# Book Of Abstracts

## EREP2021

# Invited Speaker

**Name:** <u>Sonia Antón</u>

**Affiliation:** CIDMA

**Title:** Chasing binary and displaced SMBH systems

**Abstract:** According to hierarchical assembly models, massive galaxies and their associated supermassive black holes (SMBH) are constructed by the merging of smaller galaxies, each with its own SMBH. In this scenario, there will be periods that the systems are formed by pairs of SMBH, and eventually displaced SMBH. The latter happens when there is a merger of the initial SMBHs, the final SMBH being kicked from the initial position due to the emission of gravitational waves. However, the number of known displaced SMBH or binary SMBH systems is surprisingly small, with less than 20 pinpointed systems in the kpc/pc separation scale, and that triggers the question of why there is such discrepancy.  Maybe the scarcity of the systems is due to the limitations of sensitivity and resolution of the current searches. We propose to explore different search methods, taking advantage of the new window of parameter space offered by recent surveys, that go deeper in flux and astrometry accuracy.

# Invited Speaker

**Name:** Juan Garcia Bellido

**Affiliation:** Universidad Autónoma de Madrid

**Title:** Covariant formulation of non-equilibrium thermodynamics in General Relativity: Cosmic Acceleration from First Principles

**Abstract:** We construct a generally-covariant formulation of non-equilibrium thermodynamics in General Relativity. We find covariant entropic forces arising from gradients of the entropy density, and a corresponding non-conservation of the energy momentum tensor in terms of these forces. We also provide a Hamiltonian formulation of General Relativity in the context of non-equilibrium phenomena and write the Raychaudhuri equations for a congruence of geodesics. We find that a fluid satisfying the strong energy condition could avoid collapse for a positive and sufficiently large entropic-force contribution. We then study the forces arising from gradients of the bulk entropy of hydrodynamical matter, as well as the entropy of boundary terms in the action, like those of black hole horizons. We apply the covariant formulation of non-equilibrium thermodynamics to the expanding universe and obtain the modified Friedmann equations, with an extra term corresponding to an entropic force satisfying the second law of thermodynamics. General relativistic entropic acceleration theory may explain the present cosmic acceleration from first principles without the need of introducing a cosmological constant. Following the covariant formulation of non-equilibrium phenomena in the context of a homogeneous and isotropic Friedmann-Lemaitre-Robertson-Walker (FLRW) metric, we find that the growth of entropy associated with the causal horizon of our universe (inside a finite bubble in eternal inflation) induces an acceleration that is essentially indistinguishable from that of ΛCDM, except for a slightly larger present rate of expansion compared to what would be expected from the CMB in ΛCDM, possibly solving the so-called H0 tension. The matter content of the universe is unchanged and the coincidence problem is resolved since it is the growth of the causal horizon of matter that introduces this new relativistic entropic force. The cosmological constant is made unnecessary and the future hypersurface is Minkowsky rather than de Sitter.

# Invited Speaker

**Name:** Geoffrey Compère

**Affiliation:** Université Libre de Bruxelles

**Title:** Centerless BMS4 charge algebra and (A)dS uplift

**Abstract:** Asymptotically flat spacetimes admit as asymptotic symmetry group the generalized BMS group which consists of supertranslations and super-Lorentz transformations which extend the Lorentz group and are associated with non-trivial flux-balance laws and memory effects. In (anti-) de Sitter spacetime, a generalization of this group represents the asymptotic symmetry group in the presence of open or "leaky" boundaries. I will present several features of the realization of these symmetries including the covariant renormalization procedure, the centerless representation at spatial infinity, the definition of angular momentum and the flat limit from the realization in asymptotically (anti-) de Sitter spacetimes.

# Invited Speaker

**Name:** Pedro Cunha

**Affiliation:** University of Aveiro

**Title:** Testing the Kerr hypothesis using the black hole shadow and gravitational lensing

**Abstract:** The image of M87* by the Event Horizon Telescope (EHT) has created a valuable opportunity to test the nature of Black Hole (BH) candidates in the cosmos. The Kerr hypothesis, which is motivated by multiple uniqueness theorems, states that astrophysical BHs are well described by the Kerr metric. However, alternative Kerr objects with possible astrophysical relevance can be constructed by circumventing these theorems. This talk will discuss the prospect of testing the Kerr hypothesis using shadow observations of the EHT. Notably, promising high-energy theories feature hypothetical ultralight bosonic fields that could spontaneously form macroscopic bosonic halos around black holes, via superradiance, transferring part of the mass and angular momentum of the black hole into the halo. By studying the shadows of such "hairy" black holes, we can constrain the amount of hair which is compatible with the EHT observations of M87*. We will also discuss a recent theorem establishing that an equilibrium Black Hole must admit, under generic conditions, at least one circular Light Ring orbit outside the horizon. These orbits are critical to determine the BH shadow edge. The proof relies on a topological argument and makes virtually no assumptions on the matter content or gravity model.

# Invited Speaker

**Name:** William East

**Affiliation:** Perimeter Institute

**Title:** Compact Object Mergers Beyond Einstein

**Abstract:** Gravitational wave observations of black hole and other compact object mergers have enabled unparalleled tests our understanding of gravity, and have already been used to constrain a number of possible deviations from general relativity. However, despite the success of these observations, there is dearth of theoretical predictions for what happens in the most dynamical stage of compact object mergers for many alternative theories. Focusing on the particular case of Einstein-scalar-Gauss-Bonnet gravity, and utilizing some recently developed tools for carrying out full, non-perturbative evolutions, I will discuss the mergers and potential observational signatures of scalarized black holes and neutron stars in modified gravity.

# Invited Speaker

**Name:** Jutta Kunz

**Affiliation:** University of Oldenburg

**Title:** Black holes, wormholes and particle-like solutions in EsGB theories

**Abstract:** Einstein-scalar-Gauss-Bonnet theories feature a wide variety of interesting compact solutions, whose properties depend significantly on the coupling function of the scalar field to the Gauss-Bonnet term. This talk will focus on coupling functions, that allow for spontaneously scalarized black holes. In this case, the black holes of General Relativity remain solutions of the theory, but develop tachyonic instabilities, that give rise to new scalarized black hole branches. When scanning the domain of existence for these solutions, new types of compact solutions are found. On the one hand, novel wormhole solutions are encountered, and on the other hand particle-like solutions. Some of these solutions qualify as UCOs, ultra-compact objects. In this talk, the domain of existence and further properties of these EsGB solutions are discussed.

# Invited Speaker

**Name:** José Natário

**Affiliation:** Instituto Superior Técnico

**Title:** Compact elastic objects in general relativity

**Abstract:** After reviewing the basics of relativistic elasticity theory, we introduce a general framework to study spherically symmetric self-gravitating elastic bodies systematically within general relativity, and apply it to investigate the existence, viability, and stability under radial perturbations of compact elastic objects.

# Invited Speaker

**Name:** Luciano Rezzolla

**Affiliation:** Institute for Theoretical Physics, Frankfurt

**Title:** Imaging a supermassive black hole

**Abstract:** I will briefly discuss how the first image of a black hole was obtained by the EHT collaboration. In particular, I will describe the theoretical aspects that have allowed us to model the dynamics of the plasma accreting onto the black hole and how such dynamics was used to generate synthetic black-hole images. I will also illustrate how the comparison between the theoretical images and the observations has allowed us to deduce the presence of a black hole in M87 and to extract information about its properties. Finally, I will describe the lessons we have learned about strong-field gravity and alternatives to black holes.

# Invited Speaker

**Name:** Nico Sanchis-Gual

**Affiliation:** Universidade de Aveiro

**Title:** Dynamical bosonic stars and gravitational waves

**Abstract:** Bosonic stars are theoretical exotic compact objects made of ultralight bosonic particles that could explain part of dark matter. In this talk, I will review some recent results on the stability and dynamical formation of these objects. Then I will talk about bosonic star mergers, the emission of gravitational waves, and what we could learn about them from a real gravitational wave event, if these stars exist in the Universe.

# Invited Speaker

**Name:** Alicia Sintes

**Affiliation:** Universitat de les Illes Balears

**Title:** Present and future of gravitational wave astronomy

**Abstract:** Astrophysics is living a revolutionary epoch: new techniques, instruments and theories are providing for the first time truthful and coherent answers to great questions that humanity has been pursuing for centuries. Gravitational waves -ripples in the fabric of space-time- are now the new messengers that will allow us to open a new window onto the cosmos that could revolutionize our understanding of the Universe. The advanced detector network LIGO-Virgo-KAGRA has been making ground breaking discoveries since it switched on in 2015. From the first three observing runs, there have been many detections of signals produced by compact binary mergers. This talk will describe the status of the now-firmly-established field of gravitational wave astronomy, give some highlights of the current discoveries, and describe the role of our group.

# Invited Speaker

**Name:** Thomas Sotiriou

**Affiliation:** University of Nottingham

**Title:** Black Hole Scalarization

**Abstract:** Strong gravity observations are providing new insights into the structure of compact objects and can potentially detect new fundamental fields if they affect it. However, such fields have not been detected in high-precision weak field test so, if they exist, there ought to be some mechanism that suppresses them there. Spontaneous scalarization does precisely that. Models that predict this phenomenon for neutron stars date back to the 90s and have been studied thoroughly. More recently it was understood that more general models can lead to black hole scalarization. Moreover, it has been shown that scalarization can be triggered, not only by curvature, but also by spin. Hence, black holes in certain mass or spin ranges can have scalar hair, while outside these ranges they would be described by the Kerr metric, as in general relativity. I will give an overview of the recent developments and future prospects in this topic.

# Invited Speaker

**Name:** Frederic Vincent

**Affiliation:** Paris Observatory / LESIA

**Title:** Probing the vicinity of the supermassive black hole at the center of the Galaxy with GRAVITY

**Abstract:** The Very Large Telescope (VLT) Interferometer instrument GRAVITY is ableto combine the infrared light from the four 8-meter telescopes of the VLT. With the help of adaptive optics and fringe tracking for correcting the atmospheric turbulence, GRAVITY is able to follow astrometric motion close to the supermassive black hole at the heart of the Milky Way with the exquisite precision of few 10s of microarcseconds only (the size of a grapefruit on the Moon!). In this talk, I will review the main results of GRAVITY at the Galactic center, focusing on the detection of gravitational redshift and Schwarzschild precession of the innermost star S2, as well as on the detection of orbital motion very close to the black hole's event horizon.

# Invited Speaker

**Name:** Elizabeth Winstanley

**Affiliation:** The University of Sheffield

**Title:** Quantum expectation values on black hole space-times

**Abstract:** The renormalized expectation value of the stress energy tensor (RSET) is an object of central importance in quantum field theory in curved space-time, but calculating this on black hole space-times is far from trivial. The original methodology was developed in the 1980s and 1990s and successfully applied to a range of quantum fields on four-dimensional Schwarzschild black holes. The subject has enjoyed a renaissance in the past few years with the development of novel approaches to computing the RSET and renormalized vacuum polarization (VP). These advances have enabled calculations on a wider range of black hole space-times to be performed. In this talk we will review both the original and latest methodologies and recent results for the RSET and VP on asymptotically flat, de Sitter and anti-de Sitter black holes.

# Contributed Talk

**Name:** Juan Calderon Bustillo **Position:** Post-Doc/Research Fellow

**Affiliation:** University of Santiago de Compostela

**Title:** Exploring the strong regime of gravity with mergers of heavy compact objects.

**Abstract:** Gravitational-wave observations of compact binary mergers have granted us access for the first time to the strong regime of gravity. Because their merger-ringdown emission falls in the most sensitive band of Advanced LIGO and Virgo, mergers with masses above 100Msun are excellent arenas to dig for new gravitational-wave observables and even search for new exotic compact objects. Todate, however, only one such observation exists, known as GW190521. In this talk I will discuss efforts towards increasing the detection rate of these objects exploiting higher-order harmonics and alternative interpretations of existing events beyond the black-hole scenario, such as boson-stars.

