# 1st TEONGRAV international workshop on theory of gravitational waves

Monday, 16 September 2024 - Friday, 20 September 2024

Sapienza University of Rome

# Book of Abstracts

# Contents

**Poster Session / 1**

## The footprint of nuclear saturation properties on the neutron star f mode oscillation frequencies: a machine learning approach

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We investigate the intricate relationships between the non-radial f mode oscillation frequencies of neutron stars (NS)s and the corresponding nuclear matter equation of state (EOS) using a machine learning (ML) approach within the ambit of the relativistic mean field (RMF) framework for nuclear matter. With two distinct parameterizations of the Walecka model, namely, (1) with non-linear self interactions of the scalar field (NL) and, (2) a density dependent Bayesian model (DDB), we perform a thorough examination of the f mode frequency in relation to various nuclear saturation properties. The correlations between the f mode frequencies and nuclear saturation properties reveal, through various analytical and ML methods, the complex nature of NSs and their potential as the cosmic laboratory for studying extreme states of matter. A principal component analysis (PCA) has been performed using mixed datasets from DDB and NL models to discriminate the relative importance of the different components of the EOS on the f mode frequencies. Additionally, a Random forest feature importance analysis also elucidates the distinct roles of these properties in determining the f mode frequency across a spectrum of NS masses. Our findings are further supported by symbolic regression searches, yielding high-accuracy relations with strong Pearson coefficients and minimal errors. These relations suggest new methodologies for probing NS core characteristics, such as energy density, pressure, and speed of sound from observations of non-radial f mode oscillations of NSs.

**TEONGRAV Session / 2**

## Primordial black holes or else? TIdal tests on subsolar gravitational wave observations

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The detection of a subsolar object in a compact binary merger is regarded as one of the smoking gun signatures of a population of primordial black holes (PBHs). We critically assess whether these systems could be distinguished from stellar binaries, for example composed of white dwarfs or neutron stars, which could also populate the subsolar mass range. At variance with PBHs, the gravitational-wave signal from stellar binaries is affected by tidal effects, which dramatically grow for moderately compact stars as those expected in the subsolar range. We forecast the capability of constraining tidal effects of putative subsolar neutron star binaries with current and future LIGO-Virgo-KAGRA (LVK) sensitivities as well as next-generation experiments. We show that, should LVK O4 run observe subsolar neutron-star mergers, it could measure the (large) tidal effects with high significance.

**Contributed Talks / 3**

## Establishing connection between neutron star properties and nuclear matter parameters through a comprehensive multivariate analysis

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We have attempted to mitigate the challenge of connecting the neutron star (NS) properties with the nuclear matter parameters that describe equations of state (EOSs). The efforts to correlate various neutron star properties with individual nuclear matter parameters have been inconclusive.
A Principal Component Analysis is employed as a tool to uncover the connection between multiple nuclear matter parameters and the tidal deformability as well as the radius of neutron stars within the mass range of $1.2-1.8M_{\odot}$. The essential EOSs for neutron star matter at low densities have been derived using both uncorrelated uniform distributions and minimally constrained joint posterior distributions of nuclear matter parameters. For higher densities ($\rho > 0.32\text{fm}^{-3}$), the EOSs have been established through a suitable parameterization of the speed of sound, which consistently maintains causality and gradually approaches the conformal limit. Our analysis reveals that in order to account for over 90\% of the variability in NS properties, it is crucial to consider two or more principal components, emphasizing the significance of employing multivariate analysis. To explain the variability in tidal deformability needs a greater number of principal components compared to those for the radius at a given NS mass. The contributions from iso-vector nuclear matter parameters to the tidal deformability and radius of NS decrease by $\sim$ 25\% with the increase in mass of NS from $1.2M_{\odot}$ to $1.8M_{\odot}$.

**Poster Session / 4**

## POST-NEWTONIAN GENERATION OF GRAVITATIONAL WAVES IN EINSTEIN-CARTAN THEORY

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In this seminar, we investigate the topic of gravitational waves in the context of Einstein-Cartan theory by exploiting the Blanchet-Damour formalism.
Einstein-Cartan model has been formulated to extend the concepts of general relativity to the microphysical realm in order to establish a connection between gravity and the other fundamental interactions. In this framework, the quantum intrinsic spin carried by elementary particles is described geometrically by means of the torsion tensor, defined as the antisymmetric part of the affine connection.
On the other hand, the Blanchet-Damour approach has been devised in general relativity to deal with the radiation produced by compact binary systems during their early inspiralling stage. It employs two approximation techniques: the multipolar-post-Minkowskian scheme, which combines a post-Minkowskian algorithm and a multipolar decomposition, and the post-Newtonian method.
We demonstrate that the Blanchet-Damour pattern can be exploited in Einstein-Cartan model as well. This enables the solution of the so-called gravitational-wave generation problem, which consists in formally relating the asymptotic features of radiative gravitational fields, observed far away from their sources, to the structure and the motion of the sources themselves. Then, we show that

Einstein-Cartan corrections, imprinted in the gravitational-wave signal of an inspiralling compact binary endowed with a quantum spin, can be potentially detected by means of the pulsar timing array technique. We conclude the seminar with a discussion regarding open problems and future perspectives.

**TEONGRAV Session / 6**

## Classifying binary black holes from Population III stars using machine learning and the Einstein Telescope

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Third-generation (3G) gravitational-wave (GW) detectors like the Einstein Telescope (ET) will observe binary black hole (BBH) mergers at redshifts up to z ~ 100. However, unequivocal determination of the origin of high-redshift sources will remain uncertain, due to the low signal-to-noise ratio (SNR) and poor estimate of their luminosity distance. This study proposes a machine learning approach to infer the origins of high-redshift BBHs, specifically differentiating those arising from Population III (Pop. III) stars —likely the first progenitors of stellar-born BBH mergers in the Universe —and those originated from Population I-II (Pop. I-II) stars. We have considered a wide range of state-of-the-art models encompassing current uncertainties on Pop. III BBH mergers. We then estimate parameter errors of detected sources with ET using the Fisher-information-matrix formalism, followed by classification using XGBoost, a machine learning algorithm based on decision trees. For a set of mock observed BBHs, we provide the probability that they belong to the Pop. III class while considering the parameter errors of each source. In our fiducial model, we accurately identify ~ 10% of detected BBHs originating from Pop. III stars with > 90% precision. Our study demonstrates how machine learning enables to achieve some pivotal aspects of ET science case by exploring the origin of individual high-redshift GW observations. We set the basis for further studies, which will integrate additional simulated populations and account for population modeling uncertainties.

**Contributed Talks 2 / 7**

## Geometric template bank for low-mass compact binaries with moderately eccentric orbits

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Compact binaries on eccentric orbits are another class of sources for gravitational wave (GW) detectors that can provide a wealth of information on binaries'formation pathways and astrophysical environments. However, historically, eccentricity in template waveforms is often ignored in modelled search analyses for compact binaries, which assumes templates for non-precessing quasi-circular binaries. We show that quasi-circular template banks are highly ineffectual in detecting binary neutron stars and neutron star-black hole systems that enter Advanced LIGO at the projected O4 sensitivity with eccentricities in the range $e \in [0-0.15]$. With populations of marginally eccentric binaries with aligned/anti-aligned component spins in binary neutron stars (BNS) and neutron star-black hole (NSBH) parameter space, we demonstrate that quasi-circular template banks incur 27% and 20% loss in detection rates of GW signals from BNS and NSBH systems, respectively. Motivated by the inefficiencies of current searches of compact binaries, we developed a geometric template bank that included masses, spins, and eccentricity in the parameter space for searches of compact binaries on moderately eccentric orbits. This TaylorF2Ecc waveform model-based geometric template bank improves eccentric signal recovery significantly, as less than 6

**Poster Session / 9**

## Scalar waves in conformally symmetric spacetimes

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Solutions to Einstein's field equations (EFEs) are useful in describing compact stellar objects which have very strong gravitational fields and high densities. Finding these solutions is difficult in general because they are a system of complicated nonlinear partial differential equations. Ad hoc methods need to be employed to make them simpler to work with such as assuming a type of symmetry, for example, conformal symmetry. We study the kinematical and dynamical properties of spacetimes that admit a conformal Killing vector (CKV) through a geometrical spacetime decomposition. This provides new insights into the behaviour of physical quantities such as acceleration, expansion, shear and vorticity. Constraint equations are obtained that must be satisfied for a CKV to exist through the decomposition of the energy-momentum tensor. We apply our results to the perfect fluid model and noteworthily we show that the conformal factor satisfies a damped scalar wave equation. We preview spacetime decomposition applied to black holes and comment on gravitational waves.

**Contributed Talks / 10**

## The conundrum of tidal Love number

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Tidal Love numbers provide us a handle to test the nature of compact objects, as well as theories of gravity. There have been several clarifications recently, which makes our understanding of these Love numbers better. But further investigations have led to more confusion. I plan to discuss these recent developments and the confusing nature of recent literature on these issues. I will show that the tidal Love numbers of a non-rotating black hole identically vanishes, but for a rotating black holes things are not so straightforward. Besides black holes, I will also highlight some remarkable novel features, for ultra-compact objects with non-trivial reflectivity.

