way that the conical sections for Keplerian orbits provide additional insights beyond Newton's 1/r^2 law. Over the years, our multi-timescale approach led to an explosion of new predictions ranging from spin morphologies to new dynamical instabilities, resonances, and maximal nutations. Our multi-timescale solutions are now at the backbone of some state-of-the-art waveform templates used in gravitational-wave parameter estimation. Recent progress includes extensions to eccentric sources, and reconstructions of spin effects in both simulated and real gravitational-wave data.

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Resuming PM and PN Gravitational Waveform Expansions

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In this presentation we expose the results of a recent study concerning a new way of resuming, at a given order in the soft limit, the infinite series of PM or PN corrections to the gravitational waveform produced by a particle moving around a Schwarzschild black hole in the test mass limit. The tool that has allowed to do this is a novel hypergeometric representation of the confluent Heun functions. Indeed the propagation of the emitted gravitational waves is described by the radial part of Teukolsky equation, which can be recast as a confluent Heun equation. In order to analyze the development of this procedure, we compute the total energy flux at infinity in case of circular orbits. We find very good agreement with MST method. For this reason, we are considering some more-in-depth applications of the previous proposal, consisting in writing the waveform in the factorized form proposed by 0811.2069. The goal is seeing how the new resumed version of the tail contributions describes the result against the numerical one. We find that the relative error at the LSO can be even decreased at 10^{-6}. Furthermore, we discover that this method can be extended also to the case of binary systems with comparable masses. Based on 2501.19257 and on an ongoing work with Alessandro Nagar, Francesco Fucito and Josè Francisco Morales.

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Spin-eccentricity interplay in merging binary black holes

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Orbital eccentricity and spin precession are precious observables to infer the formation history of binary black holes with gravitational-wave data. We present a post-Newtonian, multi-timescale analysis of the binary dynamics able to capture both precession and eccentricity over long inspirals. We show that the evolution of an eccentric binary can be reduced that of effective source on quasi-circular orbits, coupled to a post-Newtonian prescription for the secular evolution of the eccentricity. Our findings unveil an interplay between precession and eccentricity: the spins of eccentric binaries precess on shorter timescales and their nutation amplitude is altered compared to black holes on quasi-circular orbits, consequently affecting the so-called spin morphology. Even if binaries circularize by the time they enter the sensitivity window of our detectors, their spin orientations retain some memory of the past evolution on eccentric orbits, thus providing a new link between gravitational-wave detection and astrophysical formation. At the same time, we point out that residual eccentricity should be considered a source of systematics when reconstructing the past history of black-hole binaries using the spin orientations.

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Gauge Flexibility in post-Minkowskian EOB models

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Spurred on by recent advances in post-Minkowskian (PM) gravity, highly accurate models of black hole scattering have emerged. By incorporating PM information in the effective one body (EOB) framework, its range of validity can be extended to the strong field regime. Central to these models is the EOB mass-shell condition, which relies upon a number of different choices of gauge and a specific resummation scheme. In this talk I will discuss the impact of gauge choices, highlighting the strong dependence on both coordinate and EOB gauge in the final model. I will also describe how the gauge choices interact with the choice of resummation scheme. Finally, I will describe a new gauge based on the centrifugal radius, which can offer improvements for the scattering of spinning black holes.

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Real modes and null memory contributions in effective-one-body models

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We briefly discuss how to incorporate real ($m = 0$) modes in EOB models for circularized binary black holes, considering both the oscillatory part (Bondi mass aspect) and the null memory contribution. Using numerical data, we then explicitly construct and validate a model for the $(2, 0)$ multipole.

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A novel Lagrange-multiplier approach to the effective-one-body dynamics of binary systems in post-Minkowskian gravity

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In this talk, based on the recent work \[2503.05487\], I will present a new way of formulating the effective-one-body (EOB) dynamics, particularly useful for implementing post-Minkowskian results in waveform models for compact binaries. After having motivated the change of paradigm that this new approach brings forth, I will go over its main characteristics and show how it yields, with the crucial use of a Lagrange multiplier in the EOB action, new EOB equations of motion in Euler-Lagrange form. Finally, I will show the performance of an EOB model, built upon this new Lagrange-EOB dynamics, that combines post-Newtonian and post-Minkowskian information.

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Black-hole - neutron-star mergers: new numerical-relativity simulations and multipolar effective-one-body model with spin precession and eccentricity

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In this talk, we present 52 new numerical-relativity (NR) simulations of black-hole-neutron-star merger (BHNS) mergers and employ the data to inform TEOBResumS-Dalí: a multipolar effective-one-body model also including precession and eccentricity. Our simulations target quasicircular mergers and the parameter space region characterized by significant tidal disruption of the star. Convergent gravitational waveforms are produced with a detailed error budget after extensive numerical tests. We study in detail the multipolar amplitude hierarchy and identify a characteristic tidal signature in the (ℓ,m)=(2,0), and (3,0) modes. We also develop new NR-informed models for

the remnant black hole and for the recoil velocity. The numerical data is then used to inform next-to-quasicircular corrections and the ringdown of TEOBResumS-Dalí for BHNS. We show an overall order of magnitude improvement in the waveform's amplitude at merger and more consistent multipoles over our older TEOBResumS-GIOTTO for BHNS. TEOBResumS-Dalí is further validated with a new 12 orbit precessing simulation, showing phase and relative amplitude differences below ~0.5 (rad) throughout the inspiral. The computed mismatches including all the modes lie at the one percent level for low inclinations. Finally, we demonstrate for the first time that TEOBResumS-Dalí can produce robust waveforms with both eccentricity and precession, and use the model to identify the most urgent BHNS to simulate for waveform development. Our new numerical data are publicly released as part of the CoRe database.

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Parameter estimation of gravitational waves from hyperbolic black hole encounters

Binary black hole systems with unbound orbits can produce a diverse array of gravitational wave signals with rich morphology. This parameter space encompasses both hyperbolic orbit scattering events and dynamical captures, including zoom-whirl orbits with multiple flybys and direct plunge mergers. These signals challenge traditional parameter estimation infrastructure, which is largely optimized for quasicircular inspiral binaries. In this work we discuss the adaptation of the Rapid Iterative FiTting (RIFT) algorithm to this problem using the TEOBResumSDALI waveform model which can simulate generic orbits. We present results from a study of simulated signals emulating a scatter and plunge event, utilizing the design sensitivity of the forthcoming Cosmic Explorer interferometer. Our analysis demonstrates that RIFT accurately recovers the mass, spins, and hyperbolic orbit parameters: the system energy and angular momentum defined at a fiducial initial separation.