# Contributed Talk

**Name:** David Keitel **Position:** Post-Doc/Research Fellow

**Affiliation:** Universitat de les Illes Balears

**Title:** Gravitational lensing of gravitational waves

**Abstract:** Gravitational lensing has a long and productive history in electromagnetic astronomy. Lensing can also affect gravitational waves (GWs), though this has not yet been confidently detected due to lensing effects on GWs being subtle to identify and the lensing rate only becoming substantial for the most distant sources. But with the second-generation detectors now observing ever-larger numbers of compact binary coalescences from deeper in the cosmos, our chances for a first detection of GW lensing are rapidly increasing. This talk will cover the basic phenomenology of GW lensing such as lensing magnification, strongly lensed multiple images, and microlensing; as well as the searches for lensing effects performed so far in LIGO-Virgo O1, O2 and O3a data; and future prospects for detections of lensed GWs and their use in cosmology and fundamental physics.

# Contributed Talk

**Name:** Kyriakos Destounis **Position:** Post-Doc/Research Fellow

**Affiliation:** Universität Tübingen

**Title:** Gravitational-wave imprints of non-integrable extreme-mass-ratio inspirals

**Abstract:** The detection of gravitational waves from extreme-mass-ratio inspirals (EMRIs) with upcoming space-borne detectors will allow for unprecedented tests of general relativity in the strong-field regime. Aside from assessing whether black holes are unequivocally described by the Kerr metric, they may place constraints on the degree of spacetime symmetry. Depending on exactly how a hypothetical departure from the Kerr metric manifests, the Carter symmetry, which implies the integrability of the geodesic equations, may be broken. In this talk, I will discuss the impact of non-integrability in EMRIs which involve a supermassive compact object with anomalous multipolar structure. After reviewing the features of chaotic phenomena in EMRIs, I will argue that non-integrability is precisely imprinted in the gravitational waveform. Explicit examples of non-integrable EMRIs will be discussed, as well as their role in LISA data analysis.

# Contributed Talk

**Name:** Cláudio Gomes **Position:** Post-Doc/Research Fellow

**Affiliation:** University of the Azores & CF-UM-UP

**Title:** Surfing a (dark) gravitational wave

**Abstract:** Gravitational waves are solutions of General Relativity and have been directly detected in recent years. Notwithstanding, alternative theories of gravity also present such solutions with some new interesting features. In general, in alternative metric theories of gravity they may present up to six polarisation states. However, when matter is included, some additional features arise. Hence, in the context of non-minimal matter-curvature coupling theories these issues need to be addressed. We shall present the results of such analysis, both from the usual linearisation process and from the Newman-Penrose formalism. Some comments on different gravity models will be presented, thus giving some insights on how to surf dark gravitational waves!

# Contributed Talk

**Name:** Marta Colleoni **Position:** Post-Doc/Research Fellow

**Affiliation:** University of the Balearic Islands

**Title:** A new model for binary neutron star coalescences: PhenomX meets NRTidalv2

**Abstract:** We present IMRPhenomXP_NRTidalv2, a new waveform model for the gravitational-wave signal emitted by binary neutron star systems. The model builds upon the state-of-the-art PhenomX waveform family, and includes both an analytical and numerical description of double-spin precession effects. We incorporate into the binary-black-hole baseline tidal corrections obtained by blending post-Newtonian results and information extracted from numerical relativity waveforms. When analysing GW170817, we find that the new model recovers a larger signal-to-noise ratio and yields tighter constraints on the source parameters with respect to previous models.

# Contributed Talk

**Name:** Soham Bhattacharyya **Position:** Post-Doc/Research Fellow

**Affiliation:** AEI Hannover

**Title:** Stumbling around in the modified gravity landscape.

**Abstract:** Parameters extracted from Gravitational Wave (GW) data allow observers to quantify certain physical aspects of GW producing sources, like neutron stars (NS) and black holes (BH). In the case of an isolated BH, its physical shape in space, as a freely falling asymptotic observer would deduce from data, combined with its inertial mass, gets encoded in GWs radiated from these sources. In classical terms, a multipolar structure of radiating sources can be established from the GW data, giving a freely falling observer a dynamic view of the 'horizon' of a BH as it undergoes a damped oscillation towards a stable shape. However, the dynamical behavior is the opposite when the source is a binary system. Two 'symmetric' bodies mutually deform each other to a maximally distorted single compact object, radiating GWs that increase in frequency and amplitude (to specific maximum values) along with the distortion. Using a Zangenbewegung approach towards the maximal distortion (known in GW literature as the merger) from both sides (ring-down and inspiral, respectively), I will talk about GR's predictions and the corresponding predictions made by extended theories of gravitation like f(R) and dynamical Chern-Simons.

# Contributed Talk

**Name:** Carlos Frajuca **Position:** Staff

**Affiliation:** FURG

**Title:** Calibration of laser interferometric Gravitational Wave Detector

**Abstract:** In 2015, the first direct detection of gravitational waves was reported. Data analysis indicated that the waves had originated from the violent collision of two black holes, which scattered them through space–time as Einstein predicted. That detection was made possible by many advances in measurement technology, mainly vibration isolation of the detector optics, since, at 10 Hz, the motion of the laser-interferometric detector mirrors is at least one billion times smaller than the seismic motion of the ground. As well, it is difficult to lock the laser in the detection configuration in a large band of the spectrum; this was made possible by using many feedback and feed-forward control loops. However, in order to meet the many demanding requirements, more than a hundred of such active systems are included in a detector to allow locked acquisition and locked stability to, eventually, reach the desired sensitivity. In this work, challenges faced to reach some of these requirements will be described and we analyze how this scenario impacts the calibration of such detectors. In order to help reduce false alarm rates and provide data for veto systems, in this work we propose a specific kind of resonant-mass detector to operate in coincidence with laser-interferometric ones.

# Contributed Talk

**Name:** Rodrigo Tenorio **Position:** PhD Student

**Affiliation:** Universitat de les Illes Balears

**Title:** All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems

**Abstract:** We present a search for continuous gravitational waves emitted by neutron stars in binary systems conducted on data from the early third observing run of the Advanced LIGO and Advanced Virgo detectors using the semicoherent, GPU-accelerated, BinarySkyHough pipeline. The search analyzes the most sensitive frequency band of the LIGO detectors, 50 - 300 Hz. Binary orbital parameters are split into four regions, comprising orbital periods of 3 - 45 days and projected semimajor axes of 2 - 40 light-seconds. No detections are reported. We estimate the sensitivity of the search using simulated continuous wave signals, achieving the most sensitive results to date across the analyzed parameter space.

# Contributed Talk

**Name:** Gabriel Andres Piovano **Position:** PhD Student

**Affiliation:** Sapienza, University of Rome

**Title:** Assessing the detectability of the secondary spin in extreme mass-ratio inspirals with fully-relativistic numerical waveforms

**Abstract:** Extreme mass-ratio inspirals (EMRIs) are unique sources of gravitational waves (GW). A secondary in EMRIs completes hundreds of thousands of orbits in the strong-field regime near a supermassive black hole. Hence, an EMRI signal provides a faithful atlas of the primary spacetime, which allow testing astrophysics and fundamental physics with unprecedented precision. One of the key elements in EMRI dynamics is the spin of the secondary, which gives a relevant contribution to the GW waveform. This talk will present our results of a Fisher-matrix error analysis of EMRI parameters with fully relativistic numerical waveforms. Our analysis mainly focused on the measurability of secondary spin in a Kerr background for circular orbits, taking into account the motion of the LISA constellation and higher harmonics. I will discuss the effect of higher harmonics in the error of the parameters and the detectability of the secondary spin. This talk will be based on the preprint https://arxiv.org/abs/2105.07083, submitted on May 2021.

# Contributed Talk

**Name:** Thomas Mieling **Position:** PhD Student

**Affiliation:** University of Vienna

**Title:** Amplitude and Polarisation of Light in Gravitational Wave Detectors

**Abstract:** Most theoretical descriptions of laser interferometric gravitational wave detectors are based on the eikonal equation which determines the optical phases of the light rays reaching the detector. While this method provides the key ingredient to describe the observed signal, it neglects amplitude and polarisation degrees of freedom and thus provides only incomplete information about the field producing the signal. In this talk, I will describe the extension of such models to also include the electromagnetic amplitude and polarisation, using both ray-optics and wave-optics methods.

# Contributed Talk

**Name:** Syed Umair Husain Naqvi **Position:** PhD Student

**Affiliation:** Jagiellonian University

**Title:** Freely-falling bodies in standing wave spacetime

**Abstract:** The phenomena of standing waves is well known in mechanical and electromagnetic setting where the wave has the maximum and minimum amplitude at the antinodes and nodes, respectively. In context of exact solution to Einstein Field equations, we analyze a spacetime which represents standing gravitational waves in an expanding Universe. The study the motion of free masses subject to the influence of standing gravitational waves in the polarized Gowdy cosmology with a three-torus topology. We show that antinodes attract freely falling particles and we trace the velocity memory effect.

# Contributed Talk

**Name:** Joan Moragues Roca **Position:** PhD Student

**Affiliation:** Universitat de les Illes Balears

**Title:** Search for long-duration transient gravitational waves from glitching pulsars during LIGO-Virgo third observing run

**Abstract:** Pulsars are spinning neutron stars which emit an electromagnetic beam. We expect pulsars to slowly decrease their rotational frequency. However, sudden increases of the rotational frequency have been observed from different pulsars. These events are called glitches, and they are followed by a relaxation phase with timescales from days to months. Gravitational waves (GWs) emission may follow these peculiar events. We give an overview of an analysis of GW data from the Advanced LIGO and Virgo third observing run (O3) searching for transient GW signals lasting hours to months after glitches in known pulsars during the 2019-2020 run period. The search method consists of placing a template grid in frequency-spindown space with fixed grid spacings. Then, for each point we compute the transient F-statistic which is maximized over a set of transient parameters like the duration and start time of the potential signals. A threshold on the detection statistic is then set, and we search for peaks over the parameter space for each candidate.

# Contributed Talk

**Name:** Priyanka Giri **Position:** PhD Student

**Affiliation:** INFN Pisa

**Title:** Cold aberrations and locking of Central Interferometer of Advanced Virgo+

**Abstract:** The target sensitivity of Advanced Virgo for O4 is about 90-120 Mpc for the BNS range. To achieve this, several hardware upgrades are under process. One of the most relevant concerns installation of the Signal Recycling Mirror, which forms an additional marginally stable cavity along with the power recycling cavity already present in Advanced Virgo. Therefore, to compensate for these (cold) optical aberrations, new Central Heating benches were installed by the TCS subsystem. I will describe the installation and pre-commissioning of CO_2 central heating, which assists the lock of DRMI by compensating for the (cold) optical aberrations, and the procedure followed for locking the Dual Recycled Michelson Interferometer along with the tuning of CO_2 central heating

# Contributed Talk

**Name:** Paulo Jorge Valente Garcia **Position:** Staff

**Affiliation:** CENTRA/FEUP

**Title:** Current status of the GRAVITY experiment

**Abstract:** We will present the current status of the GRAVITY experiment on the Galactic Centre supermassive black hole. GRAVITY is the most advanced optical-infrared instrument in a ground-based observatory. It sharpens the light of four giant 8 m telescopes with advanced adaptive optics and them combines it interferometrically achieving exquisite precision. It was central for the experimental breakthrough justifying part of 2020 Physics Nobel Prize. We will conduct a review of past achievements since the last Workshop: a) detection of Schwazchild precession; b) advances in the modelling and interpretation of matter orbiting the ISCO; c) preparatory work for the detection of higher-order effects.

# Contributed Talk

**Name:** João Luís Rosa **Position:** Post-Doc/Research Fellow

**Affiliation:** University of Tartu

**Title:** Modelling a bosonic star at the galactic centre with GYOTO

**Abstract:** The GRAVITY collaboration has recently detected a continuous circular relativistic motion during infrared flares of Sgr A*, which has been interpreted as orbital motion near the event horizon of a black-hole. In this work, we use the ray-tracing code GYOTO to analyze the possibility of these observations being consistent with a central bosonic star instead of a black-hole. Our model consists of an isotropically emitting hot-spot orbiting a central boson or Proca star. Images of the orbit at different times and the integrated flux were obtained for both models and compared with the case of a Schwarzschild black-hole. Although the overall qualitative picture is comparable, the bosonic star models present an extra image when the emitting hot-spot passes behind the central object caused by photons travelling through the interior of the star. Furthermore, there are also measurable differences in the angles of deflection, orbital periods, and centroid of the flux, which can potentially be detected.

