# GraSP23 || GravityShapePisa 2023

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Università di Pisa - Dipartimento di Fisica

# Book of Abstracts

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**Poster Session / 4**

## Reconstructing star formation rate for compact binary populations with Einstein telescope

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Einstein Telescope (ET) is a proposed third generation, wide-band gravitational wave (GW) detector. Given its improved detection sensitivity in comparison to the second generation detectors, it will be capable of exploring the universe with GWs up to very high redshifts. In this work we present the algorithm to answer three main questions regarding the star formation rate density (SFR) (i) when did the formation terminate?, (ii) at what redshift does the SFR peak?, and finally (iii) what is the functional form of SFR at high redshift? for a given population. We infer the functional form of SFR for different populations of compact binaries originating in stars from Population (Pop) I+II and Pop III, using ET as a single instrument. We conclude that the reconstruction of SFR is essentially independent of the time delay distributions up to z~14 and the accuracy of the reconstruction strongly depends on the time delay distribution only at high redshifts of z⊠14. In this analysis we constrain the peak of the SFR as a function of redshift and show that ET as a single instrument can distinguish the termination redshifts of different SFRs.

**Poster Session / 5**

## Binary black hole mergers from Population III stars

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In this presentation, I will provide a comprehensive analysis of the uncertainty regarding the merger rate density and mass spectrum of binary black holes (BBHs) originating from Population III (Pop. III) stars. I will explore four distinct formation histories of Pop. III stars and investigate 11 models concerning the initial orbital properties of their binary systems.

The results I have obtained demonstrate a significant impact of uncertainties of the orbital properties on the BBH merger rate density, potentially varying up to two orders of magnitude. Specifically, models with shorter initial orbital periods tend to lead to higher merger rates. Additionally, the uncertainty in the star formation history significantly influences both the shape and normalisation of the BBH merger rate density. Depending on the assumed star formation rate, the peak of the merger rate density can shift from $z \sim 8$ to $z \sim 16$. Moreover, the maximum BBH merger rate density for our fiducial model ranges from $\sim 2$ to $\sim 30$ Gpc$^{-3}$ yr$^{-1}$.

I find that the typical BBH masses are not affected by the star formation rate model and only mildly influenced by the binary population parameters. Pop. III primary black holes are generally more massive, ranging from 30 to 40 $M_\odot$, compared to those formed from metal-rich stars (8 - 10 $M_\odot$).

Finally, I estimate that the Einstein Telescope will detect 10 – $10^4$ Pop. III BBH mergers per year, depending on the star formation history and binary star properties.

**Poster Session / 7**

## Fermion soliton stars

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Fermion soliton stars are a motivated model of exotic compact objects in which a nonlinear self-interacting real scalar field couples to a fermion via a Yukawa term, giving rise to an effective fermion mass that depends on the fluid properties. For the first time, we study this model within General Relativity without approximations, finding static and spherically symmetric solutions. If the scalar potential features asymmetric vacua, the mass and radius of a fermion soliton star are comparable to those of a neutron star for natural model parameters at the GeV scale. Moreover, the asymmetric scalar potential inside the star can provide either a positive or a negative effective cosmological constant in the interior, being thus reminiscent of gravastars or anti-de Sitter bubbles, respectively. Finally, we explore embedding in particle-physics contents, showing that if the fermion is strongly coupled to the scalar field, non-perturbative bound states describing false vacuum pockets are found. Possible connections with dark matter and cosmology are also briefly discussed.

**Poster Session / 8**

## Targeted search for continuous gravitational waves from pulsars in binary systems in O3: a semi-coherent approach

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The detection of continuous gravitational wave emission from a neutron star in a binary system is challenging for present and future LIGO-VIRGO-KAGRA searches. The motivation is the accurate modelling of the phase that depends on the binary orbital parameters. Indeed, even when the parameters are known within some uncertainties, search strategies are usually computationally prohibitive due to the necessity of exploring a large parameter space.
In this poster, I will present a new semi-coherent method that, given an ephemeris with uncertainties on binary orbital parameters, can detect the GW signal efficiently in a feasible computational time.

**Poster Session / 9**

## Gravity and the Superposition Quantum Principle

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The relation between gravity and quantum mechanics is investigated in this work. The link is given by the wave packet expansion process, rooted from the Uncertainty Principle.

The wave packet spreading is studying in spherical coordinates, whose width $\sigma(t)$ is expressed in terms of $G$ and $c$, instead of $\hbar$. Therefore, for masses larger than the Planck mass, a faster dispersion rate of $\sigma(t)$ is obtained, compared to the standard case. The dispersion of the wave packet is observed only by a free falling observer and the process stops once the observer hits the surface of the object. Different observers notice different rates of expansion of the wave packet and the source of gravity is in a quantum superposition.

**Poster Session / 11**

# Two forms of dark energy in Fractal cosmological model using Specific Hubble parameter

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The main objective of this article is to study the fractal FRW cosmological model consisting two forms of dark energy. We studied behavior of the universe in a fractal framework using dark energy accommodated in our universe. The solution of field equations are obtained by using Hubble parameter for transit scale factor $H(z) = \epsilon\left(a^{-\delta} + \lambda\right)$
. We have obtained the best fitting values of the model parameters $\epsilon, \delta$ and $\lambda$ by constraining our model with latest Hubble data sets consisting 57 data points. Finally we perform statefinder diagnosis and observe that obtained model close to standard $\Lambda$CDM model.

**Exotic Compact Objects / 14**

# Tests of the nature of black holes with gravitational waves

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Gravitational waves open the possibility to investigate the nature of compact objects and probe the existence of horizons in black holes. This is of particular interest given some quantum-gravity models which predict the presence of horizonless and singularity-free compact objects. Such exotic compact objects can emit a different gravitational-wave signal relative to the black hole case. In this talk, I derive the characteristic oscillation frequencies of horizonless compact objects in the ringdown. Finally, I describe how parametrised tests on general relativity can allow for tests of the black hole paradigm.