**Poster Session / 11**

## Echoes from braneworld wormhole

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We have studied the stability of wormhole geometries, under massless scalar, electromagnetic, and axial gravitational perturbations, in the context of higher dimensional spacetimes. Intriguingly, the construction of a wormhole spacetime in the presence of higher dimensions, known as braneworld wormholes, does not require the existence of exotic matter fields, unlike the scenario in four spacetime dimensions. Being a nonvacuum spacetime, the effective potential experienced by the axial gravitational perturbation differs considerably from the scenarios involving black holes. In particular, the present work provides one of the first attempts to study the gravitational perturbations of the wormhole spacetimes. Our analysis, involving both analytical and numerical techniques, demonstrates that there are echoes in the time domain signal of all the perturbations and the echo time delay is intimately related to the parameters originating from higher dimensions. Thereby combining the attempt to search for wormholes and extra dimensions, with the existence of gravitational wave echoes. Implications and future directions have also been discussed.

**Contributed Talks 2 / 12**

## Inspiral-merger-ringdown waveforms in Einstein-scalar-Gauss-Bonnet gravity within the effective-one-body formalism

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Gravitational waves (GWs) provide a unique opportunity to test general relativity (GR) in the highly dynamical strong-field regime. So far, the majority of the tests of GR with GW signals have been carried out following parametrized, theory-independent approaches. An alternative avenue consists in the development of inspiral-merger-ringdown (IMR) waveform models in specific beyond-GR theories of gravity, by combining analytical and numerical-relativity results. In this work, we provide the first example of a full IMR waveform model in a beyond-GR theory, focusing on Einstein-scalar-Gauss-Bonnet (ESGB) gravity, a theory that has attracted particular attention due to its rich phenomenology for binary black-hole (BH) mergers, thanks to the presence of non-trivial scalar fields. Starting from the state-of-the-art, effective-one-body (EOB) multipolar waveform model for spin-precessing binary BHs SEOBNRv5PHM, we add theory-specific corrections to the EOB Hamiltonian, the GW and scalar energy fluxes, the GW modes, the quasi-normal-mode spectrum and the mass and spin of the remnant BH. We also propose a way to marginalize over the uncertainty in the merger morphology with additional nuisance parameters. By performing Bayesian parameter estimation for the GW events GW190412, GW190814 and GW230529, we are able to place constraints on the fundamental coupling of the theory and to perform Bayesian model selection between ESGB and GR. Our model can be used to improve constraints on modifications of GR with upcoming GW observations, and to provide forecasts for next-generation GW detectors on the ground, such as the Einstein Telescope and Cosmic Explorer.

**TEONGRAV Session 2 / 13**

## Compact objects in and beyond the Standard Model.

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Compact objects are unique probes of the strong gravity regime and may be the key to understanding long-standing puzzles in fundamental physics. These include the nature of dark matter, the possible extension of Einstein's gravity, and the fate of spacetime singularities. The advent of gravitational-wave astronomy provides new observations with present and future interferometers and is a great opportunity to address such foundational issues. We consider a theory in which a real scalar field is Yukawa-coupled to a fermion and has a potential with two non-degenerate vacua. If the coupling is sufficiently strong, a collection of N fermions deforms the true vacuum state, creating energetically-favored false-vacuum pockets in which fermions are trapped. We embed this model within General Relativity and prove that it admits self-gravitating compact objects where the scalar field acquires a non-trivial profile due to non-perturbative effects. We discuss some applications of this general mechanism in and beyond the Standard Model.

**Contributed Talks / 15**

## Model-independent cosmology with joint observations of gravitational waves and $\gamma$-ray bursts

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The multi-messenger (MM) observations of binary neutron star (BNS) mergers provide a novel approach to trace the distance-redshift relation, crucial for understanding the expansion history of the Universe and, consequently, testing the presence of Dark Energy (DE). While the gravitational wave (GW) signal offers a direct measure of the distance to the source, the combined efforts of wide-field X-/gamma- ray observations and ground-based optical telescopes yield the redshift of the host galaxy. In my presentation, I will discuss the use of gamma-ray bursts from BNS mergers observed by high-energy satellites, such as the Fermi Gamma-ray Space Telescope and the Neil Gehrels Swift Observatory, to construct a large set of mock MM data through a complete posterior reconstruction of the GW parameters beyond the standard Fisher matrix approach. We explore combinations of current and future generations of GW detectors and work within various underlying cosmologies. I will present how these mock data are used to perform an agnostic reconstruction of the DE phenomenology, thanks to Machine Learning and Gaussian Process techniques. Our study highlights that the bottleneck in combined GRB-GW detection for generating improved cosmological inferences lies in the availability of GRBs with known redshifts in the coming years. We stress the need to couple future interferometers, like the Einstein Telescope, with a new set of high-energy satellites that can improve the sky localization of the events.

**Poster Session / 16**

## Quantum Gravity Origin of (Un)Stable PBHs and Gravitational Waves

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We explore the phenomenological consequences of breaking discrete global symmetries in quantum gravity (QG). We explore how quantum gravity effects, manifested through the breaking of discrete symmetry responsible for the production of primordial black holes (PBH) resulting from Domain Wall annihilations, can have observational effects through gravitational waves. While stable PBHs formed in this process can play the role of dark matter, an unstable PBH produced can result in the production of dark matter from its evaporation. Since such QG symmetry breaking leads to DW annihilation, this may generate the characteristic gravitational wave background that can be tested in the current and future gravitational wave detectors. On top of this for unstable (ultralight) PBHs, the dominant contribution to the gravitational wave spectrum comes from the PBH distribution that generates gravitational waves at the second order. This work therefore highlights a tantalizing possibility of probing the effective scale of QG from Gravitational Wave observations.

**Contributed Talks 2 / 17**

## A Fisher matrix code for population analysis of gravitational-wave events

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We develop a modular and user-friendly python code based on the Fisher information matrix formalism to perform population analysis of gravitational- wave events and to make population-level predictions for third-generation detectors. This project is based on the work of [Gair et al (2021) MNRAS 519 2736] who derived a Fisher Matrix formalism to estimate the hyperparameters that characterize a population of gravitational-wave events assuming Gaussian noise and taking into account selection effects. We apply this Fisher formalism to realistic population models, such as those exploited by the LIGO-Virgo-Kagra collaboration for masses, spins and redshift for both black-hole and neutron-star binaries. As a validation test, we compute the Fisher Matrix for the population of 90 events published in third gravitational-wave transient catalog (GWTC-3) to prove the effectiveness of the formalism for the observed catalog and to compare our results with the ones obtained through the state-of-the-art hierarchical Bayesian analysis.

**Contributed Talks / 18**

## Exploring Composition of Dense Nuclear Matter with Astrophysical Observations

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Astrophysical observations of neutron stars allow us to study the physics of matter at extreme conditions which are beyond the scope of any terrestrial experiments. In this work, we perform a Bayesian analysis putting together the available knowledge from the nuclear physics experiments, observations of different X-ray sources, and gravitational wave events to constrain the equation of state of supranuclear matter. In particular, we employ a relativistic metamodel to explore the uncertainties of the saturation properties of nuclear matter such as the symmetry energy and its higher-order derivatives, incompressibility, skewness, kurtosis etc. We further probe the fractions of different particle species within our model that the interior of a neutron star may contain, particularly the proton fraction in the core and the observational consequences of the allowed compositions. We also incorporate the possible emergence of hyperons in the system and the number of ways that the density functional can accommodate hyperons in the neutron star matter. Finally, we calculate the strangeness content in the star and discuss its observational implications.

**TEONGRAV Session 2 / 19**

## Phenomenological Properties of EMD Black Hole Binaries

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Einstein-Maxwell-Dilaton-Black-Holes (EMDBHs) are a black hole solution of Einstein's equation of General Relativity. EMDBH's have electromagnetic charge (here non-spinning) and a stable scalar field configuration centred on the black hole due to the dilaton coupling in the action between the scalar field and electromagnetism. In this talk we will discuss various phenomenological properties of these compact objects and their binaries and collisions.

**Contributed Talks / 20**

## Perturbation of the Vaidya metric in frequency domain: Quasi-normal modes and tidal response

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The mass of a black hole can dynamically evolve due to various physical processes, such as for instance accretion, Hawking radiation, absorption
of gravitational/electromagnetic waves, superradiance, etc. This evolution might have an impact on astrophysical observables like the ringdown gravitational signal. An effective description of a spherically symmetric black hole with evolving mass is provided by the Vaidya metric. In our investigation, we explore the dynamics of linear perturbations on this background, assuming a slow evolution (i.e. expanding at linear order also in the rate of change of the mass). Despite the time-dependent background, our approach allows for treating the perturbations in the frequency domain, and for computing explicitly the quasi-normal modes and the tidal Love number.

**Contributed Talks / 21**

## Neutron stars and the cosmological constant problem

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Phase transitions can play an important role in the cosmological constant problem, allowing the underlying vacuum energy, and therefore the value of the cosmological constant, to change. Deep within the core of neutron stars, the local pressure may be sufficiently high to trigger the QCD phase transition, thus generating a shift in the value of the cosmological constant. The gravitational effects of such a transition should then be imprinted on the properties of the star. In this talk, working in the framework of General Relativity, I provide a new model of the stellar interior, allowing for a QCD and a vacuum energy phase transition. I determine the impact of a vacuum energy jump on mass-radius relations, tidal deformability-radius relations, I-Love-Q relations and on the combined tidal deformability measured in neutron star binaries.