# Contributed Talk

**Name:** Pablo A. Cano **Position:** Post-Doc/Research Fellow

**Affiliation:** KU Leuven

**Title:** Ringing of black holes in higher-derivative gravity

**Abstract:** Quasinormal modes describe the gravitational waves emitted by a black hole after it is perturbed, and hence they characterize the so-called ringdown phase after the merger of a black hole binary. The measurement of these modes and comparison with the theoretical prediction will provide a strong test on GR, but this will also allow us to search for deviations with respect to it. However, computing the QNMs of black holes in beyond-GR theories is a very complicated problem. In this talk, I will review recent progress on the computation of the quasinormal modes of rotating black holes in higher-derivative gravity. I will explain the main obstacles in this computation, and show how they can be tackled in certain cases. I will show some results in the case of perturbations of a test scalar field for fully rotating black holes, and report progress on the gravitational perturbations of slowly rotating ones.

# Contributed Talk

**Name:** Filip Hejda **Position:** Post-Doc/Research Fellow

**Affiliation:** CEICO, Institute of Physics of the Czech Academy of Sciences

**Title:** Charged particle collisions and energy extraction from extremal electrovacuum black holes

**Abstract:** In the last decades, a lot of attention has been devoted to test particle collisions with arbitrarily high energy in the vicinity of extremal black holes, which constitute an idealised best-case scenario for the collisional Penrose process. One studied possibility requires fine-tuned particles corotating with an extremally spinning black hole, whereas another variant of such process relies on particles with fine-tuned charge moving near an extremally charged black hole. Even in this simplified setup, the energy that can be extracted turned out to be capped by unconditional upper bounds, yet only in the more interesting maximally rotating case, but not in the more hypothetical maximally charged one. We have recently studied a more general process for charged particles orbiting an extremal electrovacuum black hole, which unifies the two mentioned cases [Phys. Rev. D 95, 084055 (2017)]. Following up on those results, our present work examines energy extraction through this general process. We show that the unconditional upper bounds on the extracted energy are absent whenever both the black hole and the escaping particle have a non-zero charge. We also discuss that the process in the equatorial plane does not suffer from additional limitations that we found for the simpler case of charged particles moving along the axis of symmetry [Phys. Rev. D 100, 064041 (2019)].

# Contributed Talk

**Name:** Filipe Moura **Position:** Staff

**Affiliation:** ISCTE - Instituto Universitário de Lisboa and Instituto de Telecomunicações

**Title:** Eikonal quasinormal modes and shadow of string-corrected d-dimensional black holes

**Abstract:** We compute the quasinormal frequencies of d -dimensional spherically symmetric black holes with leading string α′ corrections in the eikonal limit for tensorial gravitational perturbations and scalar test fields. We find that, differently than in Einstein gravity, the real parts of the frequency are no longer equal for these two cases. The corresponding imaginary parts remain equal to the principal Lyapunov exponent corresponding to circular null geodesics, to first order in α′ . We also compute the radius of the shadow cast by these black holes. Work published in Phys.Lett.B 819 (2021) 136407.

# Contributed Talk

**Name:** Màrius Josep Fullana i Alfonso **Position:** Staff

**Affiliation:** IMM. UPV. València.

**Title:** Computing positioning errors in Relativity Positioning Systems

**Abstract:** General Relativity Theory provides a framework to compute the most precise orbits of Earth satellites. Four satellites are needed to locate a user in Relativistic Positioning Systems. In 2014, Puchades and Sáez (Astrophys. Space Sci. 352, 307, 2014) computed the difference in positioning taking satellites world lines with Schwarzschild metric and with a statistical perturbation of such world lines. Such differences are named the U-errors. To compute the photons null geodesics of the satellites signals they used the solution given by Coll, Ferrando and Morales Lladosa (Class. Quantum Grav. 27, 065013, 2010). Our team (Puchades, Arnau and Fullana, 2021, Astrophys. Space Sci., in press) has taken more accurate satellites trajectories as perturbations of Schwarzschild world lines. These more accurate trajectories take into account the gravitational effects of the Earth, the Moon and the Sun and also the Earth oblateness. A robust algorithm has been built to compute the U-errors with this more accurate description of satellites orbits. We are now incorporating more relativistic perturbations in the metric to describe the satellites world lines. Our method is applied to the ESA Galileo Satellites Constellation. However our algorithm is also applied to other satellites at different heights. In this presentation a summary of this research is presented.

# Contributed Talk

**Name:** Lorenzo Annulli **Position:** PhD Student

**Affiliation:** CENTRA

**Title:** Generalizing the Close Limit Approximation

**Abstract:** The ability to model the evolution of compact binaries from the inspiral to coalescence is central to gravitational wave astronomy. Current waveform catalogues are built from vacuum binary black hole models, by evolving Einstein equations numerically and complementing them with knowledge from slow-motion expansions. Much less is known about the coalescence process in the presence of matter, or in theories other than General Relativity. In this talk, I will show how to use the Close Limit Approximation as a powerful tool to understand the head-on collision of two equal-mass, compact but horizonless objects. Hence, I will show the appearance of “echoes”, that indicate that a significant fraction of the merger energy goes into these late-time repetitions.

# Contributed Talk

**Name:** Jorge F. M. Delgado **Position:** PhD Student

**Affiliation:** University of Aveiro

**Title:** Equatorial timelike circular orbits around generic ultracompact objects

**Abstract:** For a stationary, axisymmetric, asymptotically flat, ultra-compact [i.e. containing light-rings (LRs)] object, with a Z_2 north-south symmetry fixing an equatorial plane, we establish that the structure of timelike circular orbits (TCOs) in the vicinity of the equatorial LRs, for either rotation direction, depends exclusively on the stability of the LRs. Thus, an unstable LR delimites a region of unstable TCOs (no TCOs) radially above (below) it; a stable LR delimites a region of stable TCOs (no TCOs) radially below (above) it. Corollaries are discussed for both horizonless ultra-compact objects and black holes. We illustrate these results with a variety of exotic stars examples and non-Kerr black holes, for which we also compute the efficiency associated with converting gravitational energy into radiation by a material particle falling under an adiabatic sequence of TCOs. For most objects studied, it is possible to obtain efficiencies larger than the maximal efficiency of Kerr black holes, i.e. larger than 42%.

# Contributed Talk

**Name:** Riccardo Della Monica **Position:** PhD Student

**Affiliation:** Universidad de Salamanca

**Title:** Orbital precession of the S2 star in Scalar-Tensor-Vector-Gravity

**Abstract:** The GRAVITY Collaboration achieved the remarkable detection of the orbital precession of the S2 star around the Galactic centre supermassive black hole, providing yet another proof of the validity of the General Relativity. The departure from the Schwarzschild precession is encoded in the parameter $f_{\rm SP}$ which multiplies the predicted general relativistic precession. Such a parameter results to be $f_{\rm SP}=1.10\pm0.19$, which is consistent with General Relativity ($f_{\rm SP}=1$) at 1$\sigma$ level. Nevertheless, this parameter may also hide an effect of modified theories of gravity. We used the Schwarzschild-like metric of Scalar-Tensor-Vector-Gravity to predict the orbital motion of S2-star, and to compare it with the publicly available astrometric data, which include 145 measurements of the positions, 44 measurements of the radial velocities of the S2 star along its orbit, and the recent measurement of the orbital precession. We employed a Monte Carlo Markov Chain algorithm to explore the parameter space, and constrained the only one additional parameter of Scalar-Tensor-Vector-Gravity to $\alpha \leq 0.410$ at $99,7\%$ confidence level, where $\alpha=0$ reduces this modified theory of gravity to General Relativity.

# Contributed Talk

**Name:** João Rodrigues **Position:** PhD Student

**Affiliation:** Universidade de Coimbra

**Title:** Asymptotic quasinormal modes of string-theoretical d-dimensional black holes

**Abstract:** We compute the quasinormal frequencies of d-dimensional spherically symmetric black holes with leading string $\alpha'$ corrections for tensorial gravitational perturbations in the highly damped regime. We solve perturbatively the master differential equation and we compute the monodromies of the master perturbation variable (analytically continued to the complex plane) in different contours, in order to obtain the quasinormal mode spectra. We proceed analogously for the quasinormal modes of test scalar fields. Differently than in Einstein gravity, we obtain distinct results for the two cases.

# Contributed Talk

**Name:** David Pereñiguez **Position:** PhD Student

**Affiliation:** IFT UAM/CSIC, Madrid

**Title:** Quasinormal modes of NUT-charged black branes in AdS/CFT

**Abstract:** Quasinormal modes (QNM) of black holes in Anti-de Sitter space correspond, according to AdS/CFT, to poles of thermal correlators in the dual theory. Using the powerful results of 4d black hole perturbation theory — namely the Newman-Penrose formalism, Teukolsky's equations and Hertz's reconstruction map, I will derive master equations and holographic boundary conditions for gravitational perturbations. This leads, for the first time, to the QNM frequency spectrum of a NUT-charged space. The results provide definite holographic predictions regarding the hydrodynamic behaviour of the dual plasma. I will conclude by discussing stability against scalar and gravitational perturbations.

# Contributed Talk

**Name:** Barbora Bezdekova **Position:** PhD Student

**Affiliation:** Faculty of Mathematics and Physics, Charles University, Prague

**Title:** On the Light Rays Propagating in Plasma Medium around Relativistic Objects

**Abstract:** When starting from distant galaxies, light rays propagate also through regions with matter (usually plasma) of various densities, not only through vacuum. A precise description of such a transfer is important since the medium through which rays propagate may affect substantially their form. If the rays are at the same time passing near a strongly gravitating compact object, both plasma and gravitational effects have to be taken into account. The impact of refractive and dispersive media around compact objects typically manifests itself in problems related to gravitational lensing. In our work we focus on how the regions allowed for propagation of rays are modified due to the presence of refractive and dispersive media with various density profiles. Specifically, we investigate the form of allowed regions in the equatorial plane of a Kerr black hole. We show that in the medium with the density distributions corresponding to typical profiles of lensing galaxies (exponential or power-law distributions), as well as with the density distribution of a nonsingular isothermal sphere, allowed regions are substantially reduced in comparison with corresponding regions in vacuum. We also study allowed regions as seen by observers freely falling from the rest at infinity onto the black hole, and discuss the propagation of rays near the axis of rotation of the hole and near the equatorial plane.

# Contributed Talk

**Name:** Benliang Li **Position:** Staff

**Affiliation:** Southwest Jiaotong University

**Title:** Time dilation in Classical and quantum clocks

**Abstract:** We study the underlying mechanism of atomic clock based on quantum field theory in curved space-time and verify theoretically that time recorded by atomic clocks obey relativity. Further, we raise the question whether time dilation predicted by relativity can be verified by any other kinds of clocks, such as pendulum clocks and spring clocks? Based on the analysis of different kinds of clocks, we introduce a new coordinate transformation which maintains the period of clocks, then we verify that such coordinate transformation present real time transformation in curved space-time. At last, we present a new perspective on the nature of time and the role it played in relativity and quantum theory.

# Contributed Talk

**Name:** Eugen Radu **Position:** Post-Doc/Research Fellow

**Affiliation:** Departamento de Matematica da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications, Aveiro University

**Title:** Multipolar boson stars

**Abstract:** We show, by explicitly constructing the fully non-linear solutions, that static boson stars with a single complex scalar field, can have a non-trivial multipolar structure, yielding the same morphologies for their energy density as those that elementary hydrogen atomic orbitals have for their probability density. This includes static configurations without any continuous symmetries. Axially symmetric boson star chains, with several distinct components located on the symmetry axis, are also discussed.

# Contributed Talk

**Name:** Pablo Bueno **Position:** Post-Doc/Research Fellow

**Affiliation:** CERN

**Title:** Regular black holes in three dimensions

**Abstract:** I will present a new broad family of analytic black holes and globally regular horizonless spacetimes in three dimensions. The solutions involve a single real scalar field $\phi$ which always admits a magnetic-like expression proportional to the angular coordinate. The new metrics, which are characterized by a single function and represent continuous generalizations of the BTZ one, solve the equations of Einstein gravity corrected by a new family of densities (controlled by unconstrained couplings) constructed from positive powers of $(\partial \phi)^2$ and certain linear combinations of $R^{ab} \partial_a \phi \partial_b$ and $(\partial \phi)^2 R$. Some of the solutions obtained describe black holes with one or several horizons. A set of them possesses curvature singularities, while others have conical or BTZ-like ones. Interestingly, in some cases the black holes have no singularity at all, being completely regular. Some of the latter are achieved without any kind of fine tuning or constraint between the action parameters and/or the physical charges of the solution. An additional class of solutions describes globally regular and horizonless geometries.