**Poster Session / 15**

# The LANCELOT project: Cosmological simulations for Large Scale Structure in the modified theories of gravitation with massive neutrinos

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We present LANCELOT: LibrAry for N-body large sCale structurE simuLations in mOdified Theories of gravitation. This library not only incorporates various modified cosmologies but additionally includes massive neutrinos. For modified theories of gravitation, in the current work, we consider three cases: modified teleparallel gravitation $f(T) = T + \alpha(1 - e^{-p\frac{T}{T_0}})$, it's non-minimal matter-torsion coupled extension with $f_1(T) = T$ and $f_2(T) = 1 + \lambda(T/T_0)^b$, Palatini-$f(R)$ gravitation with $f(R) = R - 2\Lambda\left(1 - e^{-R/b\Lambda}\right)$ respectively. For each modified theory of gravity, we obtain the cosmological constraints using various observables. Besides, in order to probe the validity of the aforementioned theories of our consideration, we derive various cosmological parameters, such as deceleration parameter $q(z)$, effective Equation of State (EoS) $\omega_{\text{eff}}$, effective gravitational constant $G_{\text{eff}}$, age of the universe and linear growth function $f\sigma_8$. As well, we analyze the tension between various free parameters. Furthermore, we modify the N-body simulations suite SWIFT to include non-standard $H(z)$ and $G_{\text{eff}}$, run the simulations with $N^{1/3} = 1024$ resolution respectively for each of the 6 models that we consider with both $L_{\text{box}} = 100h^{-1}$Mpc and $L_{\text{box}} = 1h^{-1}$Gpc. Smaller $L_{\text{box}}$ is used to probe the evolution of separate Dark Matter (DM) halos, to construct the Halo Mass Function (HMF) and void abundance profiles, void size function. The latter simulations with huge box size are designed in order to construct the full-sky maps of ISW linear effect and simulate the neutral hydrogen distribution within DM halos.

**Neutron Stars: Matter at the Extremes / 16**

## The neutron star matter Equation of State: a challenge for nuclear physics theory

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I will review the recent developments in the construction of the Equation of State of hot and dense matter and its application to neutron stars observations, which have become recently a fundamental tool to constrain the properties of nuclear matter. I will discuss the main open questions in the nuclear many-body theory and its future perspectives.

**Gravity in the weak field / 19**

## Gravitoelectromagnetic analogies: theory and experimental perspectives

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In this talk we briefly review the gravitoelectromagnetic analogies that arise in General Relativity: they are powerful tools to explain peculiar general relativistic effects in terns of known results of classical electromagnetism. In particular, we focus on the perspective of measuring these effects on the Earth and in the Solar System, with emphasis on the detection of the magnetic-like component of the field of gravitational waves.

**Neutron Stars to test Cosmology scenarios** / **22**

## Infinite-duration Continuous Gravitational Waves from neutron stars in binary systems

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The gravitational-wave astronomy field has been resolutely founded seven years ago, thanks to the first direct
detection of transient gravitational waves from the collision of two black holes.
The first detection of continuous gravitational waves from fastly rotating neutron stars, either isolated or in binary systems, has yet to be done, and it may be around the corner, representing a further revolutionary big discovery.
The search for this kind of signals, which is among the most interesting targets of the Advanced LIGO-Virgo-KAGRA detectors is challenging due to their expected weakness, and can be very computationally expensive especially when the source parameters are not well constrained, and especially for sources in binary systems.
In this talk I will present the methodologies used in CW searches from neutron stars in binary systems, and recent results from the latest advanced LIGO-Virgo-KAGRA observational runs.

**Black Holes Astrophysics** / **23**

## The effects of orbital precession on hyperbolic encounters

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The hyperbolic encounters of two massive objects are characterized by the emission of a gravitational wave burst, with most of the energy released during the closest approach (near the periastron). The detection of such events, different from the well-known inspiral emission, would be an interesting discovery and provide complementary information to observations of binary mergers of black holes and neutron stars in the observable Universe, shedding light, for instance, on the clustering properties of black holes and providing valuable hints on their formation scenario. Here, we analyse the dynamics of such phenomena in the simplest case where two compact objects follow unbound/hyperbolic orbits. Moreover, we explore the effects of orbital precession on the gravitational wave emission, since the precession encodes certain general relativistic effects between two bodies. We also provide templates for the strain of gravitational waves and the power spectrum for the emission, and analytical expressions for the memory effect associated with such signals.
(Based on arXiv:2307.00915)

**Poster Session / 24**

## Binary neutron star mergers in massive scalar-tensor theory: an adiabatic look

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In massive scalar-tenor theories, a Compton length-scale will be introduced by the scalar mass. In the context of binary systems, the influences of such length-scale include the suppressions in the scalar interaction between the two members when the orbital separation well exceeds the scale, and in the emissivity of scalar radiation with wavelength longer than that. We focus here on coalescing binary neutron stars, where we investigate the scalar effect on the late-inspiral dynamics. It has been found that the scalar activity becomes dynamically important only when the orbital separation shrinks within a few times of the Compton length-scale. Therefore, certain constraints may be placed on the theory by scrutinising the late-inspiral waveforms. Here we adopt quasi-equilibrium states to approximate the leading order evolution of binaries, whereby we find that a lower bound on the scalar mass of $m_\phi$
$gtrsim 10^{-11}$ eV is suggested by the event GW170817 if the progenitors were spontaneously scalarized.

**Poster Session / 25**

## Non-Gaussianity from the Cross-correlation of the Astrophysical Gravitational Wave Background and the Cosmic Microwave Background

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Since the first LIGO/Virgo detection, Gravitational Waves (GWs) have been very promising as a new complementary probe to understand our Universe. One of the next challenges of GW search is the detection and characterization of the stochastic gravitational wave background (SGWB), that is expected to open a window on the very early Universe (cosmological background) and to provide us new information on astrophysical source populations (astrophysical background). In this talk, I will focus on the anisotropic contribution of such a signal, imprinted both at the production and in the propagation towards the Earth, accounting for the properties of the astrophysical sources. Specifically, I will present the cross-correlation between these anisotropies and the Cosmic Microwave Background (CMB) ones. Furthermore, I will talk about the possibility to measure non-Gaussianity (nG)
accounting for large-scale corrections to the bias and the capability of next generation space-based interferometers to detect such a cross-correlation signal.

**Neutron Stars: Matter at the Extremes / 26**

## Pions, hyperons and quark matter in neutron star mergers

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We discuss recent calculations investigating the detailed impact of various “non-nucleonic” degrees of freedom in neutron star mergers. Pions are neglected in equation of state tables for merger simulations but might actually occur in neutron star matter. We quantify their potential impact on the obseravbles of neutron star mergers. We describe a weak but potentially measurable signature of hyperons on neutron star mergers. Finally, we discuss the effects of deconfined quark matter.