**Contributed Talks / 22**

## Gravitational waves from mergers of Population III binary black holes: roles played by two evolution channels

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The gravitational wave (GW) signal from binary black hole (BBH) mergers is a promising probe of population III (Pop III) stars, which are more efficient at producing massive black holes (BHs) than their population I/II (Pop I/II) counterparts. To fully unleash the power of the GW probe, one important step is to understand the relative importance and unique features of different evolution channels. We implement two channels, i.e., isolated binary stellar evolution (IBSE) and nuclear star cluster-dynamical hardening (NSC-DH), in the semi-analytical model A-SLOTH to predict the properties of Pop III BBH mergers under various assumptions on Pop III initial mass function (IMF), binary statistics and high-z nuclear star clusters (NSCs). In the NSC-DH channel, Pop III BBHs fall into NSCs by dynamical friction and are driven to merge by dynamical hardening from binary-single encounters. The NSC-DH channel contributes 8-95% of Pop III BBH mergers across cosmic history, with higher contributions achieved by initially wider binary stars, more top-heavy IMFs, and more abundant high-z NSCs. The stochastic GW background (SGWB) produced by Pop III BBH mergers has a peak value of 1-8*10^-11 around observer-frame frequencies 10-100 Hz, which can be a non-negligible (~2-32%) component in the total SGWB below 10 Hz. The estimated detection rates of Pop~III BBH mergers by the Einstein Telescope are ~6-230 and ~30-1230 events per year for the NSC-DH and IBSE channels, respectively. BBH mergers in NSCs are more massive than those from IBSE, so they dominate the Pop III SGWB below ~20 Hz in most cases. Besides, the detection rate of Pop III BBH mergers involving at least one intermediate-mass BH above 100 Msun by the Einstein Telescope is 0.5-200/yr in NSCs but remains below 0.1/yr for IBSE.

**Poster Session / 23**

## Forecast cosmological constraints from the number counts of Gravitational Waves events

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We present a forecast for the upcoming Einstein Telescope (ET) interferometer with two new methods to infer cosmological parameters. We consider the emission of Gravitational Waves (GWs) from compact binary coalescences, whose electromagnetic counterpart is missing, namely Dark Sirens events. Most of the methods used to infer cosmological information from GW observations rely on the availability of a redshift measurement, usually obtained with the help of external data, such as galaxy catalogues used to identify the most likely galaxy to host the emission of the observed GWs. Instead, our approach is based only on the GW survey itself and exploits the information on the distance of the GW rather than on its redshift. Since a large dataset spanning the whole distance interval is expected to fully represent the distribution, we applied our methods to the expected ET's far-reaching measuring capabilities. We simulate a dataset of observations with ET using the package `darksirens`, assuming an underlying $\Lambda$CDM cosmology, and including the possibility to choose between three possible Star Formation Rate density (SFR) models, also accounting for possible population III stars (PopIII). We test two independent statistical methods: one based on a likelihood approach on the theoretical expectation of observed events, and another applying the \emph{cut-and-count method}, a simpler method to compare the observed number of events with the predicted counts. Both methods are consistent in their final results, and also show the potential to distinguish an incorrect SFR model from the data, but not the presence of a possible PopIII. Concerning the cosmological parameters, we find instead that ET observations by themselves would suffer from strong degeneracies, but have the potential to significantly contribute to parameter estimation if used in synergy with other surveys.

**Poster Session** / **24**

## Prospects on the Detection of Neutrino Driven Core-Collapse Supernovae Gravitational Waves

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The detection of gravitational waves from core-collapse supernovae presents a unique opportunity to explore the physics of these cataclysmic events. Despite being generated by one of the most energetic phenomena in the universe, the waveform emitted by core-collapse supernovae remains elusive. Traditional detection methods like the matched filter technique are ineffective due to this waveform uncertainty. In this study, we propose a new approach integrating machine learning to tackle this challenge. Our study begins with generating phenomenological gravitational waveforms, providing an efficient alternative to computationally demanding direct simulations. We then train a convolutional neural network injecting these waveforms into real detector data, enabling the effective detection of gravitational wave signals in real data. Through comprehensive evaluation using different datasets, our approach demonstrates promising performance compared to conventional methods. Looking ahead, our method holds potential for application in future gravitational wave detectors such as the Einstein Telescope and Cosmic Explorer, paving the way for enhanced detection and analysis capabilities in gravitational wave astronomy. Furthermore, our approach could be extended to explore gravitational wave signals from rotating progenitor supernovae, enriching our understanding of these intriguing astrophysical phenomena.

**Contributed Talks** / **25**

## A new multipolar waveform model for eccentric, spin-aligned binary black holes within the effective-one-body formalism

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The detection of orbital eccentricity in gravitational waves (GWs) will provide us with unique and valuable information about the astrophysical origin and evolution of compact binary systems. In recent years, the expectations for observing eccentricity signatures in GWs have increased due to the continuous improvement of GW detectors and data-analysis techniques. For this purpose, eccentric waveform models are being improved since they will play a fundamental role in the characterization of eccentric GW signals. Here, we present SEOBNRv5EHM, a new time-domain inspiral-merger-ringdown multipolar waveform model for eccentric binary black holes (BBHs) with aligned spins. This model is developed within the effective-one-body (EOB) formalism and has been successfully validated against eccentric numerical-relativity (NR) simulations. Its accuracy, robustness, and speed are suitable for data analysis and astrophysical applications, such as searches for eccentric GWs, parameter estimation of the signals, waveform systematic tests, and BBH population studies. Finally, we also discuss a possible generalization to eccentric, spin-precessing BBHs, which is required for a complete understanding of binary formation channels.

**TEONGRAV Session 2 / 26**

## Quasi-local masses and cosmological coupling of astrophysical compact objects

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The possibility of a non-zero coupling between local astrophysical objects, such as black holes (BHs), and the large-scale cosmological dynamics, has a quite long history. Recently, there have been interesting developments on the issue, from both theoretical and observational points of view.
In this talk, I will discuss a General Relativity framework allowing the embedding of local objects into the cosmological background, giving rise to a general description of the coupling between local inhomogeneities and the large-scale homogeneous background. In this framework, if BHs are singularity-free objects, they must couple to the large-scale cosmological dynamics.
I will show that the coupling is associated to a curvature term in Einstein's equations, yielding to the precise prediction ⊠(⊠) ∝ ⊠, where ⊠(⊠) is the Misner-Sharp (MS) mass of the object, and ⊠ is the scale factor. I will show that the cosmological coupling occurs whenever the energy of the central object is quantified by the quasi-local MS mass, whereas the decoupling occurs whenever the MS mass is fully equivalent to the nonlocal Arnowitt-Deser-Misner (ADM) mass, i.e. in the case of singular BHs.
Finally, aiming at determining whether we will be able to assess if BHs are singular or not, I will discuss observational prospects to distinguish between the two scenarios, by means of gravitational wave signals from binary BH mergers from both 2G and 3G detectors.

**Contributed Talks / 27**

## Late-time signal from binary black hole coalescences

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Recently, studies on numerical evolutions of eccentric binary inspirals found a several orders of magnitude enhancement of the post-ringdown tail amplitude. This characteristic might render the

tail a phenomenon of observational interest, opening the way to experimental verification of this general relativistic prediction in the near future. I will present an analytical perturbative model that accurately predicts the numerically observed tail evolution.

Considering a source term describing an infalling test-particle in generic non-circular orbits, driven by post-Newtonian radiation reaction, I derive an integral expression over the system's entire history, showing how the post-ringdown tail is inherited from the non-circular inspiral in a non-local fashion. Beyond its excellent agreement with numerical evolutions, the model explains the tail amplification with the progenitors' binary eccentricity. Specifically, I will show that the tail is enhanced by motion at large distances from the black hole, with small tangential velocity.

I will prove the tail to be a superposition of many power-laws, with each term's excitation coefficient depending on the specific inspiral history. A single power law is recovered only in the limit of asymptotically late times, consistent with Price's results and the classical soft-graviton theorem. I will conclude by discussing future directions, including the non-linear extension to comparable masses, exploiting the fact that for highly eccentric binaries, our model predicts the tail amplitude to be determined mainly by the motion near the last apastron.

**Contributed Talks / 28**

# Tidal heating in eccentric orbit

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Tidal heating in a binary black hole system is driven by the absorption of energy and angular momentum by the black hole's horizon. This phenomenon becomes particularly significant during the late stages of an extreme mass ratio inspiral (EMRI). Past analyses have largely focused on quasi-circular inspiral geometry, with some of the most detailed studies looking at equatorial cases. I will discuss the importance of tidal heating in equatorial EMRIs with generic eccentricities. Our results suggest that accurate modeling of tidal heating is crucial to prevent significant dephasing and systematic errors in EMRI parameter estimation. Alongside a phenomenological model for EMRIs around exotic compact objects by parameterizing deviations from the black hole picture in terms of the fraction of radiation absorbed compared to the BH case will be discussed. I will also discuss the observable impact. It will be primarily based on arXiv:2404.04013v2 [gr-qc].

**Contributed Talks / 29**

# Magnetic dissipation in short gamma-ray burst jets

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The multimessenger event GRB 170817A confirmed that short gamma-ray burst jets can be launched from the remnants of a binary neutron star merger environment. The electromagnetic properties of such jets are expected to strongly affect their structure and propagation. In particular, the impact of a finite conductivity may play a key role in the early stages of propagation, i.e. when the jet propagates in the post-merger remnant.

Here I present a systematic numerical study of the propagation of astrophysical magnetized relativistic jets, in the context of resistive relativistic magnetohydrodynamics (RRMHD) simulations. First, I will briefly discuss the investigation of different values and models for the plasma resistivity coefficient, Here I will assess their impact on the level of turbulence, the formation of current sheets

and reconnection plasmoid, and the electromagnetic energy content, demonstrating how a physical resistivity model can lead to the formation of current sheets and potential reconnection sites.
I will then discuss the propagation of short gamma-ray burst jets beyond the ideal magnetohydrodynamics assumption, assessing the impact of the resistivity on the jet propagation and dynamics. By employing different resistivity models I will present 2D and 3D simulations which show the role of magnetic resistivity in the energetics and evolution of the jet.