# Contributed Talk

**Name:** Jorge Rocha **Position:** Staff

**Affiliation:** ISCTE - Instituto Universitário de Lisboa & CENTRA

**Title:** Love numbers of black holes in modified gravity

**Abstract:** Finite-sized bodies deform in the presence of external tidal fields created, for instance, by surrounding objects. This effect is encoded in the so-called Love numbers and this is particularly important in the merging process of black holes or neutron stars. The phase of the gravitational waveform produced is affected by such tidal Love numbers and this idea has been used to constrain the nuclear matter equation of state from the gravitational wave detection of binary neutron star mergers. It is a well known fact that non-rotating black holes in General Relativity (GR) have vanishing Love numbers. Nevertheless, this exact same spacetime is also a solution of a broad class of modified gravity theories, for which the linearized perturbations equations generically differ from those of GR. Consequently, tidal Love numbers can depend not only on the object itself, but also on the gravitational theory supporting it, offering the possibility of ruling out theories with detections of gravitational waves from binary black hole mergers. I will discuss linear perturbations of f(R) gravity on the background of a Schwarzschild-AdS black hole, and its associated tidal Love numbers. While axial sector perturbations remain unaltered with respect to GR --and are therefore universal for this class of theories--, the polar sector is affected. Nevertheless, the non-universality arising in the polar sector is controlled by a single quantity, namely $f''(R)/f'(R)$.

# Contributed Talk

**Name:** Masato Minamitsuji **Position:** Post-Doc/Research Fellow

**Affiliation:** CENTRA, IST, U-Lisboa

**Title:** Black holes in the extended vector-tensor theories

**Abstract:** We investigate the static and spherically black hole solutions in the quadratic-order extended vector-tensor theories without suffering from the Ostrogradsky instabilities, which include the quartic-order (beyond-)generalized Proca theories as the subclass. We investigate the two classes of black hole solutions, for constant and nonconstant norms of the vector field, respectively. In the first case, we obtain the black hole solutions with the Schwarzschild, Schwarzschild-de Sitter/ anti-de Sitter, Reissner-Nordstr\"{o}m-type, and Reissner-Nordstr\"{o}m-de Sitter/ anti-de Sitter-type metrics. We show that the conditions for the existence of these solutions are compatible with the degeneracy conditions for the Class-A theories, and recover the black hole solutions in the generalized Proca and degenerate higher-order scalar-tensor theories in the certain limits. In the latter case, we obtain a variety of the black hole solutions with various asymptotic properties. We also argue the implication of these solutions for stability and strong coupling problems.

# Contributed Talk

**Name:** Mostafizur Rahman **Position:** Post-Doc/Research Fellow

**Affiliation:** Indian Institute of Technology, Gandhinagar

**Title:** Ringdown properties of compact objects

**Abstract:** Black holes are an integral part of the standard model of astrophysics and cosmology. However, their existence poses some serious fundamental problems. In recent years, several horizonless compact object models were proposed to address those issues. As the gravitational wave detectors started to observe more and more merger events with a large signal-to-noise ratio, gravitational wave spectroscopy could hold the key to uncover the existence of these objects. This is because the late time ringdown signals of horizonless compact objects differ from that of the black holes. In this talk, I will discuss the ringdown properties of compact objects and compare them with those obtained in the black hole scenario. Since the internal structure and the equation of state of these compact objects are largely unknown, we employ the membrane paradigm to obtain appropriate boundary conditions for the perturbations of these objects. This model can describe the ringdown properties of a large variety of compact objects.

# Contributed Talk

**Name:** António Morais **Position:** Post-Doc/Research Fellow

**Affiliation:** Universidade de Aveiro

**Title:** Particle physics models for ultralight bosons

**Abstract:** I will discuss a family of simple extensions of the Standard Model and the main principles behind such a construction that can yield ultralight complex vectors or scalars with potential astrophysical relevance. Specifically, the preferred mass range for these putative fundamental bosons (~10^{-10} to 10^{-20} eV) can lead dynamically to, e.g., compact objects such as bosonic stars or new non-Kerr black holes with a stellar to supermassive mass range. For each model, I will discuss the properties of the mass spectrum and interactions, its theoretical viability as well as some of its potential and most relevant phenomenological implications.

# Contributed Talk

**Name:** Ivica Smolić **Position:** Staff

**Affiliation:** Department of Physics, Faculty of Science, University of Zagreb

**Title:** Black hole thermodynamics in the presence of nonlinear electromagnetic fields

**Abstract:** As the interaction between the black holes and highly energetic infalling charged matter receives quantum, nonlinear corrections, the basic laws of black hole mechanics have to be carefully rederived. Nonlinear electrodynamics (NLE) has its roots back in the 1930s, within the problem of infinite self-energy of the point charges, proliferating into a vast web of modern NLE theories. In this talk we shall discuss recent generalizations [1,2] of the basic laws of black hole thermodynamics in the presence of NLE fields, defined by Lagrangians depending on both quadratic electromagnetic invariants, $F_{ab} F^{ab}$ and $F_{ab} {*F}^{ab}$. Resting upon several complementing proofs of the zeroth law of black hole electrodynamics, "equilibrium state" and "physical process" versions of the first law have been derived [1] using the covariant phase space formalism. Smarr formula, originally generalized via Bardeen-Carter-Hawking mass formula [2], has been deduced from the first law with "scaling argument", giving us yet another consistency check. Finally, we shall discuss under which conditions the generalized Smarr formula attains linear form. [1] A. Bokulić, T. Jurić and I. Smolić: "Black hole thermodynamics in the presence of nonlinear electromagnetic fields", Phys. Rev. D 103 (2021) 124059 [arXiv:2102.06213]. [2] L. Gulin and I. Smolić: "Generalizations of the Smarr formula for black holes with nonlinear electromagnetic fields", Class. Quantum Grav. 35 (2018) 025015 [arXiv:1710.04660]

# Contributed Talk

**Name:** Thomas Helfer **Position:** Post-Doc/Research Fellow

**Affiliation:** Johns Hopkins University

**Title:** Boson Star initial data

**Abstract:** We show a new simple way of generating initial data for binary Boson Stars, which reduces initial excitations significantly. We show that it will dramatically improve the quality of the extracted gravitational waves and reduce initial hamiltonian constraint violation by one order of magnitude. Lastly, we present results from merger using this initial data.

# Contributed Talk

**Name:** João Oliveira **Position:** Post-Doc/Research Fellow

**Affiliation:** Instituto Superior Técnico

**Title:** Virial Identities and the Gibbons-Hawking-York term

**Abstract:** We present a brief review of Virial identities and discuss the role that the Gibbons-Hawking-York (GHY) term plays when calculating the identities for asymptotically flat spacetimes. The inclusion of the surface GHY term in the calculation might allow a more general approach to the calculation of the Virial identity, one that might be independent of the metric ansatz. We present examples for the spherical case and briefly discuss implications for the stationary and axisymmetric case.

# Contributed Talk

**Name:** Alexandre M. Pombo **Position:** PhD Student

**Affiliation:** Aveiro University

**Title:** The imitation game: Proca stars that can mimic the Schwarzschild shadow

**Abstract:** Can a \textit{dynamically robust} bosonic star (BS) produce an (effective) shadow that mimics that of a black hole (BH)? We focus on models of spherical BSs with free scalar or vector fields, as well as with polynomial or axionic self-interacting fields. The BH shadow is linked to the existence of light rings (LRs). For free bosonic fields, yielding \textit{mini}-BSs, it is known that these stars can become ultra-compact - $i.e.$, possess LRs - but only for perturbatively unstable solutions. We show this remains the case even when different self-interactions are considered. However, an effective shadow can arise in a different way: if BSs reproduce the existence of an innermost stable circular orbit (ISCO) for timelike geodesics (located at $r_{\rm ISCO}=6M$ for a Schwarzschild BH of mass $M$), the accretion flow morphology around BHs is mimicked and an effective shadow arises in an astrophysical environment. Even though spherical BSs may accommodate stable timelike circular orbits all the way down to their centre, we show the angular velocity $\Omega$ along such orbits may have a maximum away from the origin, at $R_{\Omega}$; this scale was recently observed to mimic the BH's ISCO in some scenarios of accretion flow. Then: $(i)$ for free scalar fields or with quartic self-interactions, $R_{\Omega}\neq 0$ only for perturbatively unstable BSs; $(ii)$ for higher scalar self-interactions, $e.g.$ axionic, $R_{\Omega}\neq 0$ is possible for perturbatively stable BSs, but no solution with $R_{\Omega}=6M$ was found in the parameter space explored; $(iii)$ but for free vector fields, yielding Proca stars, perturbatively stable solutions with $R_{\Omega}\neq 0$ exist, and indeed $R_{\Omega}=6M$ for a particular solution. {Thus, dynamically robust spherical Proca stars succeed in the imitation game: they can mimic the shadow of a (near-)equilibrium Schwarzschild BH with the same $M$, in an astrophysical environment, despite the absence of a LR, at least under some observation conditions, as we confirm by explicitly comparing the lensing of such Proca stars and Schwarzschild BHs.

# Contributed Talk

**Name:** Miguel Duarte **Position:** PhD Student

**Affiliation:** CAMGSD and CENTRA, Tecnico, Lisbon

**Title:** Peeling in Generalized Harmonic Gauge

**Abstract:** We show that a very large class of systems of non-linear wave equations, based on the good-bad-ugly model, admits polyhomogeneous expansions near null infinity. Exploiting these formal expansions of the metric components, the Peeling property of the Weyl tensor is revisited. The impact on the peeling property of the gauge choice and constraint additions is discussed. Finally, the special interplay between gauge and constraint addition, as well as its influence upon the asymptotic system and the decay of each of the metric components, is exploited to find a particular gauge which prevents the existence of logs to arbitrarily high order, hence recovering peeling.

# Contributed Talk

**Name:** Ángel Murcia Gil **Position:** PhD Student

**Affiliation:** Instituto de Física Teórica UAM/CSIC

**Title:** Duality-invariant extensions of Einstein-Maxwell theory

**Abstract:** We investigate higher-derivative extensions of Einstein-Maxwell theory that are invariant under electromagnetic duality rotations, allowing for non-minimal couplings between gravity and the gauge field. Working in a derivative expansion of the action, we characterize the Lagrangians giving rise to duality-invariant theories up to the eight-derivative level, providing the complete list of operators that one needs to include in the action. We also characterize the set of duality-invariant theories whose action is quadratic in the Maxwell field strength but which are non-minimally coupled to the curvature. Then we explore the effect of field redefinitions and we show that, to six derivatives, the most general duality-preserving theory can be mapped to Maxwell theory minimally coupled to a higher-derivative gravity containing only four non-topological higher-order operators. We conjecture that this is a general phenomenon at all orders, i.e, that any duality-invariant extension of Einstein-Maxwell theory is perturbatively equivalent to a higher-derivative gravity minimally coupled to Maxwell theory. Finally, we study charged black hole solutions in the six-derivative theory and we investigate additional constraints on the couplings motivated by the weak gravity conjecture. The talk would be mainly based on arXiv:2104.07674.

# Contributed Talk

**Name:** Ander Urio **Position:** PhD Student

**Affiliation:** University of the Basque Country

**Title:** Loop decay in Abelian-Higgs string networks

**Abstract:** The evolution of cosmic strings, in particular cosmic string loops, has been an open question for a number of years. The dynamics observed by field theory lattice simulations and by the Nambu-goto approximation do not agree, giving big differences in the lifetimes of loops, which for example affects their gravitational wave production. In this talk we will discuss the results obtained from lattice field theory loop evolution simulations, focusing on loops produced during the evolution of an actual realistic cosmic string network. We show that those loops decay proportional to L, but with a larger proportionality constant than the decay by GW. We see no dependency on the behaviour on the string decay on the string length. Moreover, motivated by recent results that show L^2 decay for loops created by artificially setting up string configurations, we propose another method that confirms the L^2 decay. This shows that the decay proportional to L is intrinsic to network loops, and requires further investigation.