**Black Holes Astrophysics / 28**

# The massive black hole binary path to coalescence

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Massive black hole binaries (MBHBs) are expected to form at the centre of merging galaxies during the hierarchical assembly of the cosmic structure and are expected to be the loudest sources of gravitational waves (GWs) in the low frequency domain surveyed by the ongoing Pulsar Timing Array (PTA) campaigns and by the forthcoming LISA observatory.
A meaningful assessment of the detection prospects of the above experiments critically depends on the abundance and properties of MBHBs that form and evolve during the cosmic history. Therefore, understanding the MBH dynamical evolution before and after these binaries form is of paramount importance.
In this talk I will review the current understanding of MBHB evolution by analysing the several dynamical processes driving MBHBs at different scales and highlighting possible evolutionary bottlenecks that may arise along their path to coalescence.

**Poster Session / 29**

# On the fate of the light ring instability

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There is a scientific consensus about the reality of black holes (BHs) as key ingredients of the physical Universe. Yet, both the inability to observationally proof the “BH hypothesis”and its challenging and far-reaching theoretical consequences, demand a thorough scrutiny of its alternatives. In this spirit, a variety of horizonless exotic compact objects (ECOs) have been proposed: the “ECO hypothesis”. Any putative ECO model must overcome theoretical and observational tests to become a contender, either replacing or co-existing, with black holes.

In this talk I will address a key challenge for horizonless BH imitators, discussing how the very same property that seems to be required to make them effective BH foils - the existence of bound photon orbits, or light rings - can source their own demise.

**Poster Session / 30**

## Low-latency searches for strongly lensed gravitational wave signals in the third observing run of LIGO-Virgo detectors

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Gravitational waves (GWs) from stellar-mass compact binary coalescences (CBCs) are expected to be strongly lensed when encountering large agglomerations of matter, such as galaxies or clusters. Searches for strongly lensed GWs have been conducted using data from the first three observing runs of the LIGO-Virgo GW detector network. Although no confirmed detections have been reported, interesting candidate lensed pairs have been identified. In this talk, I will describe the low-latency methods used to rapidly identify potential lensing candidates of both detectable (super-threshold) CBC pairs and pairs involving counterparts from targeted sub-threshold searches to confidently detect super-threshold CBC events. I will also summarize the results, follow-up strategies and challenges for the identification of strong lensing. The most significant candidate "super-sub" pair deemed by this analysis was subsequently found, by more sophisticated and detailed joint-PE analyses, to be among the more significant candidate pairs, but not sufficiently significant to suggest the observation of a lensed event.

**Science with Einstein Telescope / 31**

## Fundamental Physics and Cosmology with the Einstein Telescope

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The observation of gravitational waves by the LIGO/Virgo collaboration has opened a new window on the Universe. In this decade, however, these experiments will reach the limit of their capabilities, and a new generation of ground-based detectors is being planned. In Europe, this has led to the proposal of the Einstein Telescope. With order of magnitude improvement in the sensitivity, Einstein Telescope will explore the depth of the Universe using gravitational waves, and has the potential of triggering revolutions in astrophysics, cosmology and fundamental physics. We will give a broad overview of its capabilities and scientific targets.

**Science with Einstein Telescope / 32**

## Einstein Telescope and the future generation of Gravitational Wave observatories.

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Gravitational waves (GWs) are the newest tool for exploring the Universe. Advanced Virgo and Advanced LIGO have opened a new window on the Universe, detecting GW signals in the Hz-kHz

frequency range. The Pulsar Timing Array experiments have just announced the detection of GWs in the nano-Hz frequency range.
A new generation of GW interferometric observatories is under preparation and will take over from the current generation of GW detectors in the next decade. This will make it possible to probe almost the entire Universe for GW signals. The Einstein Telescope (ET) and the Cosmic Explorer (CE) are at the forefront of the design, preparation and realisation of a next-generation gravitational wave observatory in Europe and the USA respectively. The space-based GW detector LISA will be launched in the next decade and will complete the new series of GW observatories.
With a special focus on the Einstein Telescope observatory, an overview of the scientific objectives, the observatory design, the required technologies and the project organisation will be presented.

**Poster Session / 33**

## On the Testability of the Quark-Hadron Transition Using Gravitational Waves From Merging Binary Neutron Stars

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Elementary particles such as quarks and gluons are expected to be fundamental degrees of freedom at ultra high temperatures or densities, while natural phenomena in our daily lives are described in terms of hadronic degrees of freedom. Massive neutron stars and remnants of binary neutron star mergers may contain quark matter, but it is not known how the transition from hadron matter to quark matter occurs. Different transition scenarios predict different gravitational waveforms emitted from binary neutron star mergers. If the difference between the equations of state only occurs at sufficiently high density, it is expected that the difference between waveforms mainly appears in the merger or the post-merger phase rather than in the inspiral phase. The typical frequency of gravitational waves after the coalescence is higher than 2 kHz, which is difficult to observe using current detectors. In this work, we performed Bayesian model selection for two scenarios proposed as representatives in Fujimoto *et al.* (2023) and investigated whether observations with future detectors will allow us to identify the correct model. We assume that the relatively low density equation of state around the nuclear saturation density is completely known from accumulated observations. Under this assumption, we find that it is reasonable to expect to be able to identify the correct transition scenario with third-generation detectors or specialized detectors with high sensitivity at high frequencies designed for post-merger signal observation, *e.g.*, NEMO (Ackley *et al.* 2020).

**Machine Learning for Gravitational Waves / 34**

## Binary black holes at the dawn of the Universe

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The next generation gravitational-wave detectors will probe binary black hole mergers at redshift higher than 10, when the Universe was in its infancy. Is the mass function of black holes in the high-redshift Universe the same as we observed with LIGO and Virgo? In my talk, I will present the result of new simulations of binary black holes born from metal-poor and metal-free stellar progenitors.

I will show that such binary black holes tend to be top-heavy: their primary masses pile up at ~35 Msun and under-populate the low-mass region of the mass function when compared to black holes born from metal-rich stars. I will discuss the main uncertainties, and their implications for our knowledge of the very first stars. Finally, I will show that the merger rate density of binary black holes encodes crucial information to explain the formation of such extreme systems as a function of redshift.