**Contributed Talks / 30**

## Comparing gravitational waveform models for binary black hole mergers through a hypermodels approach

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The inference of source parameters from gravitational-wave signals relies on theoretical models that describe the emitted waveform. Different model assumptions on which the computation of these models is based could lead to biases in the analysis of gravitational-wave data. In this work, we sample directly on four state-of-the-art binary black hole waveform models from different families, in order to investigate these systematic biases from the 13 heaviest gravitational-wave sources with moderate to high signal-to-noise ratios in the third Gravitational-Wave Transient Catalog (GWTC-3). All models include spin-precession as well as higher-order modes. Using the "hypermodels" technique, we treat the waveform models as one of the sampled parameters, therefore directly getting the odds ratio of one waveform model over another from a single parameter estimation run. From the joint odds ratio over all 13 sources, we find the model NRSur7dq4 to be favored over SEOBNRv4PHM, with an odds ratio of 29.43; IMRPhenomXPHM and IMRPhenomTPHM have an odds ratio, respectively, of 4.70 and 5.09 over SEOBNRv4PHM. However, this result is mainly determined by three events that show a strong preference for some of the models and that are all affected by possible data quality issues. If we do not consider these potentially problematic events, the odds ratio do not exhibit a significant preference for any of the models, and, overall, we do not find one model to be consistently preferred over the others. This is unexpected, considering that we included NRSur7dq4 in the analysis, which is predicted to be the most accurate model for high-mass signals, being interpolated from NR simulations. Nonetheless, we systematically find that the models recovering evidence of precession are the ones with the higher probabilities.
Although further work studying a larger set of signals will be needed for robust quantitative results, the presented method highlights one possible avenue for future waveform model development.

**Contributed Talks 2 / 31**

## Binary mergers in strong gravity background of Kerr black hole

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Binary-black-hole (BBH) mergers can take place close to a supermassive black hole (SMBH) while being in a bound orbit around the SMBH. In this paper, we study such bound triple systems and show that including the strong gravity effects of describing the SMBH with a Kerr metric

can significantly modify the dynamics, as compared to a Newtonian point particle description of the SMBH. We extract the dynamics of the system, using a quadrupole approximation to the tidal forces due to the SMBH. We exhibit how the gyroscope precession is built into this dynamics, and find the secular Hamiltonian by both averaging over the inner and outer orbits, the latter being the orbit of the BBH around the SMBH. We study the long-time-scale dynamics, including the periastron precession and GW radiation-reaction of the binary system, finding that the strong gravity effects of the SMBH can enhance the von Zeipel-Lidov-Kozai mechanism, resulting in more cycles, higher maximum eccentricity, and thereby a shorter merger time, particularly when the binary is close to, or at, the innermost stable orbit of the SMBH. We end with an analysis of the peak frequency of the GW emission from the binary system, highlighting possible observable signatures in the ET and LISA frequency bands.

**Contributed Talks / 32**

# Radiation reaction at fourth-and-a-half post-Newtonian order

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Gravitational radiation reaction for compact binary systems has historically been studied using post-Newtonian theory, which is well adapted for the inspiraling phase and has the advantage of yielding fully analytical results. I will present recent work where we obtain the equations of motion for the two-body problem at 4.5PN order, in a generic frame. We prove for the first time the validity of the four balance equations (energy, angular momentum, linear momentum and center-of-mass position) at 2PN order, and find a novel nonlocal term when expressing the acceleration in the center-of-mass frame.

**Poster Session / 34**

# Cosmological Consequences of Unconstrained Gravity and Electromagnetism

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Motivated by the quantum description of gauge theories, we study the phenomenological effects of relaxing the Hamiltonian and momentum constraints in general relativity. We show that the unconstrained theory has new source terms that mimic a pressureless dust that only follows geodesics. The source term may be the simplest explanation for dark matter and generically predicts a charged component. We comment that the discovery of such terms would rule out inflation and be a direct probe of the initial conditions of the universe.

**Poster Session / 35**

## Inverse problem of analog systems to ultra compact objects: from scattering properties to perturbation potentials

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In this talk, we present a method to study the properties of ultra-compact, horizonless objects starting from their scattering properties in terms of an inverse problem. The method is based on a combined inversion of Gamow's formula and the Bohr-Sommerfeld rule. Since the direct measurements of transmission and reflection coefficients of astrophysical compact objects are not available from existing gravitational wave measurements, we show that the method is well suited for laboratory based experiments of analogue gravity systems. To demonstrate its capabilities, we apply it to an analogue model of ultra compact horizonless objects which consists of an imperfect draining vortex in a bathtub. Our method cannot only reconstruct the surface reflectivity and compactness, but also yields a good approximation of the effective perturbation potential encoding the dynamical properties of the system. We conclude that this approach is complementary to methods based on the source's quasi-normal mode spectrum and discuss possible extensions.

**TEONGRAV Session 2 / 36**

## Analytical coordinate time at first post-Newtonian order

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In this presentation, we exploit the Damour-Deruelle solution to derive the analytical expression of the coordinate time in terms of the polar angle. This formula has advantageous applications in both pulsar timing and gravitational-wave theory.

**Poster Session / 37**

## Modeling mode amplitudes in precessing binary black-hole ringdown

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Amplitudes of quasi-normal modes in the gravitational-wave signal emitted during the ringdown phase of a binary black-hole merger provide valuable insights into the strong-field non-linear dynamics of the pre-merger phase. While several studies have modeled mode amplitudes for spin-aligned sources, the more complex scenario of precessing sources has received less attention. In this work, we analyze approximately 2000 waveforms from the SXS catalog of numerical relativity simulations to investigate the phenomenology of mode amplitudes in precessing systems. Similar to the spin-aligned case, we find that the (2,±2) modes are generally dominant. However, the hierarchy of subdominant modes for precessing sources is more complex, with modes such as (2,±1) and (2,0) sometimes becoming as prominent as the (2,±2) modes in some rare edge cases. Additionally, we introduce initial models for (2,m) and (3,±3) modes using Gaussian Process Regression, a Bayesian supervised regression algorithm which can address the high dimensionality of the parameter space and data sparsity.

**Poster Session / 38**

## Scalarized Black Hole Solutions in Modified Theories

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This presentation delves into the study of 'hairy' black holes within the framework of Einstein scalar Maxwell gravity and Einstein scalar Gauss-Bonnet theories, with a focus on revealing new scalarized black hole solutions. We revisit established scalarization phenomena and venture into new solution territories, particularly highlighting the blend of linear and non-linear scalarization in Einstein Scalar Maxwell gravity. Our goal also includes the identification of new scalarized black hole solutions in Gauss-Bonnet theory with a Maxwell field, while outlining their observational significance. Our approach leverages numerical techniques to scrutinize asymptotically flat, spontaneous, and non-linear scalarized black holes in the Einstein-Maxwell-Scalar model, with a keen emphasis on the horizon radii and scalar field intensities. We culminate with an analysis of how scalarization sources shape the horizon area. Our research enhances the comprehension of black hole scalarization and paves the way for continued investigation in this exciting field.

**Contributed Talks / 39**

## IMPROVED EOB MODEL FOR EMRIs SIMULATION

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The Extreme Mass Ratio Inspirals (EMRIs) are critical astrophysical systems in the study of gravitational waves, where a stellar-mass compact object spirals into a supermassive black hole. Accurate modeling of EMRIs is essential for the success of space-based gravitational wave detectors like LISA. This work presents an improved Effective-One-Body (EOB) model tailored for simulating the EMRIs inspiral with enhanced precision and computational efficiency.
For the orbital part the changes include a new resummation at lower PN compared to the 22PN previously used, with a different treatment of the logarithmic term. In the scenario where the SMBH is a Kerr black hole a different resummation technique is developed based on a separation between

the spin even part - which includes the purely orbital part- and the spin odd part.
The model is tested against Gravitational Self Force datas, demonstrating substantial improvements and an improved mathematical consistency. This enhanced EOB model offers a significant step forward in our ability to detect and analyze gravitational wave signals from EMRIs, providing deeper insights into the nature of strong-field gravity and the astrophysical environments surrounding supermassive black holes.

**Contributed Talks / 40**

# Extreme mass-ratio inspirals as fundamental physics probes

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The LISA satellite, recently adopted by ESA, is ready to open a new gravitational wave window, targeting sources dim to ground based detectors like LIGO and Virgo.
Extreme mass-ratio inspirals (EMRIs), composed by a massive black hole and a stellar mass secondary, are a among the most peculiar of such new family of binaries. The inspiral phase of these systems falls within the mHz regime of the LISA band. Depending on their mass ratios EMRIs will be continuously observed over long periods, ranging from months to years. Such long evolution is key to provide a measurement of the source parameters with exceptional accuracy, and to allow to perform precise tests of gravity.
In this talk I will discuss how, from a theoretical perspective, we can model the dynamics of these systems beyond vacuum General Relativity, and how to construct gravitational wave templates that can be used for LISA searches. I will also show how EMRI observations, supplied by such waveforms can be used to probe the existence of new fundamental fields and particles.

**Contributed Talks / 41**

# Consistent dynamics of eccentric black hole binaries.

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Describing the dynamics of eccentric black hole binaries remains an open problem in General Relativity. Oscualting equations based on energy and angular momentum balance have been found inconsistent with predictions obtained via orbit averaging, particularly in the parabolic regime. This inconsistency arises from the gauge-dependent definitions of energy and angular momentum. We reparametrize these quantities to obtain gauge-independent definitions, leading to a consistent set of equations that fully describe the evolution of eccentric orbits across arbitrary eccentricities. These equations align with the expected orbit-averaged behavior at small eccentricities. Utilizing this consistent framework, we quantify the regime of validity for orbit averaging prescriptions, which are currently prevalent in gravitational wave astronomy.

