NewFunFiCO meeting 2025
Abstracts

I. PLENARY SESSIONS: 3 DAYS

- **Machine Learning Techniques in Strong Gravity**

  Raimon Luna

  Abstract: In this short course we will review some recent uses of machine learning techniques to perform calculations in strong gravity. These will include physics-informed neural networks (PINNs) for the solution of differential equations. We will focus on the uses of PINNs as a valuable tool for the extraction of quasinormal modes of black hole ringdown. We will also explore some simple examples of generative models such as GANs or autoencoders for the creation of surrogate gravitational wave models. We will also overview a series of techniques that can be used to extract the orbital dynamics from the waveforms of extreme mass ratio inspirals.

- **Synthetic images of black holes and exotic compact objects**

  Héctor Olivares

  Abstract: The interpretation of event-horizon-scale observations of supermassive black hole candidates such as Sgr A* and M87* relies on comparisons with sizable libraries of synthetic observations. This three-session course will consist of an overview of the process to generate these models. In particular, we will cover the basics of modeling hot accretion flows seminanalytically and numerically, the production of synthetic images through ray-tracing and radiative transfer calculations, the observing process of very-long-baseline interferometry experiments such as the Event Horizon Telescope, and the application of these techniques to predict the observational properties of exotic compact objects. The course will have an optional hands-on component on general relativistic magnetohydrodynamic (GRMHD) and radiative transfer (GRRT) codes.

- **Exploring exotic compact objects with numerical relativity**

  Daniela Cors

  Abstract: In this course we will discuss numerical relativity techniques employed in the modelling of exotic compact objects composed of fundamental fields. We will first review the cornerstones of numerical relativity, the framework needed to computationally solve Einstein's field equations on the computer. Then, we will see how the resulting simulations play a role in assessing basic features of compact objects, such as their stability. Lastly, we will review numerical relativity's key part in determining the detectability of these objects through gravitational-wave astronomy.

- **Parameter inference in gravitational-wave astronomy**

  Juan Calderón Bustillo

  Abstract: In this course I will introduce several techniques used in gravitational-wave astronomy used to understand the parameter of gravitational-wave sources, the measurability of certain gravitational-wave effects and population-level studies. In particular, I will first cover full Bayesian parameter inference and model selection. Next, I will introduce the concept of Fisher Matrices, which are handy for cases where full Bayesian parameter inference is prohibitive. Last, I will introduce the concept of mixture models. In particular, I will show how the latter can be used to detect physical effects at the population level which may be undetectable in individual gravitational-wave events.

II. TUESDAY 20TH MAY

1. **Proto-neutron star oscillations including accretion flows**

   Dimitra Tseneklidou

   Abstract: The gravitational wave signature from core-collapse supernovae (CCSNe) is dominated by quadrupolar oscillation modes of the newly born proto-neutron star (PNS), and could be detectable at galactic distances. We have developed a framework for computing the normal oscillation modes of a PNS in general relativity, including, for the first time, the presence of an accretion flow and a surrounding stalled accretion shock. These new ingredients are key to understand PNS oscillation modes, in particular those related to the standing-accretion-shock instability (SASI). Their incorporation is an important step towards accurate PNS asteroseismology. For this purpose, we perform linear and adiabatic perturbations of a spherically symmetric background, in the relativistic Cowling approximation, and cast the resulting equations as an eigenvalue problem. We discretise the eigenvalue problem using collocation Chebyshev spectral methods, which is then solved by means of standard and efficient linear algebra methods. We impose boundary conditions at the accretion shock compatible with the Rankine-Hugoniot conditions. I am going to present several numerical examples to assess the accuracy and convergence of the numerical code, as well as to understand the effect of an accretion flow on the oscillation modes, as a stepping stone towards a complete analysis of the CCSNe case.

2. **The role of magnetic fields in r-process nucleosynthesis from neutron star binary mergers**

   Fabrizio Venturi Piñas

   Abstract: The coincident detection of gravitational waves and electromagnetic signals from neutron star binary mergers offers a unique opportunity to study the origin of heavy elements produced in these extreme events. The ultraviolet, optical, and near-infrared emissions observed from GW170817 were consistent with being powered by the radioactive decay of nuclei synthesized in the merger ejecta via the rapid neutron-capture (r-process). This observational evidence suggests that neutron star binary mergers play a crucial role as cosmic forges for the production of heavy elements. However, an open question remains: What impact do magnetic field configurations have on the resulting r-process abundance? As a step forward in addressing this question, we perform general relativistic magnetohydrodynamic simulations of neutron star binaries, incorporating a neutrino leakage scheme, that merge and form a hypermassive neutron star remnant lasting more than 20 ms, followed by a nuclear reaction network simulation to explore how different magnetic field geometries and strengths may leave imprints on the final composition of the merger ejecta.