**Poster Session / 35**

## Bounds on Ultralight Dark Matter from NANOGrav

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The detection of the stochastic gravitational wave background by NANOGrav imposes constraints on the mass of compact cores of ultra-light dark matter, also known as "solitons", surrounding supermassive black holes found at the centers of large galaxies. The strong dynamical friction between the rotating black holes and the solitons competes with gravitational emission, resulting in a suppression of the characteristic strain in the nHz frequency range. Our findings robustly rule out ultralight dark matter particles with masses ranging from $1.3 \times 10^{-21}$eV to $1.4 \times 10^{-20}$eV condensing into solitons around supermassive black holes.

**Neutron Stars in Gravitational Wave Physics / 36**

## A Gravitational-Wave Perspective on Neutron Star Seismology

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Neutron star seismology, which aims to probe the extreme physics associated with these objects, is of increasing relevance for gravitational-wave astronomy. Focussing on the fundamental mode of oscillation, which is an efficient gravitational-wave emitter, I will the outline the seismology aspects of a number of astrophysically relevant scenarios; ranging from the star's birth in a core collapse through to transients (like pulsar glitches and magnetar flares), the dynamics of tides in inspiralling neutron-star binaries, the oscillations of the final merged object and instabilities that may be acting in the remnant (or, indeed, isolated rapidly rotating, neutron stars). The main aim is to introduce the key ideas and highlight issues that need further attention if we want to realize the potential of the next generation of gravitational-wave instruments.

**Machine Learning for Gravitational Waves / 37**

## Neural network time-series classifiers for gravitational-wave searches in single-detector periods

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The search for gravitational wave signals in the data collected by the current ground-based interferometers is a complex problem, especially when only one detector operates. Modern deep learning approaches could contribute to find a solution. I'll discuss the detection problem and present the work detailed in arXiv:2307.09268 where we investigate the performance of neural network classifiers based on three types of architectures: convolutional neural network, temporal convolutional network, and inception time. The last two architectures are specifically designed to process time-series data. We apply the trained classifiers to LIGO data from the O1 science run, focusing specifically on single-detector times. We find a promising candidate on 2016-01-04 12:24:17 UTC compatible with a black hole merger with masses 50 M☒ and 24 M☒.

**Poster Session / 38**

## A resampling search method for sub-solar mass binary inspirals

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Primordial black holes are proposed to have formed in the very early universe and a first detection of them would provide valuable insights into cosmology, dark matter, and physics of the very early universe. Primordial black holes could form binaries systems with chirp masses of the order of $\mathcal{O}(10^{-5})M_\odot - \mathcal{O}(10^{-3})M_\odot$, which would emit long transient gravitational waves signals that last of the orders of hours - years. We present an implementation of a resampling algorithm to search for such signals in gravitational wave data. An estimate for the distance sensitivity of the technique suggests that the Galactic Centre can be probed for large portions of the parameter space studied. We also present preliminary results about efficiently construct a search grid and the expected computational cost of a directed search towards the Galactic Centre.

**Quasi Normal Modes for Kerr Black Holes / 39**

## Black hole spectroscopy beyond Kerr

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Black-hole spectroscopy is one of the most promising tools to test gravity in extreme regimes and to probe the nature of black holes. However, tests based on ringdown observations are currently limited by the lack of parametrization that are both robust and accurate, able to capture generic modifications of the Kerr spectrum. In this talk I will present a new observable-based parametrization of the ringdown of spinning black holes beyond general relativity, ParSpec, and its application to future detections by 3G interferometers. I will discuss projected measurements on the ringdown parameters, and how to map such agnostic constraints on bounds on the fundamental couplings of modified theories of gravity. Finally I will exploit ParSpec to discuss generic limitations of ringdown tests.

**Neutron Stars to test Cosmology scenarios / 41**

# Non-local Gravity Cosmology

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Recently the so-called Non-Local Gravity acquired a lot of interest as an effective field theory towards the full Quantum Gravity. In this talk, we sketch its main features, discussing, in particular, possible infrared effects at astrophysical and cosmological scales. In particular, we focus on general non-local actions, including curvature or torsion invariants. In all cases, characteristic lengths emerge at cosmological and astrophysical scales. Furthermore, it is possible to fix the form of the Lagrangian and to study the cosmological evolution considering the existence of Noether symmetries. We discuss also possible astrophysical and cosmological applications for non-local gravity models considering late time cosmic expansion, the structure of galaxy clusters, the S2 orbit around the Galactic Center, the possibility of further modes in gravitational waves. As a final comment it is worth saying that non-locality can be tested in various infrared regimes bringing together physics of short and large scales. Clearly, the possibility to find further gravitational wave modes could be an important test bed for the theory.

**Exotic Compact Objects / 42**

# Searching for continuous gravitational waves: the remainder of the zoo

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While the prototypical source of continuous gravitational waves is represented by asymmetric spinning neutron stars, there are several other mechanisms which are expected to cause the emission of long-lasting semi-periodic signals which, if detected, would provide a wealth of information about several aspects of fundamental physics, astrophysics and cosmology.
They include newborn magnetars, ultra-light dark matter and sub-solar mass primordial black holes, object of a very intense research activity in the gravitational wave community.
In this talk I will briefly review these sources, discussing their emission processes, the main data analysis techniques used for their search, recent upper limits obtained by the LIGO-Virgo-Kagra Collaboration and future prospects.

**Gravity in the weak field / 43**

# Advancements in geodetic observations with large ring laser gyroscopes

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A multitude of different globally distributed and independent mass transport phenomena lead to non-predictacle fluctuations in the Earth's rotation rate $\Omega_e$. Large Sagnac interferometers in the form of ring lasers enable the instantaneous observation of variations in $\Omega_e$ at a level of a few ppb. Here, the benefit of this technique, as well as recent advancements and future possibilities are discussed.