**Contributed Talks / 42**

## Ringdowns for black holes with scalar hair: the large mass case

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Black hole quasi-normal mode (QNM) frequency spectrums can probe deviations from General Relativity. We construct an effective field theory scheme for QNMs in shift-symmetric scalar-tensor theories with second order equations, exploiting the behaviour of the black hole's scalar charge in the large mass limit. We find a drastic simplification; the QNM calculation reduces to solving sourced QNMs on a Kerr background. Our analysis, which is particularly suited for black holes in the LISA range, places limits on the prospects of detecting evidence of scalar hair with ringdown signals.

**Contributed Talks / 43**

## The importance of gauge choices in the EOB conservative dynamics

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The effective one-body (EOB) approach is a proven technique for generating fast and accurate models for the motion and radiation of coalescing compact binaries. At its core, it consists of a specific resummation strategy that takes as input the results of the perturbative schemes used to tackle the two-body problem, notably the post-Newtonian (PN) expansion, the post-Minkowskian (PM) expansion, and Gravitational Self Force. While the main aspects of the EOB method are fixed and well established, its application to a given source of perturbative information is always subject to arbitrary gauge choices that have non-negligible impact on the final model. On this note, I will devote my talk to the discussion of recent work on the effect that gauge choices have in the conservative dynamics of EOB models, specifically addressing the gauge freedom in (i) the spin-orbit component of the PN-based EOB Hamiltonian and (ii) in the definition of alternative PM-rooted iterations of the EOB dynamics.

**Contributed Talks / 45**

## Chemically-Homogeneous Evolution's Impact on Stellar Populations and Compact Binary Mergers

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Compact binary mergers mark the final stage of a complex journey that begins with massive stellar binaries. These binary systems undergo complex processes throughout their lifetime, involving phenomena such as mass transfer and tidal interactions, and ultimately culminating in the formation of neutron star or black hole pairs. Among these binary processes, chemically-homogeneous evolution notably impacts the formation of compact binary mergers by inducing rapid spin increases and subsequent alterations in stellar properties and their evolution.
In my talk, I will present the effects of binary interactions and of chemically-homogeneous evolution both on observable stellar populations and the detectability of compact binary mergers using

gravitational wave interferometers. My population-synthesis simulations reveal how chemically-homogeneous evolution alters the ratio of red supergiants to Wolf-Rayet stars, dramatically affecting stellar populations progenitors of gravitational wave sources that are potentially observable through electromagnetic surveys. Notably, Wolf-Rayet stars produced by chemically-homogeneous evolution are, on average, more massive, more numerous, and more luminous than Wolf-Rayet produced either via single or common binary evolution. The effects of chemically-homogeneous evolution are eventually inherited by the compact objects produced by these stellar progenitors: neutron star production is suppressed in favor of black holes, leading to an increased ratio of binaries composed of neutron stars and black holes or massive black holes. Conversely, chemically-homogeneous evolution strongly suppresses the production of compact binary mergers. These findings emphasize the intricate interplay between chemically-homogeneous evolution, stellar populations, and compact binary mergers.

**Contributed Talks / 48**

# Scattering and dynamical capture of two black holes: synergies between numerical and analytical methods

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Dense astrophysical environments, such as globular clusters, could host populations of black holes undergoing scatterings and dynamical captures. The gravitational wave event GW190521 may have originated from such a system, underscoring the need for accurate descriptions to fully leverage the scientific potential of current and future gravitational wave detectors.

We briefly introduce the topic by discussing the nonspinning test-mass limit, where we compute numerical waveforms by solving the Zerilli equation with the time-domain code RWZHyp for different dynamical capture scenarios. These results are then used to gain insights into the waveform properties and to test analytical prescriptions for effective-one-body (EOB) waveforms.

Next, we examine scatterings and dynamical captures for comparable mass spin-aligned systems. We present a dataset of numerical relativity simulations produced with the code GR-Athena++, which we use to study various phenomenological aspects, including waveforms and scattering angles. We also study in detail the transition from scattering to capture. Our numerical results validate the EOB model TEOBResumS-Dalí, showing remarkable agreement for initial energies $E_0$
$lesssim 1.02$, confirming the significant role that EOB models could play in describing these systems. Challenges and future steps, both on the numerical and analytical fronts, are also highlighted.

**Contributed Talks / 49**

# Fast and Reliable Gravitational Waveform Model for Binary Neutron Star Coalescences

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Efficient gravitational waveform models enable us to analyze gravitational wave signals and extract information about the source properties of the compact binary involved in the merger. In this talk, we discuss the improvements made to the NRTidal model, a state-of-the-art model used to describe the tidal interactions between the components of binary neutron stars. The updates include a new closed-form expression calibrated to a suite of numerical relativity simulations including high-mass ratio systems and a variety of equations of state. The model also considers dynamical tidal effects and post-Newtonian mass-ratio dependence of the calibration parameters. It has been implemented in LALsuite by attaching it to existing binary black hole waveform models. The validity of the model is tested on a larger parameter space by comparing it with numerical-relativity waveforms and other tidal models. We show how the model performs when analyzing previously detected gravitational-wave signals and how it can be used to place constraints on the equation of state of supranuclear-dense matter. Finally, we discuss the outlook and future directions of the model.

**Poster Session / 51**

# Black hole spectroscopy: GR and beyond

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According to the no-hair theorem, quasi-normal mode frequencies and damping times are exclusively determined by a black hole's mass and spin. Black hole spectroscopy has shifted from theoretical conjecture to an empirical method for testing these assumptions using current LIGO-Virgo-Kagra observations. We employ a time-domain analysis in an agnostic framework to identify multiple ringdown modes, and verify their agreement with Kerr solution predictions. Analyzing a "controlled" dataset of GW150914-like signals, we investigate deviations from General Relativity using Bayesian model comparison. We explore various scenarios, including how waveform systematics and data quality issues might lead to biased results or false claims of GR violation, and analyse beyond-GR signals, focusing on Kerr-Newman simulations as the most well-posed cases beyond GR.

**Contributed Talks 2 / 53**

# Gravitational wave mergers of black holes in active galactic nuclei

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Despite eight years since the initial detection of gravitational waves from stellar-mass compact-object binaries, the astrophysical origin of these phenomena remains elusive. Recent years have witnessed a growing interest in a novel gravitational wave formation pathway: the active galactic nuclei (AGN) channel. I will describe the key features of the AGN channel, discuss our ongoing efforts in modeling compact objects within accretion disks in AGNs, and highlight the primary challenges associated with modeling black hole-gas disk interactions. Partially based on: arXiv:2403.00060, arXiv:2312.13281

**TEONGRAV Session / 54**

## Black-hole ringdown and their progenitors: from numerical Relativity to tests of GR

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Black-hole ringdowns from binary coalescences encode information about the final state of the remnant through their modes of oscillation, and about their progenitors through the degree of excitation of different modes. We present novel surrogate fits for the excitation amplitudes of black-hole ringdowns from quasi-circular binaries. They are calibrated to numerical relativity simulations and make use of parametric-free regression algorithms, which provide functional flexibility and automatic estimates of the fitting uncertainties. We apply our results to test the consistency of detected black-hole ringdowns with the predictions of GR and with the assumption of quasi-circularity.

**Contributed Talks 2 / 55**

## Eccentricity and spin precession: an Effective-One-Body model informed by Post-Newtonian studies

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Gravitational wave models have in recent years expanded beyond circularized compact binary systems to cover a larger and larger swath of the parameter space. Models incorporating the spin-precession effect, which occurs when the components' spins are misaligned with the orbital angular momentum, in the quasi-circular case are now routinely used for parameter estimation; meanwhile, several groups have developed prescriptions to accurately describe planar non-circular (eccentric, hyperbolic-like) motion. Models combining both these effects have only recently started to see active work by the community.

In this talk I would outline the development of one such model (introduced in https://arxiv.org/abs/2404.15408), first highlighting valuable insights gained in the Post-Newtonian regime regarding the interplay of eccentricity and spin precession (particularly focusing on the Euler and scattering angles). With this knowledge in hand, I would then show how a state-of-the-art non-circular, planar Effective-One-Body model can be extended to cover eccentric, precessing systems through a simple, in both concept and implementation, but effective prescription, as validated through comparisons with Numerical Relativity.

**Contributed Talks / 56**

## A covariant approach to relativistic large-eddy simulations

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The first detection of a neutron star binary merger has made sharp reality the long-standing paradigm that these cosmic fireworks are exciting laboratories for extreme physics. To get the most out of observations, however, we need accurate modelling of the merger dynamics via numerical relativity simulations. In this respect, the large amount of numerical work carried out over the last decade has allowed us to obtain a robust, but broad-brush, picture of the merger dynamics. Current simulations are in fact far from resolving the full range of scales involved, particularly because of the development of turbulence in the merger remnant. This has motivated recent efforts towards adapting the large-eddy simulation strategy to the relativistic setting relevant for binary mergers. Despite the impressive results that such efforts have already delivered, however, all the practical implementations so far are problematic in that they break covariance. In this talk, I will discuss a theoretical framework that allows us to overcome said limitations, and go on to present a practical implementation of the first fully-covariant filtering strategy in relativity.