# Contributed Talk

**Name:** Prado Martín-Moruno **Position:** Staff

**Affiliation:** Universidad Complutense de Madrid

**Title:** Hawking-Ellis classification of the stress-energy tensor: test-fields versus back-reaction

**Abstract:** We consider the Hawking-Ellis classification of stress-energy tensors, both in the test-field limit, and in the presence of back-reaction governed by the usual Einstein equations. For test fields one can get a type IV stress-energy tensor via quantum vacuum polarization effects. However, in the presence of back-reaction driven by the ordinary Einstein equations the situation is often much more constrained. In particular, in many physically interesting situations once one includes back-reaction the more unusual stress-energy types are automatically excluded.

# Contributed Talk

**Name:** Brien Nolan **Position:** Staff

**Affiliation:** Dublin City University

**Title:** Motion of a gyroscope on a closed timelike curve

**Abstract:** We consider the motion of a gyroscope on a closed timelike curve (CTC). A gyroscope is identified with a unit-length spacelike vector - a spin-vector - orthogonal to the tangent to the CTC, and satisfying the equations of Fermi-Walker transport along the curve. We investigate the consequences of the periodicity of the coefficients of the transport equations, which arise from the periodicty of the CTC, which is assumed to be piecewise $C^2$. We show that every CTC with period $T$ admits at least one $T−$periodic spin-vector. Further, either every other spin-vector is $T−$periodic, or no others are. It follows that gyroscopes carried by CTCs are either all $T−$periodic, or are generically not $T−$periodic. We consider examples of spacetimes admitting CTCs, and address the question of whether $T−$periodicity of gyroscopic motion occurs generically or only on a negligible set for these CTCs. We discuss these results from the perspective of principles of consistency in spacetimes admitting CTCs.

# Contributed Talk

**Name:** Ahmad Borzou **Position:** Staff

**Affiliation:** Baylor University

**Title:** Non-Geometrodynamic Lorentz Yang-Mills Theory of Gravity

**Abstract:** We present a non-geometrodynamic quantum Yang-Mills theory of gravity based on the homogeneous Lorentz group within the general framework of the Poincare gauge theories. The obstacles of this treatment are that first, on the one hand, the gauge group that is available for this purpose is non-compact. On the other hand, Yang-Mills theories with non-compact groups are rarely healthy, and only a few instances exist in the literature. Second, it is not clear how the direct observations of space-time waves can be explained when space-time has no dynamics. We show that the theory is unitary and is renormalizable to the one-loop perturbation. Although in our proposal, gravity is not associated with any elementary particle analogous to the graviton, classical helicity-two space-time waves are explained. Five essential exact solutions to the field equations of our proposal are presented as well. We also discuss a few experimental tests that can falsify the presented Yang-Mills theory.

# Contributed Talk

**Name:** Norbert Van den Bergh **Position:** Staff

**Affiliation:** Ghent University

**Title:** Non-aligned Einstein-Maxwell-Robinson-Trautman fields of Petrov type D

**Abstract:** In the quest for exact solutions of the Einstein-Maxwell equations a considerable amount of research has been devoted to the study of aligned EM fields, in which at least one of the principal null directions of the electromagnetic field F is parallel to a PND of the Weyl tensor, a so called Debever-Penrose (DP) direction. One of the main triumphs of this effort --spread out between 1960 and 1980-- has been the complete integration of the field equations (with a possible non-0 cosmological constant Λ), for the Petrov type D doubly aligned non-null EM fields, in which both real PNDs of F are parallel to a corresponding double DP vector. In a recent systematic treatment of the non-aligned algebraically special EM fields it was noted that, at least for non-0 Λ, the double alignment condition is actually a consequence of the multiple DP vectors being geodesic and shear-free. A natural question therefore arises as to whether EM solutions exist which are of Petrov type D, have Λ=0 and in which the two real DP vectors are geodesic and shear-free, but both being non aligned with the PND's of F. Recently [Class. Quantum Grav. 37, 21, 2020] we have been able to answer this question affirmatively, by completing the full integration of the EM field equations for the double Robinson-Trautman family, under the additional assumption that also the complex eigenvectors of the canonical Weyl-tetrad are hypersurface-orthogonal.

# Contributed Talk

**Name:** Ivan Kolar **Position:** Post-Doc/Research Fellow

**Affiliation:** University of Groningen

**Title:** Exact solutions with null radiation in higher and infinite derivative gravity

**Abstract:** I will describe methods we recently used for finding solutions with null radiation in generic theories of gravity with quadratic curvature; these include, not only the well-known Stelle's fourth derivative gravity but also, for example, the non-local gravity with an infinite number of derivatives. Although the field equations are very complicated in general, they simplify drastically for pp-waves of type III and some other non-expanding gravitational waves. The resulting equations can be solved exactly due to partial decoupling and linearity. To provide explicit examples, I will present some solutions describing gravitational waves generated by (spinning) null matter propagating in Minkowski and (anti-)de Sitter spacetimes, which are higher-derivative/non-local analogues of Aichelburg-Sexl, Hotta-Tanaka, and gyraton metrics.

# Contributed Talk

**Name:** Daniele Gregoris **Position:** Post-Doc/Research Fellow

**Affiliation:** Jiangsu University of Science and Technology

**Title:** Thermodynamics of shearing massless scalar field spacetimes is inconsistent with the Weyl curvature hypothesis

**Abstract:** In my talk, I will critically examine the Penrose conjecture according to which the gravitational entropy should be quantified via the Weyl curvature, with the Clifton-Ellis-Tavakol entropy being one specific realization of this proposal. In fact, I will show that in some exact inhomogeneous and anisotropic cosmological models which arise in general relativity with either closed and open topologies, the Clifton-Ellis-Tavakol gravitational entropy is increasing in time despite the decrease of the magnitude of the Weyl curvature: this is possible thanks to the growth of the spacetime shearing effects. The matter content driving the dynamics of this model comes in the form of a chameleon massless scalar field. The values of the free parameters entering the metric tensor we choose are those consistent with the holographic principle and the second law of thermodynamics. Finally, I will mention the possible formation of some primordial structures, like the Large Quasar Groups, in this class of models as suggested by the growth of gravitational entropy, and whose existence cannot be accounted for by standard perturbation techniques over a Friedman background. My talk is based on Phys. Rev. D 102, 023539 (2020).

# Contributed Talk

**Name:** Sumanta Chakraborty **Position:** Staff

**Affiliation:** Indian Association for the Cultivation of Science

**Title:** Gravitational multipole moments for asymptotically de Sitter spacetimes

**Abstract:** We provide a prescription to compute the gravitational multipole moments of compact objects for asymptotically de Sitter spacetimes. Our prescription builds upon a recent definition of the gravitational multipole moments in terms of Noether charges associated to specific vector fields, within the residual harmonic gauge, dubbed multipole symmetries. We first derive the multipole symmetries for spacetimes which are asymptotically de Sitter; we also show that these symmetry vector fields eliminate the non-propagating degrees of freedom from the linearized gravitational wave equation. We then apply our prescription to the Kerr-de Sitter black hole and compute its multipole structure. Our result recovers the Geroch-Hansen moments of the Kerr black hole in the limit of vanishing cosmological constant.

## Contributed Talk

**Name:** Vesselin Gueorguiev **Position:** Post-Doc/Research Fellow

**Affiliation:** Institute for Advanced Physical Studies (IAPS))

**Title:** Geometric Justification of the Fundamental Interaction Fields for the Classical Long-Range Forces

**Abstract:** Based on the principle of reparametrization invariance, the general structure of physically relevant classical matter systems is illuminated within the Lagrangian framework. In a straightforward way, the matter Lagrangian contains background interaction fields, such as a 1-form field analogous to the electromagnetic vector potential and symmetric tensor for gravity. The geometric justification of the interaction field Lagrangians for the electromagnetic and gravitational interactions are emphasized. The concept of fictitious accelerations due to un-proper time parametrization is introduced and its implications are discussed. The framework naturally suggests new classical interaction fields beyond electromagnetism and gravity. The simplest model with such fields is analyzed and its relevance to dark matter and dark energy phenomena on large/cosmological scales is inferred. Unusual pathological behavior in the Newtonian limit is suggested to be a precursor of quantum effects and inflation-like processes at microscopic scales. Paper published by Vesselin G. Gueorguiev and Andre Maeder in Symmetry 2021, 13, 379. https://doi.org/10.3390/sym13030379 [https://arxiv.org/abs/1907.05248]

# Contributed Talk

**Name:** Nadja Simão Magalhães **Position:** Staff

**Affiliation:** Physics Department, Federal University of Sao Paulo (UNIFESP)

**Title:** Gravitational wave Poynting vector and gravitoelectromagnetism

**Abstract:** Gravitoelectromagnetism (GEM) is a formalism based on general relativity that uses mathematical tools from the electromagnetic theory to investigate gravitational systems. This is possible when one seeks a general linear solution of the gravitational field equations while the Minkowski metric is perturbed due to the presence of gravitating sources and the perturbation obeys the transverse gauge condition. The source in general rotates and must consist of a finite distribution of slowly moving matter. As the perturbation is small, all terms of O(c^{-4}) are neglected. Under these conditions GEM fields, E and B, can be defined in direct analogy with electromagnetism and GEM field equations are obtained. From the Lagrangian for the motion of a massive test particle written to linear order in the scalar and vector GEM fields an analogue of the Lorentz force law can be obtained. Under the GEM gauge transformation the GEM fields are invariant in close analogy with electrodynamics. In the case of a stationary configuration the GEM Poynting vector (PV) can be defined [arXiv:gr-qc/0311030v2 (2008)]. The suggestion of a PV for gravitational waves was posed by one of us in the context of general relativity [MNRAS 274, 670 (1995)]. In this work we discuss the relation between this proposed PV and the GEM PV to analyse the possibility of relating the GEM formalism of [arXiv:gr-qc/0311030v2 (2008)] to the gravitational waves investigated in [MNRAS 274, 670 (1995)].

# Contributed Talk

**Name:** Filipe Costa **Position:** Post-Doc/Research Fellow

**Affiliation:** CAMGSD - Instituto Superior Técnico, Universidade de Lisboa

**Title:** Gravitomagnetism in the Lewis cylindrical metrics

**Abstract:** The Lewis solutions describe the exterior gravitational field produced by infinitely long rotating cylinders, and are useful models for global gravitational effects. When the metric parameters are real (Weyl class), the metrics of rotating and static cylinders are locally indistinguishable, but known to globally differ. The significance of this difference, both in terms of concrete physical effects and of the mathematical invariants where the rotation imprints itself, remained however an open problem. In this talk we will address these issues. We show that the Weyl class metric can be put into a 'canonical' form which depends explicitly only on three parameters with a clear physical significance: the Komar mass and angular momentum per unit length, plus the angle deficit. This new form of the metric reveals that the two settings differ only at the level of the gravitomagnetic vector potential which, for a rotating cylinder, cannot be eliminated by any global coordinate transformation. It manifests itself in the Sagnac and gravitomagnetic clock effects. This perfectly mirrors the electromagnetic field of a rotating charged cylinder, which likewise differs from the static case only in the vector potential, responsible for the Aharonov–Bohm effect (formally analogous to the Sagnac effect). The notions of local and global staticity are also revisited.

# Contributed Talk

**Name:** Takuya Katagiri **Position:** PhD Student

**Affiliation:** Rikkyo university

**Title:** Stability of small charged anti-de Sitter black holes in the Robin boundary

**Abstract:** We analytically and numerically study quasinormal frequencies (QNFs) of neutral and charged scalar fields in the charged anti-de Sitter (AdS) black holes and discuss the stability of the black holes in terms of the QNFs. We focus on the range of the mass squared $\mu^2$ of the scalar fields for which the Robin boundary condition parametrised by $\zeta$ applies at the conformal infinity. We find that if the black hole of radius $r_+$ and charge $Q$ is much smaller than the AdS length $\ell$, the instability of the charged scalar field can be understood in terms of superradiance in the reflective boundary condition. Noting that the s-wave normal frequency in the AdS spacetime is a decreasing function of $\zeta$, we find that if $|eQ|\ell/r_{+}$ is greater than $(3+\sqrt{9+4\mu^2\ell^2})/2$, where $e$ is the charge of the scalar field, the black hole is superradiantly unstable irrespectively of $\zeta$. On the other hand, if $|eQ|\ell/r_{+}$ is equal to or smaller than this critical value, the stability crucially depends on $\zeta$ and there appears a purely oscillating mode at the onset of the instability. We argue that as a result of the superradiant instability, the scalar field gains charge from the black hole and energy from its ambient electric field, while the black hole gives charge to the scalar field and gains energy from the scalar field but decreases its asymptotic mass parameter.