**Poster Session / 44**

## Characterization of accretion discs from binary neutron star mergers

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Accretion discs formed in binary neutron star (BNS) mergers are the engine responsible for many relevant physical processes. Numerical simulations of accretion discs have been used to investigate the outcome of such processes, but the initial configuration of the disc lack of an unique analytical description and some assumptions are still needed. In this work we analyze in detail the properties of accretion discs from 44 BNS merger simulations, with the aim of furnishing reliable initial conditions and a comprehensive characterization of the accretion discs. We found that the discs are thick, with an aspect ratio decreasing with the mass ratio of the binary from ~ 0.7 to 0.3. Despite the disc sample spans a broad range in mass and angular momentum, their ratio is independent on the equation of state (EOS) and on the mass ratio of the binary. We have found that this can be traced back to the rotational profile of the disc, characterized by a constant specific angular momentum of 3 − 5 × 10<sup>16</sup> cm<sup>2</sup> s<sup>−1</sup>. The entropy per baryon and the electron fraction depend on the mass ratio of the binary. For small mass ratio they follow a sigmoidal distribution with the density, for which we provide a detailed description and a fit. The disc properties discussed in this work can be used as a robust set of initial conditions for future long-term simulations of accretion discs from BNS mergers, posing the basis for a progress in the quantitative study of the outflow properties.

**Black Holes to probe General Relativity / 45**

## Probing scalar fields with Extreme Mass Ratio Inspirals and LISA

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Extreme Mass Ratio Inspirals (EMRIs), binary systems with a secondary stellar mass compact object inspiralling into a massive black hole, are among the main targets for LISA, as they harbour the potential for precise strong gravity tests. Although the description of these systems in modified theories of gravity can be drastically complex, for a vast class of theories with additional scalar fields great simplifications occur. At leading order in the binary mass ratio, the primary scalar charge is suppressed, so that the background spacetime is simply described by the Kerr metric. Moreover, the imprint of the scalar field on the waveform is fully captured by the scalar charge carried by the secondary and by the mass of the scalar field. In this talk I will show how, using these simplifications,

the secondary's scalar charge and the scalar field mass affect the EMRI's orbital evolution, and how such changes get imprinted on the emitted waveforms. By analysing such signals, I will finally present the results on the LISA's detectability of the scalar charge and mass, which render EMRIs encouraging probes of new fundamental fields.

**Quasi Normal Modes for Kerr Black Holes / 46**

## Explaining nonlinearities in black hole ringdowns from symmetries

**Author:** Antonio Riotto[1]

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It has been recently pointed out that nonlinear effects are necessary to model the ringdown stage of the gravitational waveform produced by the merger of two black holes giving rise to a remnant Kerr black hole. We show that this nonlinear behavior is explained, both on the qualitative and quantitative level, by near-horizon symmetries of the Kerr black hole within the Kerr/CFT correspondence.

**Black Holes to probe General Relativity / 47**

## Black holes in effective field theories –dynamics and new observational signatures

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Black holes in effective field theories, such as scalar-Gauss-Bonnet and dynamical Chern-Simons gravity, offer interesting alternatives to the Kerr solution that can be tested observationally. Interestingly, the deviations from GR can be not only quantitative but strong quantitative differences can also appear. This includes the appearance of jumps between stable branches of solutions, violation of the equatorial symmetry, etc. In the present talk, we will discuss some of the most interesting examples of such beyond-Kerr black holes. Special attention will be paid to their nonlinear dynamics and the potential problems such as loss of hyperbolicity.

**Machine Learning for Gravitational Waves / 48**

## Gravitational Wave Searches, Public Alerts, and Event Validation in the Fourth Observing Run of LIGO, Virgo and KAGRA

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The first three observational campaigns of the Advanced LIGO and Advanced Virgo gravitational-wave (GW) detectors have culminated in the confident identification of 90 signals arising from the mergers of compact binary systems composed of black holes and neutron stars. These events have

offered a new testing ground for General Relativity and better insights into the nuclear equation of state for neutron stars, as well as the discovery of a new population of black holes.
In the ongoing fourth joint observing run by the LIGO, Virgo, and KAGRA collaborations (collectively referred to as LVK), substantial improvements have been implemented to enhance the detectors' sensitivity. These enhancements are poised to significantly boost the rate of detections, promising new discoveries and more profound insights into the aforementioned domains. To support these goals, substantial progress has been made in fortifying the low-latency infrastructure to foster multimessenger searches. The operations of rapid response to GW candidate alerts and event validation procedures as been refined as well to strengthen the confidence in the detected signals.
This presentation offers an overview of the upgrades made to the detectors from O3 to O4 and the expected increase in event detection rates. Furthermore, it delves into the key aspects of GW transient searches, encompassing the dissemination of public alerts and the meticulous validation of candidate events, including the noise artifact mitigation before parameter estimation analyses, and the inclusion of the events in discovery papers or catalogs.

**Neutron Stars in Gravitational Wave Physics / 49**

# Testing strong-field gravity with multimessenger observations of neutron stars

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Neutron stars are some of the most extreme objects in Nature. Their typical masses (around 1.4 times that of the Sun) combined with their small radii (about 12 km) result in densities exceeding the nuclear saturation density, above which exotic states of matter can form. Moreover, neutron stars are among the strongest gravitational field sources known, second only to black holes. These properties make neutron stars exceptional laboratories to study matter and gravity in extreme situations, out of reach of terrestrial and Solar System experiments. I will discuss how neutron star observations, both with the x-ray Neutron Star Interior Composition Explorer (NICER) mission and with gravitational-wave observatories (LIGO-Virgo-Kagra), offer us new avenues to test general relativity and constrain modifications thereof.

**Neutron Stars in Gravitational Wave Physics / 50**

# 20 years of testing GR with the Double Pulsar

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Pulsars are extremely stable natural clocks and, when found in a relativistic binary system, they can be used as exceptional laboratories to test Relativistic gravity in the strong field regime. In this talk I will present the results obtained in this context by studying the now 20-year-long dataset on the double pulsar system J0737-3039A/B, the only binary hosting two active radio pulsars, and one of the most relativistic systems known to date. The double pulsar laboratory has indeed allowed us to confirm the validity of GR at least at 99.99% and to measure several relativistic effects for the first time.

**Quasi Normal Modes for Kerr Black Holes / 51**

## Non-linear Black Hole Ringdowns: an Analytical Approach

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Due to the nature of gravity, non-linear effects are left imprinted in the quasi-normal modes generated in the ringdown phase of the merger of two black holes. We offer an analytical treatment of the quasi-normal modes at second-order in black hole perturbation theory which takes advantage from the fact that the non-linear sources are peaked around the light ring. As a byproduct, we describe why the amplitude of the second-order mode relative to the square of the first-order amplitude depends only weakly on the initial condition of the problem.