**Contributed Talks / 57**

## Wolf-Rayet –compact object binaries: the road to gravitational wave mergers

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The properties of binaries hosting a Wolf-Rayet star and a compact object (black hole or neutron star) suggest that such systems could be the progenitors of binary compact objects merging via gravitational wave emission. It is difficult to distinctively determine the road leading to these mergers: many stellar and binary physical models are still poorly constrained and introduce uncertainties in the interpretation of the possible formation pathways. With the population-synthesis code SEVN, we quantified the impact of different assumptions on metallicity, common envelope efficiency, core-collapse supernova and natal kick models on the evolution of a binary population representative of the one observed in the Milky Way. Within the considered parameter space and for metallicity $Z \geq 0.0014$, we found that more than 99% of merging binary compact objects had a progenitor in the Wolf-Rayet - compact object configuration. Some of them exhibit properties similar to Cyg X-3, the only Wolf-Rayet –compact object candidate in the Milky Way. Future observations of Wolf-Rayet –compact object systems could be the “Rosetta stone” to calibrate models for the formation of binary compact objects.

**Contributed Talks / 58**

## Micro-Tidal Disruption Events in Star Clusters

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In dense star clusters stars may be disrupted in close encounters with stellar mass black holes. These transients are addressed as "micro-Tidal Disruption Events"(TDEs). To date, micro-TDEs have not yet been observed but they are promising multi-messenger sources predicted to be detected by next gravitational waves (GW) observatories (i.e. DECIGO) and future all-sky surveys (i.e. LSST, ULTRASAT, BlackGEM etc) up to several Gpc.
In this contribute I will discuss micro-TDEs originated in young star clusters from a dynamical perspective. I have performed a suite of numerical high-precision direct N-body simulations of massive collisional young star clusters (YSCs) with the state-of-the-art code PeTar. PeTar is an N-body code which is coupled with up-to-date stellar population synthesis codes, which are fundamental to treat star and BH progenitors. I will present some preliminary results about the population of micro-TDEs originated in YSCs through hyperbolic-parabolic encounters between single stars and BHs and, furthermore black hole binaries.

**Poster Session / 59**

## Dissipative effects in matter and metric perturbations: formal analysis

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Compact objects are usually described using the perfect fluid formalism. However, in astrophysical processes out of local equilibrium, dissipative effects become important to realistically describe the dynamics of the system.
In this work, we present for the first time the gauge-invariant non-spherical perturbations in a dissipative self-gravitating fluid in spherical symmetry. For this we use the Gerlach-Sengupta formalism to work with gauge-invariant metric perturbations, and the Gundlach-Martín-García approach to transform the tensor perturbation equations into scalar equations.
We calculate the dynamics of the dissipative contributions, e.g. bulk viscosity, heat flux, and anisotropic stress, using the Müller-Israel-Stewart equations in the gauge-invariant formalism.

We obtain the set of field equations for the evolution of matter and metric perturbations in the polar and axial sectors. In the former, we find two wave equations sourced by the anisotropic contributions, and the evolution of all matter perturbations for radiative modes ($l \geq 2$). In the latter, we find one wave equation coupled to the evolution of matter perturbations. Finally we comment on the contribution of dissipative effects in the lower-order multipoles ($l = 0, 1$) for both sectors.

**Contributed Talks / 60**

## A new phenomenological waveform model for binary neutron star systems of unequal masses

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Detections of binary neutron star mergers with gravitational waves have the potential to constrain the currently unknown neutron star equation of state through tidal measurements. This is made possible with accurate and efficient tidal waveform models. In this talk, I present PhenomGSF: a

new phenomenological tidal phase model for neutron stars with unequal masses. PhenomGSF is constructed to reproduce the gravitational self-force (GSF) informed tidal phase of TEOBResumS with high computational speed. PhenomBNS i) provides an accurate tidal description with fast evaluation speed, ii) a modular framework such that it can be linearly added to any binary black hole waveform, iii) does not assume hadronic matter or universal relations, allowing for exotic matter analyses. We validate the model by comparing it to numerical relativity (NR), and present results for GW170817 data to show consistency with other tidal waveform models.

**Contributed Talks / 61**

## Quasinormal modes of black holes with scalar hair

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Many works have explored the emergence and properties of compact object solutions including black holes, in models with a metric tensor and a scalar field within the Horndeski framework. Studying the quasinormal mode (QNM) spectrum of hairy black holes is particularly useful when considering the potential of observing hairy solutions in nature. In this talk we discuss how the QNMs of such solutions may actually deviate significantly from their General Relativity (GR) counterparts, allowing us therefore to potentially probe the validity of GR in the strong gravitational regime.

**Contributed Talks / 62**

## Orbital eccentricity in general relativity from catastrophe theory

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Eccentricity is one of the key parameters to describe a binary system, however, defining it in General Relativity is a highly nontrivial problem. Nevertheless, achieving a consistent definition of orbital eccentricity is a pressing issue for both current and future gravitational wave observations. We present a new approach to consistently define the binary eccentricity in General Relativity which has a solid foundation in the branch of mathematics called "catastrophe theory". In particular, we discover the existence of catastrophes in numerical relativity waveforms and exploit them to derive a robust and gauge invariant estimator of the orbital eccentricity.

**Contributed Talks / 63**

## Biases in tests of GR due to microlensed GW signals

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Gravitational waves (GW) from chirping binary black holes (BBHs) provide unique opportunities to test general relativity (GR) in the strong-field regime. However, testing GR can be challenging when incomplete physical modeling of the expected signal gives rise to systematic biases. In this talk, we discuss the potential influence of wave effects in gravitational lensing (also known as microlensing) on tests of GR using GWs. We present the results for an isolated point-lens model for microlensing with the lens mass ranging from $10 - 10^5$ $\mathrm{M}_\odot$ and base our conclusions on an astrophysically motivated population of BBHs in the LIGO-Virgo detector network. Our analysis centers on two theory-agnostic tests of gravity: the inspiral-merger-ringdown consistency test (IMRCT) and the parameterized tests, providing insights into deviations from GR across different evolutionary phases of GW signals: inspiral, intermediate, and merger-ringdown. Our findings reveal two key insights: First, microlensing can significantly bias GR tests, with a confidence level exceeding $5\sigma$. Second, deviations from GR correlate with pronounced interference effects, which appear when the GW frequency ($f_{\mathrm{GW}}$) aligns with the inverse time delay between microlens-induced images ($t_{\mathrm{d}}$). These false deviations peak in the wave-dominated region and fade where $f_{\mathrm{GW}} \cdot t_{\mathrm{d}}$ significantly deviates from unity. Our findings apply broadly to any microlensing scenario, extending beyond specific models and parameter spaces, as we relate the observed biases to the fundamental characteristics of lensing.

**Poster Session / 64**

## Perturbation theory with black hole quasinormal modes

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The resonant modes of a black hole consist of damped sinusoids, called quasinormal modes. Due to the dissipative nature of the system, the equation governing the modes is non-hermitian. Nevertheless, quasinormal modes have been shown to be orthogonal with respect to a suitable bilinear form defined in Green et al. (2022).
More recently, Cannizzaro et al. (2023) showed that this bilinear form is suited to compute the frequency shift of scalar quasi-bound states due to some deformation of the spacetime, at first order in the perturbative parameter.
This work builds on these recent advancements, aiming to develop a perturbative framework analog to perturbation theory in quantum mechanics, suited to investigate spectral shifts and mode corrections to Kerr quasi-normal modes.

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## Welcome from SOC and from INFN Roma1 Director

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## Registration

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## TEONGRAV: an INFN initiative for the Theory of Gravitational Wave Sources

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## Beyond the horizon: The status and future of gravitational-wave source modelling in general relativity

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This is an overview talk that will outline the progress that has been made in modelling the gravitational-wave signal emitted by coalescing compact binaries. I will briefly introduce the key paradigms and modelling techniques that have led to the successful construction of numerous waveform models before discussing some of the challenges that we face as we transition to the next generation of gravitational wave detectors. Where possible, I will highlight new avenues of exploration that are yielding novel insights into the behaviour of compact binaries in the strong-field regime.

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## Eleonora Troja

TBA

**70**

## Numerical Relativity for strong field tests of gravity.

TBA

**71**

## Walter Del Pozzo

TBA

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## Plenary Talk

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## Plenary Talk

**74**

## The origin and growth of supermassive black holes

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## TEONGRAV Members Meeting

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## Probing ultra-dense matter with gravitational waves

The first detection of gravitational waves from a merging neutron star binary system and the accompanying observations of electromagnetic counterparts in 2017 demonstrated the enormous potential of multi-messenger astronomy for understanding the properties of ultra-dense matter. Neutron stars –relict of the gravitational collapse and subsequent supernova explosion of a massive star at the end of his life– comprise the highest densities of matter that can stably exist in the Universe. During this talk, I will discuss the possibilities for insights on matter under these extreme conditions from future detections of the gravitational wave signals emitted from events involving neutron stars. In particular, results will be shown illustrating the capacity of multi-messenger observations to give us hints about a possible phase transition in neutron star matter.

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## Astrophysics with BH mergers: making sense of a jumble of everything

The rate of GW detections will soar from hundreds to millions per year as detectors improve, revealing the population properties of BH mergers in great detail. Such properties encode valuable information about how stars form and evolve in galaxies very different from our own. They can provide complementary constraints on the cosmic chemical history and on star formation in environments that evade electromagnetic observations. However, the use of GWs in astrophysics presents challenges that must be overcome to realise their full potential.
In particular, the astrophysical "interpretation challenge" that I will discuss in my talk. The observable BH merger population contains a mixture of systems formed throughout the Universe, with different chemical compositions and in very different environments (allowing for unique formation channels). Both strongly influence the formation of BH mergers and can degenerate into their population properties. One aspect

that is key to breaking such degeneracies, and which I will focus on, is constraining the iron-dependent cosmic star formation history.