# Contributed Talk

**Name:** Etevaldo Costa **Position:** Post-Doc/Research Fellow

**Affiliation:** Universidade de São Paulo

**Title:** Calculation of multipole moments of axistationary electrovacuum spacetimes

**Abstract:** The multipole moments expansion in General Relativity was introduced in the ’70s by Geroch (Hansen) for asymptotically flat static (stationary) spacetimes. For stationary axially symmetric (electro-)vacuum spacetimes, the multipole moments can be expressed in terms of the power series expansion coefficients of the Ernst potential on the axis. Although Geroch and Hansen have given a well-posed definition of the multipole moments in GR, it was only after Fodor, Hoenselaers and Perjes introduced an algorithm to evaluate the momenta that it became practical to use them to characterize new solutions. In this talk, I will present a simpler, more efficient calculation of the multipole moments, applying methods introduced by Bäckdahl and Herberthson. For the non-vacuum electromagnetic case, our results for the octupole and higher moments differ from the results already published in the literature. The reason for this difference is that we correct an earlier unnoticed mistake in the power series solution of the Ernst equations.

# Contributed Talk

**Name:** Susmita Jana **Position:** PhD Student

**Affiliation:** IIT Bombay

**Title:** Constraints on the non-minimal coupling of Electromagnetic fields from astrophysical observations

**Abstract:** Strong gravity regions, like the neighborhood of black holes or neutron stars, can induce non-minimal couplings between electromagnetic fields and gravity. In these regions, gravitational fields behave as a non-linear medium in which the electromagnetic fields propagate. For a system of mass M, and size R, the surface potential scales as M/R. Pulsar timing array, Double pulsar Shapiro delay, and Event horizon telescope probe that largest surface potentials [10 −4 − 10 −2 ]. With many future experiments, it is possible to constrain the non-minimal coupling between electromagnetic fields and gravity. As a step in this direction, we consider the non-minimal coupling of EM field tensor through Riemann tensor for a dynamical black-hole, described by the Sultana-Dyer metric. The non-minimal coupling leads to modified dispersion relations of photons, which get simplified at E/L >> 1 regime, where E and L are two conserved quantities obtained by taking into account the symmetries of the metric. We calculate polarization-dependent photon deflection angle and arrival time from these dispersion relations, which we evaluate considering different astrophysical sources of photons. We compare the analytical results with the current astrophysical observations to constraint the non-minimal coupling parameters to Riemann tensor more stringently.

# Contributed Talk

**Name:** Ruth Lazkoz **Position:** Staff

**Affiliation:** University of the Basque Country

**Title:** Observational constraints on cosmological solutions of f(Q)f(Q)f(Q) theories

**Abstract:** Over the last years some interest has been gathered by f(Q) theories, which are new candidates to replace Einstein's prescription for gravity. The nonmetricity tensor Q allows to put forward the assumption of a free torsionless connection and, consequently, new degrees of freedom in the action are taken into account. This work focuses on a class of f(Q) theories, characterized by the presence of a general power-law term which adds up to the standard (linear in) Q term in the action, and on new cosmological scenarios arising from them. Using the Markov chain Monte Carlo method, we carry out statistical tests relying upon background data such as Type Ia supernovae luminosities and direct Hubble data (from cosmic clocks), along with cosmic microwave background shift and baryon acoustic oscillations data. This allows us to perform a multifaceted comparison between these new cosmologies and the (concordance) ΛCDM setup. We conclude that, at the current precision level, the best fits of our f(Q) models correspond to values of their specific parameters which make them hardly distinguishable from our general relativity "échantillon," that is, ΛCDM.

# Contributed Talk

**Name:** Matteo Fasiello **Position:** Staff

**Affiliation:** IFT Madrid

**Title:** Probing Inflation with Primordial Messengers

**Abstract:** Some of our best ideas on early universe physics are about to be put to the test by an unprecedented array of cosmological probes. The data these will collect span a vast range of scales, from the CMB to large scale structure, from pulsar timing arrays all the way to laser interferometers. This combined wealth of new information holds the potential to transform our understanding of cosmology and, possibly, also particle physics. In this context probing the earliest accessible epoch, inflation, is crucial: inflation can provide a cosmological portal to otherwise inaccessible energy scales. This is the "cosmological collider" idea. The spectacular success of the inflationary paradigm in explaining the origin of cosmic structure demands that we tackle a number of compelling questions still in need of an answer: what is the energy scale of inflation? What fields were active during inflation? In this talk I will review recent progress on the inflationary field content. I will survey different approaches to address the most pressing challenges and provide examples including axion-inflation models and the so-called effective theory approach. I will then focus on the key observables, starting with primordial gravitational waves, and discuss their prospects for detection.

# Contributed Talk

**Name:** Mihaela Baloi **Position:** Post-Doc/Research Fellow

**Affiliation:** West University of Timisoara, Romania

**Title:** Number density of Z bosons produced in emission processes by neutrinos at the early stages of universe

**Abstract:** Production of Z bosons in emission processes by neutrinos in the expanding de Sitter universe is studied by using perturbative methods. The amplitude and probability for the spontaneous emission of a Z boson by a neutrino is computed analytically, then we perform a graphical analysis in terms of the expansion parameter. Our results prove that this process is possible only for large expansion conditions of the early Universe. The rate of transition for Z boson emission by a neutrino is computed in de Sitter geometry. Finally the density number of Z bosons is established and we analyze the variation of this quantity with the expansion parameter and temperature.

# Contributed Talk

**Name:** Alberto Roper Pol **Position:** Post-Doc/Research Fellow

**Affiliation:** APC

**Title:** Gravitational wave radiation from early universe turbulence

**Abstract:** The generation of primordial magnetic fields and its interaction with the primordial plasma during cosmological phase transitions is turbulent in nature. I will describe and discuss results of direct numerical simulations of magnetohydrodynamic (MHD) turbulence in the early universe and the resulting stochastic gravitational wave background (SGWB). In addition to the SGWB, the primordial magnetic field will evolve up to our present time and its relics can explain indirect observations of weak magnetic fields coherent on very large scales. I will apply the numerical results to magnetic fields produced at the electroweak and the QCD phase transitions and show that these signals may be detectable by the planned Laser Interferometer Space Antenna and by the Pulsar Timing Array collaborations. The detection of these signals would lead to the understanding of cosmological phase transition physics, which can have consequences on the baryon asymmetry problem and on the origin seed of observed magnetic fields coherent over very large scales at the present time.

# Contributed Talk

**Name:** Ivan de Martino **Position:** Post-Doc/Research Fellow

**Affiliation:** Universidad de Salamanca

**Title:** Distinguishing cores from cusps in the dark matter density profile using the proper motions measurements

**Abstract:** We have shown the potential of next-generation astrometric satellites for distinguishing between a cusp and a core in the dark matter density profile. This goal can be achieved with the measure of the proper motions of at least 6000 stars within a nearby dwarf galaxy with an accuracy of 1 km~s$^{-1}$ at most. We have built mock star catalogues similar to those expected in future astrometric missions like Theia. Our mocks include celestial coordinates, radial velocity, and proper motion of the stars, while density and velocity fields of the stars are sampled from an extended Navarro-Frank-White (eNWF) spherical model. Employing a Monte Carlo Markov Chain algorithm, we have shown that the eNFW parameters with a relative uncertainty of 20\%, on average can be recovered, and thus we can distinguish between a core and a cusp at $3\sigma$. Our result shows that the measure of the proper motions of stars can provide a fundamental contribution to understanding the nature and the properties of dark matter particles.

# Contributed Talk

**Name:** Saikat Chakraborty **Position:** Post-Doc/Research Fellow

**Affiliation:** Center for Gravitation and Cosmology, Yangzhou University

**Title:** Towards a ΛCDM cosmology in f(R) gravity

**Abstract:** ΛCDM model till date remains the best observationally fitting model for late time cosmology. However, this model suffers from the theoretical issue that the quantum vacuum energy, which is the only known candidate for Λ, gives from QFT calculation a value that mismatches with the observed value of Λ by orders of magnitude. This theoretical issue motivated the search for alternative late time cosmological models. Among various alternative models, a broad class of models incorporate modified gravity, within which a significant subclass are f(R) gravity models. A very pertinent question to ask is whether there are some f(R) gravity models that can exactly mimic the ΛCDM evolution history. This question is of interest because if there are indeed such f(R) gravity models, then one need not worry about the theoretical issue on Λ. This problem can be approached with the reconstruction method of f(R) gravity, although the reconstructed f(R) form is too complicated for any further analytical treatment. We approach this problem with a new model-independent dynamical systems formulation of f(R) that we recently introduced in 2103.02274. We show that there is an inherent issue in trying to reproduce ΛCDM cosmology in f(R) gravity.

# Contributed Talk

**Name:** Michael Bradley **Position:** Staff

**Affiliation:** Dept. of Physics, Umeå University

**Title:** General Perturbations of LRS Class II Cosmologies with Applications to Dissipative Fluids

**Abstract:** First order perturbations of homogeneous and hypersurface orthogonal LRS (Locally Rotationally Symmetric) class II cosmologies with a cosmological constant are considered in the framework of the 1+1+2 covariant decomposition of spacetime. The perturbations, which are for a general energy-momentum tensor, include scalar, vector and tensor modes and extend some previous works where matter was assumed to be a perfect fluid. Through a harmonic decomposition the system of equations is then transformed to evolution equations in time and algebraic constraints. This is then applied to dissipative one-component fluids, and on using the simplified acausal Eckart theory, which should be a fair approximation when relaxation times are short compared to the expansion rate, the system is reduced to two closed subsystems governed by four and eight harmonic coefficients for the odd and even sectors respectively. The system is also seen to close in a simplifed causal theory.

# Contributed Talk

**Name:** Javier Olmedo **Position:** Post-Doc/Research Fellow

**Affiliation:** Universidad de Granada

**Title:** Inhomogeneous polarized Gowdy model and inflation

**Abstract:** In this talk I will show that polarized Gowdy cosmologies on the three torus coupled to a massive scalar field are relevant physical inhomogeneous cosmological models. They admit a simple splitting between homogeneous and inhomogeneous sectors after a suitable gauge fixing. Besides, there are regimes of physical interest where we recover a linear dynamics of nonperturbative inhomogeneities, despite the metric is fully inhomogeneous. Inhomogeneities can be expressed in Fourier modes and written as linear combinations of a basis of orthonormal complex solutions to the equations of motion, with coefficients that turn out to be an infinite collection of constants of motion. We argue that this model can help us to understand nonperturbative inhomogeneous early universes dominated by the kinetic energy of an inflaton at early times that eventually reach a slow-roll regime with a mean scale factor that expands nearly exponentially at late times, reaching an isotropic and homogeneous geometry.

# Contributed Talk

**Name:** Amare Abebe **Position:** Staff

**Affiliation:** Center for Space Research, North-West University

**Title:** Dark-fluid constraints of shear-free universes

**Abstract:** We present the evolutionary constraints of shear-free cosmological solutions in the presence of a dark fluid. After describing the general evolution and constraint equations for quasi-Newtonian and anti-Newtonian spacetimes, we derive, at the level of linear perturbations, the conditions for the existence and consistent evolution of such spacetimes when they are endowed with the Chaplygin gas which mimics a unified description of dark matter and dark energy.

# Contributed Talk

**Name:** Vitor Emanuel Moreira Bessa **Position:** PhD Student

**Affiliation:** CMAT / FCUP

**Title:** Global dynamics of interacting scalar field potentials and perfect fluids in Robertson-Walker cosmologies

**Abstract:** In this talk I will give an overview of the dynamics in a warm inflationary scenario with monomial scalar field potentials. We then analyse the dynamics of the Einstein equations coupled to the Klein-Gordon equation for a minimally coupled scalar field interacting with a perfect fluid in flat Robertson-Walker spacetimes. We perform a global dynamical system's analysis of the model identifying its past and future attractors and provide detailed asymptotic estimates of the dynamics.