**Exotic Compact Objects / 52**

## Searching for evidences of Exotic Compact Objects from the spin distribution of compact binary coalescences

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Black holes (BHs) are among the most fascinating objects in the Universe. However, their description presents several theoretical difficulties such as the presence of a horizon at radius $r_+$. A class of horizonless objects, known as exotic compact objects (ECOs), have been formulated, in order to remove these difficulties. ECO's models generally predict the presence of a physical surface at a radius $r = r_+(1 + \epsilon)$, where $\epsilon$ quantifies the scale at which General Relativity should be corrected. A quantum scale would correspond to $\epsilon < 10^{-30}$.
Differently from BHs, ECOs are subject to *ergoregion instability*, i.e. a process that prevents the formation of ECOs spinning above a certain critical limit $\chi_{\rm crit}$ that depends on the compactness of the object and its reflectivity. As a result, the spin distribution of a population of ECOs will display local overdensities in correspondence of $\chi_{\rm crit}$.
Gravitational waves (GWs) from Compact Binary Coalescences (CBCs) offer a powerful tool probe for the existence of ECOs. By studying the spin distribution of CBCs, it is possible to probe the existence of ECOs.
In this talk, we propose to study the spin distribution of 90 CBCs with a population model that includes the possible presence of ECOs. When assuming that the population of CBCs is entirely composed by ECOs, we are able to set a lower limit on $\epsilon \geq 10^{-5}$ thus excluding the possibility of a population of ultra-compact objects ($\epsilon < 10^{-30}$). Instead, if we assume a population of mixed BHs and ECOs, we obtain that no more than 60 % of the CBCs observed can be composed of ultra-compact objects.

**Poster Session / 54**

## Tidal disruption of self-interacting axion clouds around black holes in binary systems

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Black hole superradiance induces the formation of a cloud of ultralight bosons, such as axions. To detect the signature of the cloud, it is important to consider black holes in binary systems. As a binary inspirals and the separation becomes sufficiently small, the cloud is disrupted by the tidal interaction from the companion. Although axions generally have self-interactions, this effect has so far been ignored in this context. Taking into account the self-interaction, it is shown that the growth of the cloud saturates due to the dissipation and the lifetime becomes longer. Therefore, we investigate the evolution of the cloud in a binary system with self-interaction and present the formulation to solve it. We show the boundary of the orbital frequency where the cloud is disrupted and mention the possibility of bosenova collapse of the cloud.

**Gravitational Waves from Scattering Amplitudes / 55**

## Gravitational Waves Observables From Scattering Amplitudes

**Author:** Giacomo Brunello[1]

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The extraordinary detection of gravitational waves (GWs) emitted by binary coalescing systems gave us a new instrument to probe our Universe and to test General Relativity (GR). The increasing precision of current and future GWs interferometers requires very accurate predictions of GWs observables. Scattering amplitudes techniques, which for decades have been developed for collider experiments, are now being used to study classical two body problems in GR. I will show how GWs observables can be expressed in terms of scattering amplitudes within the KMOC approach and will highlight how they can efficiently be computed within a heavy mass framework (HEFT).

**Poster Session / 57**

## Gravitational Wave Signals from Binary-Single Black Hole Encounters in Star Clusters

**Author:** Elena Codazzo[1]

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Star clusters are the dynamical formation channel for binary black holes (BBHs). In these dense systems, BBH mergers are not only driven by gravitational wave (GW) emission but also by binary-single encounters with other objects in the environment. The focus of the talk will be on the GW signals generated by close encounters between a BBH and a third black hole. We characterized diverse GW signatures, that are produced through numerical simulations using stellar mass black holes as input masses. The talk will also consider the potential for these burst signals to fall within the sensitivity band of current and future ground-based detectors, depending on the parameters involved.

**Science with Einstein Telescope / 59**

## The Einstein Telescope, the next generation detector for Gravitational Wave observation

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The detection of Gravitational Waves (GWs) opened a new window on the Universe. The combined observation of GW and electromagnetic signals from astrophysical phenomena in 2017 signed the beginning of the Multi-messenger Astronomy.
While LIGO-Virgo-KAGRA Collaborations keep on detect GWs, a new generation of GW observatories is under preparation and will take over in the next decade, allowing to probe almost the entire Universe. The Einstein Telescope (ET) is the European project for the future GW detection.
An overview of the scientific objectives, the status of detector design, its technological challenges and the expected implications to the Gravitational Wave Astronomy progress will be presented.

**Poster Session / 60**

## Measuring eccentricity in binary black hole mergers

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Measuring eccentricity from gravitational wave signals is of fundamental importance in order to address questions about the origin and formation of stellar-mass binary black holes. In this work we present a new, systematic set of spinning but non-precessing numerical relativity (NR) simulations of eccentric binary black hole coalescences, with initial eccentricities up to 0.3 and mass ratios between 1 and 4. We develop a robust pipeline for measuring the eccentricity evolution from numerical relativity waveforms that is applicable even to short-duration signals. We investigate the reliability of this procedure by quantifying its accuracy and assess how the length of the NR waveform impacts the measurement of eccentricity, especially when extrapolating to low frequencies. Using the measured values of eccentricity as initial conditions, we generate effective-one-body waveforms and quantify how the precision in the eccentricity measurement, and therefore the choice of the initial conditions, impacts the agreement with the NR data. We find that even small deviations in the initial eccentricity can lead to non-negligible differences in the phase and amplitude of the waveforms. However, we find that we can reliably match the eccentricities between NR data and analytic models, which is crucial for robustly building eccentric hybrid waveforms, and can subsequently be used to improve the accuracy of models in the strong-field regime.

**Machine Learning for Gravitational Waves / 61**

## Simulation-based inference for gravitational waves

**Author:** Stephen Green[1]

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With the fourth LIGO-Virgo-KAGRA observing run well underway, gravitational waves are now being detected roughly every three days. While this routine detection promises exciting results, it is becoming a significant challenge to analyze all events using our most sophisticated theoretical models. In this talk, I will describe how to overcome these challenges using deep learning techniques for rapid, amortized Bayesian inference. This approach uses simulated data to train neural networks (such as normalizing flows) to represent the Bayesian posterior. Once trained, sampling becomes extremely fast. I will also describe how to establish full confidence in results using importance sampling, as well as future prospects to enable improved accuracy in the face of non-stationary or non-Gaussian noise.