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## Neutron star equation of state measurements from binary mergers

The study of neutron stars, dense remnants of stellar core collapse, provides a unique opportunity to explore the fundamental properties of matter under extreme conditions. In this talk I will review the status of our current understanding of the neutron star equation of state (EOS) through measurements derived from multi-messenger observations of binary neutron star mergers. Then, focusing on the inspiral-to-post-merger gravitational wave emission, I will discuss the prospect of constraining the EOS with third generation detectors such as Einstein Telescope and Cosmic Explorer, pointing out their potential as well as the challenges that their increased sensitivity will pose.

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## Electromagnetic signatures from GW events

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## Final remarks and good byes

**Contributed Talks / 81**

## Nonlinearities in black hole ringdown

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Nonlinear effects in black hole perturbation theory may be important for describing a black hole ringdown, as suggested by recent works. I will describe a new class of "quadratic" quasi-normal modes at second order in perturbation theory. Remarkably, not only their frequency but also their amplitude is completely determined by the linear modes themselves. I will present how one can compute them using Leaver's algorithm. Quadratic modes could be used to improve ringdown models by adding nonlinear features without introducing any supplementary free parameter for data analysis purposes, or to test GR in the nonlinear regime.

**TEONGRAV Session 2 / 82**

## Population Properties of Massive Binary Black hole with LISA observations Using Iterative Reweighted Kernel Density Estimation

# Technique

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We propose an adaptive Kernel density estimate (KDE) with selection effects as a non parametric method to study rates and population of massive black hole binary systems, which are expected to observe in LISA Observations. We used simulated LISA data for specific models of massive black hole binaries and applied adaptive KDE to construct distribution in total mass and redshift. We incorporated selection effects using probability of detection of such systems with LISA, on our KDE distribution to reconstruct rate estimates for these models. We used an iterative re-weighting method to reduce uncertainty in posteriors of observed events. We study the advantages and limitation of such method and discuss possible improvement for future studies.

**Contributed Talks / 83**

# Computing the Bayes factor in favor of the ringdown overtone using normalizing flows

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I introduce $floZ$, an improved method based on normalizing flows, for estimating the Bayesian evidence (and its numerical uncertainty) from a set of samples drawn from the unnormalized posterior distribution. I validate it on distributions whose evidence is known analytically, up to 15 parameter space dimensions and I demonstrate its accuracy for up to 200 dimensions with $10^5$ posterior samples. I show its comparison with nested sampling (which computes the evidence as its main target). Provided representative samples from the target posterior are available, this method is more robust to posterior distributions with sharp features, especially in higher dimensions. I apply $floZ$ to compute the Bayes factor for the presence of the first overtone in the ringdown signal of the gravitational wave data of GW150914, finding good agreement with nested sampling.

**Contributed Talks / 84**

# Primordial Black Hole formation from a massless scalar field

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Assuming spherical symmetry we consider primordial black hole formation from the collapse of adiabatic cosmological perturbations of a massless scalar field, sourced by a time independent curvature profile $\mathcal{R}(r)$ imposed on super horizon scale. We have proved that a massless scalar field is equivalent to a perfect fluid where the pressure is equal to the total energy density (i.e. $p = \rho$ equation of state ). Using the comoving and the constant mean curvature gauge we build up a numerical code based on the BSSN conformal decomposition, developed specifically for this problem, computing the threshold $\delta_c$ for different initial configurations. This will allow to compute the abundance and mass distribution of PBHs formed when the early Universe is dominated by massless scalar field.

**TEONGRAV Session / 85**

## Gravitational waves from subsolar compact objects: implications for cosmology and high-density nuclear physics

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The detection of a subsolar-mass gravitational wave event would have significant implications for both cosmology and nuclear physics. In this study, we investigate the potential impact of such a discovery, which may occur during the ongoing or future LIGO-Virgo-KAGRA observing runs. The nature of a subsolar binary system—whether composed of light neutron stars, primordial black holes, or other exotic compact objects—can be identified with high statistical confidence through the analysis of tidal deformability effects on the gravitational wave signal. A primordial black hole detection could suggest a connection to dark matter and provide evidence for primordial stellar-mass mergers. Alternatively, observing a subsolar neutron star would offer critical insights into the equation of state of high-density nuclear matter and help determine the existence of quark-based strange stars.

**Contributed Talks / 86**

## Kinetic screening and scalar radiation in K-Essence

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Regarding proposals for modified gravity theories, there is a popular class commonly denominated as scalar-tensor theories, where new scalar fields are introduced that do not interact with gravity in the standard fashion. There is a subclass of such theories that present Screening mechanisms, which allow them to modify gravitational phenomena at large scales while preserving General Relativity' s predictions unaffected on smaller scales. This feature is essential since, so far (within the current precision of measurements), no deviations have been observed in gravitational wave observations, which constitute the small scale in this case. However, there are reasons to believe that puzzling phenomena at larger scales, like the accelerated cosmic expansion, can be explained with the use of scalar-tensor theories. This way, theories like the denominated K-essence are interesting since, in principle, they can modify gravity in the larger scales while leaving the smaller scales unaffected thanks to their Kinetic screening mechanism.

It is still unknown if such screening mechanisms hold in very dynamical scenarios, such as compact

binaries. The nature of this theory makes it challenging to perform the simulations necessary to make such predictions in the nonlinear regime. Problems related to the loss of hyperbolicity and the separation of scales between the different relevant scales exacerbate this challenge.
In this talk, I will present the results of simulations carried out in a simplified scenario, allowing us to explore the nature of scalar radiation in K-essence theory in non-linear and very dynamical scenarios.

**Contributed Talks / 87**

## Numerical models of magnetorotational core-collapse supernovae: explosions dynamics, gravitational waves, neutrinos, and explosive nucleosynthesis

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The gravitational collapse of a massive star with a fast-rotating core sets the stage for the onset of magnetorotational core-collapse supernovae (CCSN). The accreting central compact object (either a black hole or a proto-magnetar) is believed to be the central engine that can power up outstanding stellar explosions such as hypernovae and long gamma-ray bursts (GRBs). Current magnetohydrodynamic models allow one to make quantitative predictions on the properties of the compact remnant, the multi-messenger signatures of the explosion, the launching conditions of the jet, and the nucleosynthesis of new heavy elements contributing to the chemical evolution of galaxies.
I will present the results obtained by recent 3D magneto-rotational supernova models that aim at characterizing the multi-faceted dynamics of the outstanding stellar explosion. I will show how different magnetic field configurations during the gravitational collapse affect not only the explosion dynamics and the compact remnant properties, but also the associated multi-messenger emission (both gravitational waves and neutrinos).
I will also present recent state-of-the-art explosive nucleosynthesis calculations based on the 3D CCSN models, demonstrating the profound impact of magnetic field topology in determining the efficiency of r-processes during the explosion, the production of heavy elements, and thus the chemical evolution of galaxies. In particular, only for aligned dipolar magnetic fields the supernova ejecta are sufficiently neutron-rich to produce elements beyond atomic number A$\sim$130. Moreover, the impact of the magnetic field's dynamics dominates over the uncertainties related to nuclear physics inputs used for the nucleosynthesis calculations, demonstrating the paramount importance of accurately modeling the dynamics of central engines.

**Contributed Talks / 88**

## Development of Phenomenological Gravitational Wave Signals from Rotating Core-Collapse Supernovae in a Multi-Messenger Environment

**Author:** Alessandro Favali[None]

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My Master's thesis is focused on the reconstruction of Gravitational Wave (GW) signals from Core-Collapse Supernovae (CCSNe) by mean of the *ccphen* code written by Prof. Pablo Cerda-Duran. In

particular, type II SNe are the candidates for this work, since we haven't so far a complete theoretical model to predict the waveforms of these events. We have already detected binary mergers of two Neutron Stars (NS-NS), two Black Holes (BH-BH) or a mix of these (NS-BH), but we haven't an exhaustive representative of star collapse. Thus the main goal of my project is to reconstruct with the aforementioned C\Python hybrid code the waveforms of these sources.

What produces GW signals is the asymmetric breakdown of the star (otherwise the quadrupole moments are identically zero), that possesses some features. The shock-wave starts with the bounce of the in-falling matter over the incompressible nucleus made up by degenerate neutrons (NSs or BHs depending on the mass of the progenitor). The *Bounce phase* is the beginning of the simulations (on the x-axis there is the time after the bounce). This phase at first glance differs accordingly to the Equation of State (EoS) of the progenitor star and the magnitude of the rotation (actually only fast rotating progenitors show this signal). Nevertheless we can adopt the *Master Template* to normalize the strain amplitude $h_n$ (the one linked to the relative deformations of the interferometer's arms) of the n-th waveform with the difference between the maximum and minimum of the GW $\Delta h_n$ (also considering the distance to the source $D$). In this way, averaging all the waveforms, we obtain a template that is now the same for any EoS we use (with its own variance).

Some models show also the *Prompt convection*, which lasts for $50 - 100\,\mathrm{ms}$ at about $100\,\mathrm{Hz}$. The magnitude of this component is uncertain and is strongly correlated with the details of numerical simulations.