# Contributed Talk

**Name:** Rubén Arjona **Position:** PhD Student

**Affiliation:** Universidad Autónoma de Madrid

**Title:** Exploring the nature of dark energy with Machine Learning

**Abstract:** One of the most pressing mysteries in physics is the accelerating expansion of the Universe, usually attributed to a dark energy component. The standard model of cosmology, which contains only six free parameters describing the matter and dark energy content of the Universe is so far the best phenomenological fit to the data to percent level precision.  Machine Learning (ML) techniques will play a big role in testing accurately the standard model of cosmology, but will also help in the search for new physics and tensions in the data by placing tighter constraints on cosmological parameters. I will present a unified ML analysis of all the currently available cosmological data in order to reconstruct several key background and perturbations variables in a model-independent manner in order to explore the nature of dark energy.

# Contributed Talk

**Name:** Sebastián Nájera Valencia **Position:** PhD Student

**Affiliation:** ICN, UNAM

**Title:** Non-comoving Cold Dark Matter in a $\Lambda $CDM background

**Abstract:** We examine the evolution of peculiar velocities of cold dark matter (CDM) in localized arrays of inhomogeneous cosmic structures in a $\Lambda$CDM background that can be identified as a frame comoving with the Cosmic Microwave (CMB). These arrays are constructed by smoothly matching to this cosmological background regions of Szekeres-II models whose source is an imperfect fluid reinterpreted as non-comoving dust, keeping only first order terms in v/c. Considering a single Szekeres-II region matched along two comoving interfaces to a $\Lambda$CDM background, the magnitudes of peculiar velocities within this region are compatible with values reported in the literature, while the present day Hubble expansion scalar differs from that of the $\Lambda$CDM background value by a 10\% factor, a result that might provide useful information to the ongoing debate on the H0 tension.

# Contributed Talk

**Name:** Saboura sadat Zamani **Position:** Master Student

**Affiliation:** Golestan University

**Title:** Hubble Tension in Torsion Theories of Gravity

**Abstract:** Hubble tension, which is the apparent discrepancy between the value of $H0$ measured by cosmological probes and local measurement, is one of the most important problems in modern cosmology. The measurement of $H0$ relies on the expansion history and cosmological dynamics, specially at higher redshifts. The presence of this tension may indicate new physics beyond the flat $\Lambda CDM$ model of the standard cosmology which is based on general relativity. In this paper, we study the Hubble tension problem in the framework of torsion theories of gravity, particularly Poincare gauge theory of gravity and its special case, The Einstein-Cartan theory. Gravitational interactions are characterized by curvature and torsion in these theories. The presence of torsion affects the cosmological dynamics in many ways. Particularly, it alters the formulas for determining luminosity and angular diameter distances, as well as the time delay between various images of a lensing system. These changes may alter the measurement of $H0$ and provide a way to solve the Hubble tension problem.

# Contributed Talk

**Name:** Tomas Ortin **Position:** Staff

**Affiliation:** IFT UAM/CSIC

**Title:** On Wald entropy

**Abstract:** Wald's approach to the first law of black hole mechanics and to the computation of the black hole entropy can be straightforwardly applied to theories of pure gravity of higher order in the curvature (Iyer-Wald prescription). However, its application to theories with matter fields is less obvious (the Iyer-Wald prescription is not valid) because most matter fields have gauge freedoms and cannot be treated as simple ("world") tensors. We report on progress in the handling of matter fields with gauge freedoms, the treatment of magnetic charges and of the cosmological constant. We apply this treatment to the effective action of the heterotic string at first order in alpha' , which has very complex gauge symmetries, deriving the first law and finding a manifestly gauge-invariant entropy formula which differs from the one that fllows from the Iyer-Wald prescription, which is not gauge invariant.

# Contributed Talk

**Name:** Guillermo A. Mena Marugán **Position:** Staff

**Affiliation:** Instituto de Estructura de la Materia, CSIC

**Title:** Asymptotic Hamiltonian diagonalization in hybrid (loop) quantum cosmology

**Abstract:** We explain how to select a natural vacuum state for scalar and tensor perturbations in the context of hybrid quantum cosmology by identifying variables that are optimally adapted to the evolution of the entire cosmology, in the sense that the Hamiltonian that generates the dynamics of the perturbations remains diagonal. We check that the asymptotic conditions that follow from this diagonalization allow us to select the standard vacuum in Minkowski and in de Sitter spacetime.

# Contributed Talk

**Name:** Parthasarathi Majumdar **Position:** Staff

**Affiliation:** Indian Association for the Cultivation of Science, Kolkata, India

**Title:** Holographic Bound on Area of Compact Binary Merger Remnant

**Abstract:** Using concomitantly the Generalized Second Law of black hole thermodynamics and the holographic Bekenstein entropy bound embellished by Loop Quantum Gravity corrections to quantum black hole entropy, we show that the boundary cross-sectional area of the post-merger remnant formed from the compact binary merger in gravitational wave detection experiments like GW150914 {\it et. seq.}, by the LIGO-VIRGO collaboration, is bounded from below. This lower bound is more general than the bound obtained from application of Hawking's classical area theorem for black holes, since it does not depend on whether the inspiralling compact binary pair or the postmerger remnant consists of black holes or other exotic compact objects. The derivation of the bound entails an estimate of the entropy of the gravitational waves emitted during the binary merger which adapts to gravitational waves an extant formalism proposed originally for particle ensembles. The results for the minimal cross-sectional area of the merger remnant due to binary compact mergers observed recently by the LIGO-VIRGO collaboration are discussed. While accurate measurement of the mass of the remnant for the BNS merger GW170817 remains a challenge, we provide a {\it proof of principle} that for BNS mergers our lower bound on the cross-sectional area of the remnant provides an alternative approach to probe the validity of neutron star Equations of State, {\it independent} of the tidal deformations of the components.

# Contributed Talk

**Name:** Guilherme Raposo **Position:** Post-Doc/Research Fellow

**Affiliation:** CIDMA-CENTRA

**Title:** Multipole Moments of Fuzzballs

**Abstract:** Some of the deep conceptual problems associated with classical black holes can be addressed in string theory according to the "fuzzball" paradigm. Within this approach, a black hole can have a microscopic description in terms of regular and horizonless, microstate geometries. In this talk we discuss the multipolar structure of these microstate geometries and we will show that it can be much richer and less symmetric than the corresponding classical black hole structure. The analysis here discussed is particularly relevant in the context of measuring multipole moments of dark ultracompact objects and of observational tests to distinguish fuzzballs from classical black holes.

# Contributed Talk

**Name:** Johannes Münch **Position:** Post-Doc/Research Fellow

**Affiliation:** CPT Marseille

**Title:** Effective Quantum Black Hole Collapse via Surface Matching

**Abstract:** The fate of matter forming a black hole is still an open problem, although models of quantum gravity corrected black holes are available. In loop quantum gravity (LQG) models were presented, which resolve the classical singularity in the centre of the black hole by means of a black-to-white hole transition, but neglect the collapse process. The situation is similar in other quantum gravity approaches, where eternal non-singular models are available. A strategy is presented to generalise eternal models to dynamical collapse models by surface matching. Assuming 1) the validity of a static quantum black hole spacetime outside the collapsing matter, 2) homogeneity of the collapsing matter, and 3) differentiability at the surface of the matter fixes the dynamics of the spacetime uniquely. It is argued that these assumptions resemble a collapse of pressure-less dust and thus generalises the Oppenheimer-Snyder-Datt model. The junction conditions and the spacetime dynamics are discussed generically for bouncing black hole spacetimes, as proposed by LQG, although the scheme is approach independent. A global spacetime picture of the collapse for a specific LQG inspired model is discussed.

# Contributed Talk

**Name:** Taishi Ikeda **Position:** Post-Doc/Research Fellow

**Affiliation:** Sapienza University of Rome

**Title:** Black-hole microstate spectroscopy: ringdown, quasinormal modes, and echoes

**Abstract:** Deep conceptual problems associated with classical black holes can be addressed in string theory by the ``fuzzball'' paradigm, which provides a microscopic description of a black hole in terms of a hermodynamically large number of regular, horizonless, geometries with much less symmetry than the corresponding black hole. Motivated by the tantalizing possibility to observe quantum gravity signatures near astrophysical compact objects in this scenario, we perform the first $3+1$ numerical simulations of a scalar field propagating on a large class of multicenter geometries with no spatial isometries arising from ${\cal N}=2$ four-dimensional supergravity. We identify the prompt response to the perturbation and the ringdown modes associated with the photon sphere, which are similar to the black-hole case, and the appearance of echoes at later time, which is a smoking gun of the absence of a horizon and of the regular interior of these solutions. The response is in agreement with an analytical model based on geodesic motion in these complicated geometries. Our results provide the first numerical evidence for the dynamical linear stability of fuzzballs, and pave the way for an accurate discrimination between fuzzballs and black holes using gravitational-wave spectroscopy.

# Contributed Talk

**Name:** Ivan Agullo **Position:** Staff

**Affiliation:** Louisiana State University

**Title:** Quantum aspects of stimulated Hawking radiation on an analog white-black Hole pair

**Abstract:** The stimulated Hawking effect is commonly regarded as as classical process, of little value to enhance and measure the quantum aspects of the Hawking process in analog systems (i.e. entanglement). In this talk we will argue otherwise, and describe a protocol to amplify and observe these quantum features, based on stimulating the process with a single-mode squeezed input. Although our ideas are general, we formulated them in the context of optical systems containing the analog of a pair white-black hole. This results open the door to new possibilities of experimental verification of the Hawking effect.

# Contributed Talk

**Name:** Nikodem Poplawski **Position:** Staff

**Affiliation:** University of New Haven

**Title:** Universe in a black hole with spin and torsion

**Abstract:** We consider gravitational collapse of a spherically symmetric sphere of a fluid with spin and torsion into a black hole. We use the Tolman metric and the Einstein-Cartan field equations with a relativistic spin fluid as a source. We show that gravitational repulsion of torsion prevents a singularity and replaces it with a nonsingular bounce. Quantum particle production during contraction strengthens torsion in opposing shear. Particle production during expansion can produce enormous amounts of matter and generate a finite period of inflation. The resulting closed universe on the other side of the event horizon may have several bounces. Such a universe is oscillatory, with each cycle larger in size then the previous cycle, until it reaches the cosmological size and expands indefinitely. Our universe might have therefore originated from a black hole existing in another universe.

# Contributed Talk

**Name:** Beatriz Elizaga Navascués **Position:** Post-Doc/Research Fellow

**Affiliation:** Waseda University

**Title:** Relativistic vs. loop quantum effects in the primordial power spectrum

**Abstract:** We present an analytical study of the main imprints that a fast-roll pre-inflationary regime in General Relativity and in Loop Quantum Cosmology can leave on the primordial power spectrum of scalar and tensor perturbations. In particular, effective regimes of Loop Quantum Cosmology of phenomenological interest display a classical epoch of decelerated expansion prior to a short-lived period of slow-roll inflation. The equations that evolve this cosmology backwards in time eventually depart from Friedmann equations and describe a bounce of quantum origin. In order to extract robust predictions from these epochs when quantum cosmology effects may have been important, it is of the utmost importance to disentangle their imprints on the evolution from those coming from the fast-roll regime. The possibility of clearly understanding these differences depends strongly on the choice of initial conditions (i.e., the vacuum state) of the perturbations. We consider the same physical motivation for the choice of state in both types of cosmological backgrounds (relativistic and of loop quantum origin). Then, after performing a series of analytic approximations, we extract the main differences between the resulting power spectra and explain their fundamental origin.

# Contributed Talk

**Name:** Samuel Barroso Bellido **Position:** PhD Student

**Affiliation:** University of Szczecin

**Title:** Entanglement Entropy at Critical Points in the Multiverse

**Abstract:** Recently the entanglement entropy between universes has been calculated, an entropy which somehow describes the quantumness of a homogeneous multiverse. The third quantization formalism of canonical quantum gravity is used here. I will show improvements of the results in a more general scenario, studying what happens at critical points of the evolution of a classical universe. We infer the relation of that entanglement entropy with the Hubble parameter of single universes.