**Gravitational Waves from Scattering Amplitudes / 62**

## Gravitational observables from quantum scattering amplitudes

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Since the first detection of gravitational waves, the need for precise prediction of waveform templates has pushed to develop modern approaches to compute gravitational observables. One of the most promising programs is based on treating gravity as an effective field theory and extracting classical observables from quantum scattering amplitudes. The systematic approach lies on the eikonal expansion, in which the perturbative series in the Newton constant is organized in loop amplitudes computations. While most of the efforts are focused on on-shell scattering amplitudes, seems that exploiting the Kerr-Schild gauge in an off-shell approach can lead to new theoretical insights for a better understanding of gravity, as well as phenomenological applications, as the computation of the scattering angle of an external charged probe off a Kerr-Newman black hole at every order in the angular momentum.

**Poster Session / 63**

## On the Generalization of the Kruskal-Szekeres Coordinates: A Global Conformal Charting of the Reissner–Nordstrom Spacetime

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The Kruskal-Szekeres coordinates construction for the Schwarzschild spacetime could be viewed geometrically as a squeezing of the $t$-line associated with the asymptotic observer into a single point, at the event horizon $r = 2M$. Starting from this point, we extend the Kruskal charting to spacetimes with two horizons, in particular the Reissner-Nordström manifold, $\mathcal{M}_{RN}$. We develop a new method for constructing Kruskal-like coordinates and find two algebraically distinct classes charting $\mathcal{M}_{RN}$. We pedagogically illustrate the success of our method by constructing two compact, conformal, and global coordinate systems labeled $\mathcal{GK}_{\mathcal{I}}$ and $\mathcal{GK}_{\mathcal{II}}$ for each class respectively. In both coordinates, the metric differentiability can be promoted to $C^{\infty}$. The conformal metric factor can be explicitly written in terms of the original $t$ and $r$ coordinates for both charts.

**Poster Session / 64**

## Neutrons in the Low-Curvature Limit: post-Newtonian effects and more

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Ultracold neutrons are a great tool to explore the quantum nature of the gravitational interaction. From a theoretical perspective, starting from a Dirac equation in curved spacetime, one can derive the non-relativistic Schrodinger equation that governs the evolution of the neutron's wave function in the Earth's gravitational field. At the lowest order, this procedure simply reproduce a Schrodinger system affected by a Newtonian potential. However, in this talk, we argue that one should be very careful when calculating next-to-leading order corrections, since terms that at first glance seems negligible end up playing an important role at this level. Furthermore, also the differences in the nature of physical and coordinate distances show up in the corrections to the neutron energy spectrum and they must be taken into account. Finally, we observe that, even if the current Ultracold neutrons experiments' precision does not allow to probe for these perturbations yet, they could still be relevant in the future or in other ad-hoc circumstances.

**Neutron Stars in Gravitational Wave Physics / 65**

## RECENT RESULTS AND FUTURE CHALLENGES FOR ISOLATED SOURCES OF CONTINUOUS GRAVITATIONAL WAVE SEARCHES WITH A NETWORK OF TERRESTRIAL GRAVITATIONAL WAVE DETECTORS

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Following the historic discovery of the signals from coalescing black hole and neutron star (NS) binaries, a new frontier in gravitational wave (GW) research is the detection of sources emitting periodic continuous waves (CWs).
Fast rotating NSs, emit a nearly monochromatic CW signal, whose frequency is proportional to the spin frequency.

An electromagnetic (EM) counterpart of CWs is expected, but EM-silent NSs are also potential CW sources.
The detection of GWs from these sources is a high priority task for the LIGO/Virgo/KAGRA collaborations. The most recent efforts and results, together with future challenges, concentrating on the search for isolated neutron stars, will be presented in this talk.

**Gravity in the weak field / 67**

## GINGER

**Author:** Angela Dora Vittoria Di Virgilio[1]

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The Earth's rotation rate variations, certainly important for Earth science, are relevant also for fundamental physics investigation, as they contain general relativity terms, such as de Sitter and Lense Thirring, and unique data to investigate Lorentz violations. Long term continuous operation and very high sensitivity are required, the limit to be reached to study fundamental physics is 1 part in $10^9$ of the Earth rotation rate. Present large ring laser gyroscopes achieve record levels of performance in the measure of absolute angular rotation, and have already proved the required sensitivity. The GINGER project is based on an array of ring lasers, its apparatus is described in detail with special attention to its sensitivity limits.

**Poster Session / 68**

## Isomorphisms of Spin 1/2 to SU(1, 1)–Boson: 2 Universal Enveloping and Kangni-type Trans- formation.

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In this study we investigate the nexus between the Spin( 12 ) and the SU(1, 1)–quasi boson Lie structure and reveal related properties as well as some decomposition of spin particles. We show that the SU(1, 1)–quasi boson has a left invariant Haar measure and we ascertain its spherical Fourier transformation. We finally show that this spherical Fourier transformation of type delta is a Kangni-type transform the when the Planck's constant, ħ = 1.

**Machine Learning for Gravitational Waves / 69**

## Generative Adversarial Networks applications for gravitational wave analyses

**Author:** Ik Siong Heng[None]

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Generative Adversarial Networks (GANs) are a form of machine learning that pits a generator neural networks against a discriminator neural network. The goal of the generator is to produce 'copies' or 'fake version' of the training data. The discriminator's goal is to distinguish the fakes from the original training data. This adversarial training process can produce a generator that can produce very good versions of the training data which, for example, can be useful for data augmentation. Additionally, GANs have been shown to successfuly combine different training data features to produce data with combined features. In this talk, I will briefly describe the GAN architecture. I will also present an overview of the use of GANs in gravitational wave analyses with particular emphasis on the generation of burst signals using GANs.