The key component of the signal is due to the *g-modes* of the Proto-Neutron Star (PNS), well recognizable by the arch-like shape of its spectrogram. Its onset is immediately after the bounce or with some delay (of the order of $200\,\mathrm{ms}$) at a frequency of $100\,\mathrm{Hz}$ and its duration is till the ignition of the explosion. In this context minor modes arise, the so-called *SASI modes* (Standing Accretion Shock Instability), whose duration is comparable to the *g-modes*, but with lower frequencies (albeit it starts at $100\,\mathrm{Hz}$) according to a linear trend.
These components are simulated distinguishing the case of rotating and non-rotating PNSs. We initiate with the non-rotating case. We perform a decomposition in spin-weighted spherical harmonics (because of the tensorial nature of the GW) so to have the $l, m$ components of $h$ ($l = 2$ for the quadrupole moments, the dominant ones as of the strain, and $m = -l, \ldots, l$). This is the simplest case of GW emission. Introducing angular velocity we have a splitting of the curves in the spectrogram depending on the value of $m$ (for fixed, constant rotation). In this case we have to do a reference system change, from the co-rotating one (same formulation as before, since in the reference of the star everything is still if we exclude deformations caused by the rotation) to the laboratory system from which we see the star spinning. So we express the strain amplitude of one system in term of the other and quantify the signal. At the very end we introduce deformations in the form of perturbations of the spherically symmetric background density with the deformation vector that is purely radial (given the symmetries of the source).

The final stage of the Supernova is the actual explosion that leaves a low frequency signal below $\sim 10\,\mathrm{Hz}$. What causes the revival of the outburst (stopped by the external layers of the star) are supposedly the neutrinos produced by electron captures by protons. Neutrinos are the particles that trigger the runaway explosion and are the key ingredients in many theoretical models of CCSNe.

This kind of sources are therefore a good probe for multi-messenger observations, since we can theoretically detect both GWs and neutrinos, having a full insight of CCSNe. Modelling this phenomena with theoretical waveforms could solve some questions about GW emission and neutrino-driven mechanisms of these objects, also giving a wider knowledge of General Relativity processes.

**Contributed Talks / 89**

# Scattering amplitudes for black holes

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In this talk I will highlight recent developments in computing classical gravity observables within the post-Minkowskian scheme using QFT techniques, the double copy and modern tools of scattering amplitudes.

**TEONGRAV Session / 90**

## Effective-one-body, Post-Minkowskian and Numerical Relativity

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Detection and analysis or gravitational wave signals rely on fast and accurate theoretical models.
In particular, the effective-one-body (EOB) framework proved very fruitful in bridging the gap between
analytical (approximated) solutions of Einstein's equations and numerical relativity (NR) information.

The improved sensitivity of interferometers will allow for detection of different gravitational wave signatures, such as waves generated by eccentric and scattering binary systems. Analytical advances in post-Minkowskian (PM) computations, borrowing quantum-field theory techniques, provide us new tools
to approach the modelization of such systems.

We will present recent advances both in NR scattering simulations and analytical PM computations, and show
how resummations through the EOB approach prove crucial in improving the agreement between analytical
and numerical results. We also show analytical techniques able to deal with the increasing complexity
of perturbative results.

**Contributed Talks / 91**

## Spectroscopy of magnetized black holes and topological stars

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We present results on the linear response of four dimensional magnetic black holes and regular topological stars arising from dimensional compactification of Einstein-Maxwell theory in five dimensions.
We discuss the stability of these solutions under both radial and nonradial perturbations, both in the frequency and in the time domain.

**Contributed Talks / 92**

## Probing scalar fields with extreme mass ratio inspirals

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Extreme mass ratio inspirals (EMRIs), binary systems composed of a stellar mass compact object (SCO) inspiralling to a supermassive black hole (SMBH), are one of the target sources for the Laser Interferometer Space Antenna (LISA). Since EMRIs may spend about $10^5$ cycles in the sensitivity band of the interferometer, they are regarded as golden sources to probe new fundamental fields. Scalar fields coupled to the metric have been largely studied in recent time. They may be coupled to gravity either in the gravitational sector or in the matter sector of Einstein's equations.If the coupling of the scalar field with gravity is relevant at the scale of the SCO size, we can assume that the SMBH spacetime is well described by the Kerr metric, while the SCO is endowed with a 'scalar charge', which leaves a characteristic imprint on the emitted gravitational waveform. We discuss the detectability of this scalar charge by LISA for general EMRI orbits, for massless and massive scalar fields. We also discuss the case of a massive, ultra-light, time-dependent scalar field forming a cloud around the secondary body.

**TEONGRAV Session 2 / 93**

## Spectroscopy in Einstein-Maxwell-scalar theories

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The Einstein-Maxwell-scalar (EMS) theory provides an ideal framework to observe deviations from general relativity. A specific instance of this theory involves a scalar field that is minimally coupled to gravity and non-minimally coupled to the Maxwell field. In addition to the usual Reissner-Nordstrom solutions this theory also admits BH solutions with scalar hair. Another example is the Einstein-Maxwell-dilaton theory in four dimensions, which arises from the compactification of the Einstein-Maxwell theory in five dimensions. The latter admits magnetized black holes and topological solitons known as topological stars. We investigated the stability of these solutions by studying both spherical and non-spherical perturbations. We computed the quasinormal modes (QNMs) spectrum both in the frequency and time domain, finding significant agreement between the two methods.

**TEONGRAV Session 2 / 95**

## Could Population III binary stars be the progenitors of massive stellar black hole binaries?

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Massive stellar black hole binaries (MBHBs) descendent from population III (Pop. III) binary stars are dark sirens that could play an extremely important role in improving our understanding of the high-redshift Universe. The coalescences of these binaries will be detected by the next generation of ground-based gravitational-wave (GW) detectors; however it is possible that some of the MBHBs observed by LIGO-VIRGO interferometers
may have had metal-free or metal-poor stellar progenitors. The statistics of these MBHBs have become not negligible and we believe that their number will increase with the arrival of the O4 run data. For this reason, the right time has come to carry out studies on BH populations and figure out which are their formation channels.
In order to predict the birth and merger rate of MBHBs originated by Pop. III binary stars in a Local Group-like volume, we couple the semi-numeric galaxy evolution simulation GAMESH (Graziani et al. MNRAS, 2015,17) and the binary population synthesis (BPS) codes (Spera et al. MNRAS, 2019; Tanikawa et al. ApJ, 2021b). We adopt a self-consistent galaxy formation model, which includes a full radiative feedback treatment, to provide
accurate predictions on the physical properties of the native and coalescence environments of MBHBs across the entire cosmic evolution of the Milky Way-like halo up to redshift z=0. Furthermore, we investigate the role of the stellar initial mass function, which is still unknown for the first stars without metals, to understand how our predictions depend on its uncertainties.
Taking into account the BHs from Pop. III binary stars, we obtain a completely different stellar BH mass distribution with respect to the models that consider only Pop. II stars. We find many coalescences of MBHBs that had Pop. III stars as stellar progenitors within the LIGO-VIRGO-KAGRA observation window. This confirms the possibility of detecting a similar event with the current interferometers and it does not exclude that these coalescences are already hidden among the current detections. Indeed, our analysis reveals that many MBHBs from metal-free stars have the masses of the primary and secondary BHs and the coalescence redshift within the error bars of the O3 candidates.
Finally, we have studied the birth and merger sites of the MBHBs predicted by our galaxy formation model. From our work, it seems that almost all the currently detected MBHBs could have formed at high redshift in extremely metal-poor ($Z < 10^{-2} Z_{\odot}$) halos, namely inside mini-halos belonging to the Local Group. Nevertheless, two MBHBs of the LIGO-VIRGO catalogs (GW190426 and GW190521) are too massive to have been originated by Pop. III binary stars. This means that they could have been born by a different formation
pathway, such as a hierarchical BH merger scenario. To conclude, we show the differences in the birth and merger rate density of MBHBs when we assume different IMFs for Pop. III stars.

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# Modeling and observational status of black hole vibrational spectra

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Dark compact objects are nowadays routinely observed through multiple experimental schemes. Measurements of their vibrational spectra offer unprecedented opportunities to investigate the highly dynamical regime of General Relativity, search for signs of new physics, and increase the evidence for their "black hole nature". After an introduction to the topic, I will review recent achievements of this scientific program enabled by gravitational-wave observations, and current efforts to extend it through the inclusion of nonlinear effects and generic orbital configurations of binary mergers. Prospects for high-precision measurements through next-generation interferometric detectors will also be discussed, together with their potential to address many open questions in fundamental physics.

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## Waveform modelling for extreme and intermediate mass-ratio inspirals using a multi-scale self-force approach

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The calculation of gravitational wave templates for binaries with disparate masses can be achieved using a (small mass ratio) perturbative expansion. This "self-force"approach was recently pushed to second-order (in the mass ratio) which has enabled the modelling of a wide class of binaries with mass ratios ranging ~10^5:1 to ~30:1. Furthermore, by employing a multi-scale expansion the associated gravitational waveforms can be directly computed on sub-second timescales without the need for any further waveform acceleration. In this talk I will review the multi-scale self-force approach and outline the ongoing program to extend current calculations to cover the full precessing and eccentric parameter space

**Special Session in memory of Stefania Marassi / 101**

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**Contributed Talks / 104**

## Tidal deformability of black holes surrounded by thin accretion disks

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The tidal Love numbers of self-gravitating compact objects describe their response to external tidal perturbations, such as those from a companion in a binary system, offering valuable insights into their internal structure. For static tidal fields, asymptotically flat black holes in vacuum exhibit vanishing Love numbers in general relativity, even though this property is sensitive to the presence of an external environment. In this work we study the tidal deformability of black holes surrounded by thin accretion disks, showing that the Love numbers could be large enough to mask any effect of modified gravity and to intrinsically limit tidal tests of black-hole mimickers. Furthermore, we investigate the measurability of the tidal parameters with next-generation gravitational wave experiments, like LISA and Einstein Telescope. Our findings suggest that these parameters could be

measured with high precision, providing a powerful tool to probe the environment around coalescing binary systems.