# Contributed Talk

**Name:** Alejandro García-Quismondo **Position:** PhD Student

**Affiliation:** Instituto de Estructura de la Materia (CSIC)

**Title:** Investigating an alternative Hamiltonian derivation of the Ashtekar-Olmedo-Singh black hole solution

**Abstract:** Recently, a new proposal has been put forward for the computation of the effective equations governing the dynamics of an uncharged, nonrotating black hole in the framework of loop quantum cosmology. The key premise is to define the parameters that regulate the introduction of quantum effects in the system as suitable functions of two constants of motion, breaking the decoupling between two sectors of phase space that had previously been considered independent. In this talk, I will discuss the motivations and consequences of this choice and examine some of the features of the resulting model, seeking similarities and possible differences with respect to the original works by Ashtekar, Olmedo and Singh.

# Contributed Talk

**Name:** Rafael Jiménez Llamas **Position:** PhD Student

**Affiliation:** Universidad Autónoma de Madrid

**Title:** Effects of a scalar field potential on primordial perturbations in hybrid (loop) quantum cosmology.

**Abstract:** There is an increasing interest in cosmological models with scalar fields that present kinetically dominated phases in their evolution, since these may have played a relevant role in the very early stages of the Universe and lead to modifications in observable quantities, e.g. the cosmic microwave background. The departures of this scenario from standard slow-roll inflation prevent one for employing the approximate analytical formulas for the power spectrum that are valid in slow roll, complicating the calculations, that, in most cases, have to be done numerically. Moreover, the complexity of these calculations increases if the model takes into account the quantum behavior of the background, incorporating it by means of expectation values on the background geometry, as it happens in hybrid quantum cosmology. In this situation, an interesting possibility consists in approximating our description of the perturbations around the free evolution without potential, so that only the knowledge of the dynamics of this particular case is required in full detail. In order to consider the influence of the potential, it is necessary to include the corrections that its presence produces on this free dynamics. We analyze these corrections at dominant order. In principle, the analysis that we present can be extended to cover higher-order corrections as well. In particular, our results facilitate the study of the quantum geometry effects on the primordial perturbations, which, in models as those of LQC, occur in kinematically dominated regimes.

# Contributed Talk

**Name:** Benjamin Berczi **Position:** PhD Student

**Affiliation:** University of Nottingham

**Title:** Gravitational collapse of quantum fields

**Abstract:** Semiclassical black holes have been in the forefront of research for decades, in various shapes and forms. We have developed a formalism using which a genuine 4D quantum scalar field can be numerically simulated to collapse into a black hole. The new formalism utilises the notion of coherent states to relate the semiclassical simulation to the well-studied classical one. Thus the classical scenarios are easily replicated and also the new quantum effects can be separated straightforwardly.

# Contributed Talk

**Name:** István Rácz **Position:** Staff

**Affiliation:** Wigner RCP

**Title:** On the nature of spacetime singularities

**Abstract:** The seminal singularity theorems of Penrose and Hawking prove, under very generic and plausible conditions, the existence of inextendible causal geodesics. In contrast, it is also widely expected that some physical quantities should not remain bounded while approaching these singularities. I will discuss how results on spacetime extensions could provide vital insights concerning the generic properties of spacetime singularities.

# Contributed Talk

**Name:** Vladimir Chernov **Position:** Staff

**Affiliation:** Dartmouth College

**Title:** Linking: causality and black holes; and cosmic censorship of smooth structures

**Abstract:** Two events in a spacetime are called causally related if the information can get from one event point to the other. In the joint works with Stefan Nemirovski we established that Legendrian linking of the spheres of light rays passing through the two points completely determines causality for spacetimes of dimensions greater or equal than 4. For the spaces times of dimension 3 causal structure is completely determined by topological linking. These results settle the conjectures of Robert Low and of Jose Natario and Paul Todd. They also give an answer to the problem on the Vladimir Arnold problem list communicated by Roger Penrose. We will discuss these results and some ideas about how to apply the link theory to the study of black holes. If time permits we will explain why exotic smooth structures are likely not useful in general relativity, since the natural physical assumption impose strong censorship (similar in spirit to the one of Penrose's cosmic censorship conjecture) on the class of possible smooth structures on a spacetime. The resulting smooth structure is unique and natural.

# Contributed Talk

**Name:** Artur Alho **Position:** Post-Doc/Research Fellow

**Affiliation:** CAMGSD-IST Univ. Lisbon

**Title:** Dynamical systems analysis of quintessential inflation with alpha-attractors

**Abstract:** In this talk I will describe how regular dynamical systems on a compact state-space can give new insights into the global dynamics of quintessential inflation with alpha-attractors cosmological models. This includes: situating fine-tuning issues, an account of the kinaton epoch, and an analysis and improvements of approximations such as the slow-roll approximation, in a global dynamical systems context.

# Contributed Talk

**Name:** Benjamín Olea **Position:** Staff

**Affiliation:** Universidad de Málaga

**Title:** Null hypersurfaces and conformal vector fields

**Abstract:** Null hypersurfaces of a Lorentzian manifold are interesting geometric objects both from a mathematical as a physic viewpoint. They present obvious difficulties since they do no inherit an useful metric tensor from the ambient, so new tools have to be developed to handle them. One of them is introduced in [Gutiérrez and Olea, Mathematische Nachrichten, 289 (2016)] and it allows us to construct a Riemannian metric on a null hypersurface. The useful of this Riemannian metric has been shown in several situations, [Gutiérrez and Olea, Journal of Geometry and Physics, 145, (2019)], [Atindogbe, Gutiérrez and Hounnonkpe, Annali di Matematica Pura ed Applicata, 199 (2020)]. In this talk we show how this Riemannian metric can be used to prove some results about null hypersufaces in a Lorentzian manifold furnished with a conformal vecctor field. For example, we give conditions to ensure that a null hypersurface is contained in a null cone and we also give conditions to ensure a the null hypersurface is a Killing horizon.

# Contributed Talk

**Name:** Miguel Manzano Rodríguez **Position:** PhD Student

**Affiliation:** Universidad de Salamanca

**Title:** Null shells: general matching across null boundaries and matching across Killing horizons

**Abstract:** Null shells are a useful geometric construction to study the propagation of infinitesimally thin concentrations of massless particles or impulsive waves. In this talk, I will present the necessary and sufficient conditions for the matching of two spacetimes with respective null embedded hypersurfaces as boundaries. The point-to-point identification of the boundaries introduces a freedom whose nature and consequences are analysed in depth. We also obtain the general expression for the energy-momentum tensor of the shell. The particular situation of both boundaries being (multiple) Killing horizons is also addressed. The identification of the Killing vectors of both sides restricts the matching freedom, although not completely. The presentation ends with some explicit examples.

# Contributed Talk

**Name:** Alex Vano-Vinuales **Position:** Post-Doc/Research Fellow

**Affiliation:** CENTRA, IST, University of Lisbon

**Title:** Hyperboloidal massless scalar field in 3D

**Abstract:** Reaching future null infinity in numerical relativity simulations is of great importance, because it is on there that gravitational radiation is unambiguously defined. This can be achieved by evolving on hyperboloidal slices, which are smooth spacelike slices that asymptote to null rays and reach null infinity. In the present approach, the problem is tackled with conformal compactification methods and a stable hyperboloidal code solving the Einstein equations in spherical symmetry for regular and strong field initial data has been successfully developed. On the way towards extending these results to three spatial dimensions, first the massless scalar field is considered as a toy model evolving on a constant-mean-curvature hyperboloidal background. In this talk I will describe the current setup and results of the 3D scalar field implementation on hyperboloidal slices.

# Contributed Talk

**Name:** Isabel Suárez Fernández **Position:** PhD Student

**Affiliation:** Instituto Superior Técnico / CENTRA

**Title:** Collapse of axisymmetric Gravitational Waves in vacuum

**Abstract:** The pseudospectral code BAMPS is used to evolve axisymmetric gravitational waves in vacuum. We consider six different one-parameter families of Brill wave initial data: three prolate and three oblate, of which two of them are centered and the other four are off-centered. With the new Adaptive Mesh Refinement (AMR) feature of the code BAMPS, we can improve on previous results near the threshold of black hole formation [1]. In particular, by leveraging the increased performance and scaling behavior of the code, we can fine tune closer to the critical point between gravitational collapse and dispersion in the centered families and giving new results about the off-centered ones. Time permitting, we will discuss the relevance of our new results in the context of critical collapse beyond spherical symmetry. [1] David Hilditch, Andreas Weyhausen, and Bernd Brügmann, Phys. Rev. D 96, 104051 – Published 29 November 2017

# Contributed Talk

**Name:** Thanasis Giannakopoulos **Position:** PhD Student

**Affiliation:** Instituto Superior Técnico

**Title:** Hyperbolicity of General Relativity in null foliations

**Abstract:** Characteristic formulations of General Relativity are based on a null foliation of the spacetime. When combined with the standard Cauchy evolution they can in principle provide highly accurate waveform modelling. During this modelling process it is typical that the full non-linear Einstein field equations are solved numerically. A numerical solution to a PDE problem can converge to the continuum one with increasing resolution only for well posed PDE problems. Well posedness of the initial value problem in the L2 norm is characterized by strong hyperbolicity of the PDE system. It was recently found that the PDE systems formed by Einstein's field equations in commonly used characteristic gauges are only weakly hyperbolic. I will review the basic features of the commonly used characteristic gauges of the Bondi family and argue that within this family a strongly hyperbolic PDE system from Einstein's field equations is not possible, if at most first derivatives of the metric are introduced as variables. I will further provide an example of how weak hyperbolicity may be demonstrated in numerical simulations.

# Contributed Talk

**Name:** Shalabh Gautam **Position:** PhD Student

**Affiliation:** Inter-University Centre for Astronomy and Astrophysics (IUCAA)

**Title:** Some ongoing Efforts for Evolving Einstein Field Equations on Hyperboloidal Slices

**Abstract:** One of the challenges in numerical relativity is to include future null infinity in the computational domain with a well-posed formulation. Success will not only enable us to evolve any system of astrophysical interest, e.g. binary black holes and extracting the gravitational wave signal at future null infinity, with any desired accuracy, but also help in studying various phenomena of fundamental interest. One proposal is to use hyperboloidal slices. In this talk, I will present our ongoing efforts for obtaining a well-posed formulation of the Einstein Field Equations on hyperboloidal slices, all in spherical symmetry. The natural extension will be to generalize these methods to full 3d.

# Contributed Talk

**Name:** Samuel Santos Pérez **Position:** PhD Student

**Affiliation:** Universitat de València

**Title:** FCF formulation of Einstein equations: local uniqueness and numerical accuracy and stability

**Abstract:** We present Einstein equations in the so-called Fully Constrained Formulation (FCF). This formulation has two different sectors: the elliptic sector formed by the Hamiltonian and Momentum constraints together with the equations derived from the gauge choice, and the hyperbolic sector which encodes the evolution of the rest of degrees of freedom of the spacetime metric including the gravitational waves. We present a modification of both sectors that keeps local uniqueness properties but has a better behaviour regarding the relativistic expansion of the equations. We also comment on numerical properties of this reformulation.

# Invited Public Lecture

**Name:** Luís Crispino

**Affiliation:** Universidade Federal do Pará

**Title:** Em busca de luz na escuridão: A história da primeira comprovação experimental da Relatividade

**Abstract:** No final do século XIX e no início do século XX, astrônomos percorriam o mundo em busca dos melhores locais para observar eclipses totais do Sol. As razões principais dessa busca eram o entendimento da precessão anômala do periélio do planeta Mercúrio e de propriedades da coroa solar. No início da década de 1910, Albert Einstein investigava as bases de sua nova teoria da gravitação, que indicava que a luz proveniente das estrelas, ao passar próximo do Sol, deveria sofrer um desvio, implicando em uma mudança na posição aparente das estrelas localizadas próximas ao Sol eclipsado. A primeira tentativa de verificar este fenômeno durante um eclipse ocorreu em 10 de outubro de 1912, em solo brasileiro, mas que foi completamente frustrada devido ao mau tempo. Apresentamos detalhes da história destes "caçadores de eclipses", culminando com a primeira verificação experimental da Teoria da Relatividade Geral, em 29 de maio de 1919, na cidade de Sobral, no Brasil, e na Ilha do Príncipe, à época uma possessão portuguesa na costa ocidental da África.