**Neutron Stars to test Cosmology scenarios / 72**

## Gravitational wave generation in effective field theories of dark energy

**Author:** Enrico Barausse[None]

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I will review how non-linearities can allow for screening solar-system scales from non-tensorial gravitational polarizations, focusing on the case of scalar-tensor theories with derivative self-interactions (K-essence). I will then present fully relativistic simulations in these theories in 1+1 dimensions (stellar oscillations and collapse) and 3+1 dimensions (binary neutron stars), showing how to avoid breakdowns of the Cauchy problem that have affected similar attempts in the past. I will show that screening tends to suppress the (subdominant) dipole scalar emission in binary neutron star systems, but that it fails to quench monopole scalar emission in gravitational collapse, and quadrupole scalar emission in binaries

**Black Holes Astrophysics / 73**

## Binary black holes at the dawn of the Universe

**Author:** Michela Mapelli[1]

[1] *Padova University*

**Machine Learning for Gravitational Waves / 74**

## Simulation-based inference for gravitational waves

**Author:** Stephen Green[1]

[1] *University of Nottingham*

**Machine Learning for Gravitational Waves / 75**

## Generative Adversarial Networks applications for gravitational wave analyses

**Author:** Ik Siong Heng[None]

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## Modeling the strong-field dynamics of binary neutron star merger

**Author:** Sebastiano Bernuzzi[1]

[1] *University of Jena*

Binary neutron star mergers (BNSM) are cosmic collisions of compact stars associated to powerful gravitational and electromagnetic astronomical transients. Multimessenger observations of BNSMs promise

to deliver unprecedented insights on fundamental physics questions, including constraints on dense matter models and the production of heavy elements. Detailed theoretical predictions of the merger dynamics are a crucial aspect for extracting information from such observations. This talk reviews recent progress on the modeling of BNSMs using simulations in 3+1 numerical general relativity. In the first part, I will discuss predictions for the complete (inspiral-merger-postmerger) gravitational-wave spectrum and their application in gravitational-wave astronomy. In the second part, I will discuss merger remnants and mass ejecta, the mechanisms behind kilonova light and the application of these results to the analyses of astrophysical data.

**Neutron Stars: Matter at the Extremes / 77**

## Modeling the strong-field dynamics of binary neutron star merger

**Author:** Sebastiano Bernuzzi[None]

Binary neutron star mergers (BNSM) are cosmic collisions of compact stars associated to powerful gravitational and electromagnetic astronomical transients. Multimessenger observations of BNSMs promise to deliver unprecedented insights on fundamental physics questions, including constraints on dense matter models and the production of heavy elements. Detailed theoretical predictions of the merger dynamics are a crucial aspect for extracting information from such observations. This talk reviews recent progress on the modeling of BNSMs using simulations in 3+1 numerical general relativity. In the first part, I will discuss predictions for the complete (inspiral-merger-postmerger) gravitational-wave spectrum and their application in gravitational-wave astronomy. In the second part, I will discuss merger remnants and mass ejecta, the mechanisms behind kilonova light and the application of these results to the analyses of astrophysical data.

**Machine Learning for Gravitational Waves / 78**

## Machine Learning for Transient signal analysis in Gravitational Wave data

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The application of Machine and Deep learning techniques in astrophysics has gained significant attention also within the field of Gravitational Wave (GW) science, where numerous teams in the LIGO-Virgo collaboration have been exploring the potential of machine learning algorithms. These algorithms have been tested using both simulated and real data from LIGO and Virgo interferometers, focusing on tasks such as noise reduction and characterizing astrophysical signals.

I will provide specific examples demonstrating the effectiveness of Machine Learning in identifying and classifying transient signals arising from noise disturbances or GW events, including Core Collapse Supernovae and Compact Binary Coalescence events.

**Poster Session / 80**

## Impact of dark matter spikes on the merger rates of Primordial Black Holes

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Primordial Black Holes (PBHs) may form in the early Universe by formation mechanisms such as large density fluctuations, bubble collisions, collapse of domain walls or collapse of cosmic strings. PBHs are considered as one of the possible candidates for dark matter. A huge amount of work has been done on PBHs because it is considered that the merger of PBHs binaries can also lead to the origin of gravitational waves seen by LIGO/VIRGO/KAGRA (LVK) Scientific Collaboration. We study the current merger rate of PBHs binaries based on the assumption that PBHs are non-particle candidates of dark matter having a spike of non-annihilating cold dark matter particles such as axions around them. For that we extend the previous calculations of the merger rate of PBH binaries for extended PBH mass functions. Using analytical and numerical approaches, we calculate the current merger rates of PBH binaries with DM spikes assuming that either the DM spikes are completely thrown out of the binaries or they remain static during the merger. We found that the presence of DM spikes alters the distribution of final merger time and size of binaries in such a way that it can lead to either increase or decrease in the merger rate of PBH binaries, in comparison to the PBH binaries without DM spikes. Also, the binary black hole mergers seen in third Gravitational-Wave Transient Catalog (GWTC - 3) of LVK Collaboration can be very well explained by the mergers of PBH binaries with and without DM spikes for Lognormal and Power Law mass function (MF) in PBH mass range 5 M⊠ ≤ mpbh ≤ 100 M⊠ and 10−2 M⊠ ≤ mpbh ≤ 100 M⊠ respectively, leading to fpbh ≤ O(10−5 − 10−3) which is consistent with the previous results. As per our assumptions about the presence of DM spikes around PBHs, this work applies very well to the binaries having either comparable PBH masses or highly assymetric PBH masses, but a general formalism can be developed in future which can apply to binaries having PBHs in any mass ratios.

**Poster Session / 81**

## Diagrammatic Effective Field Theory approach to coalescing binary systems in General Relativity and gravitational waves phenomenology

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An accurate modeling of the gravitational waves emitted by coalescing binary systems, comprising black holes and neutron stars, is fundamental to fully leverage the capabilities of current and next-generation gravitational wave detectors.
In particular the inspiral phase of the binary system can be described using several approximation schemes, among which the post-Newtonian (PN) formalism.
In the last 20 years the evaluation of higher order post-Newtonian corrections has advanced further thanks to an Effective Field Theory approach and the application of multi-loop quantum field theory techniques. We study this modern approach, implementing the whole evaluation of conservative diagrams in a Mathematica code, which allows to compute also some conservative diagrams first appearing at 7PN order.
Then, employing a Fisher Information Matrix analysis, we forecast the constraints that the future space-based LISA interferometer will be able to provide regarding parametric deviations from the post-Newtonian theory.