3. **Impact of spin misalignment on electromagnetic emission from black hole binaries in circumbinary disks**

   Inês Rainho

   Abstract: Numerical relativity plays a crucial role in modeling compact binary mergers and interpreting gravitational wave signals. We present a systematic study based on general relativistic magnetohydrodynamic (GRMHD) simulations of circumbinary disks around tilted, unequal-mass binary black holes. We investigate how spin orientation influences jet and twin-jet structures during the premerger phase. Preliminary results suggest sudden changes in the outgoing Poynting luminosity around the time of merger, providing potential electromagnetic signatures of black hole mergers in active galactic nuclei. Such signatures could offer new insights into black hole growth mechanisms, the co-evolution of black holes and their host galaxies, and may contribute to explaining the formation of X-shaped radio galaxies.

4. **Galactic halos and rotating bosonic dark matter**

   Jorge Castelo Mourelle

   Abstract: Rotating bosonic dark matter halos are considered as potential candidates for modeling dark matter in galactic halos. These bosonic dark matter halos can be viewed as a dilute and very extended version of bosonic stars, and the methods used for the calculation and analysis of the latter objects can be directly applied.

Bosonic stars, a hypothetical type of astrophysical objects, are categorized into two primary families, based on the nature of the particles composing them: Einstein-Klein-Gordon stars and Proca stars. We examine various models from both families and the rotation curves which their contribution induces in different galaxies, to identify the most plausible candidates that explain the flattening of orbital velocities observed in galactic halos. By exploring different combinations of our dark matter models with observable galactic features, we propose an interesting source to compensate for the apparent lack of matter in dwarf and spiral galaxies, providing a possible explanation for this longstanding astronomical puzzle.

5. **Virial Identities across the spacetime**

   Alexandre Mira Pombo

   Abstract: Virial identities, derived via Derrick's scaling argument, serve as powerful tools for analyzing general relativistic models. They have been widely applied in proving no-go and hair theorems, as well as verifying numerical accuracy. Traditionally, these identities have only been computed in the region outside the event horizon. However, when a positive cosmological constant is introduced, an additional boundary—the cosmological horizon- emerges, making the region between horizons particularly intriguing. In this presentation, we introduce a recipe to compute virial identities in spacetimes bounded by two horizons. By employing a radial coordinate transformation, we extend Derrick's scaling argument to derive virial identities across non-asymptotically flat spacetimes.

6. **Catastrophic gravitational collapse from strings and branes**

   Alberto G. Martín-Caro

   Abstract: Topological defects such as cosmic strings or domain walls may have formed during a symmetry breaking phase transition in the early universe. After formation, defects evolve into a scaling network whose dynamics is governed by the Nambu-Goto action, which typically predicts the formation of cusps, namely, events in which defects self-intersect and where a great amount of energy is concentrated. In this talk I will present how the formation of cusps can be understood in terms of the mathematical catastrophe theory, and study the possibility of primordial black hole formation from such events in cosmologically viable scenarios.

III. WEDNESDAY 21TH MAY

7. **Rotating black holes in Einstein-Maxwell-dilaton theory**

   Etevaldo Costa

   Abstract: The (electrically) charged, rotating black holes (BHs) in Einstein-Maxwell-dilaton (EMd) theory are known in closed form for two particular values of the dilaton coupling constant γ, while the solution with arbitrary γ is known only in the slow-rotation or weakly charged limits. In this work, we propose a numerical scheme for the non-perturbative construction of such EMd BHs with an arbitrary γ. We present an overview of the parameter space of the solutions for several values of γ, together with a study of their basic properties. While, in general, the solutions are very much Kerr–Newman-like, there are, however, several new features. The emerging picture suggests that the spinning solutions with $0 < \gamma < \sqrt{3}$ possess a zero-temperature limit, which, however, exhibits a pp-singularity. A different limiting behaviour is found for $\gamma > \sqrt{3}$, in which case, moreover, we have found some indication of BH non-uniqueness in the EMd model.

8. **(In)stability of Q-Hairy BHs**

   José Pedro Mota Valente Ferreira

   Abstract: Q-Hairy BHs are a family of static, spherically symmetric solutions of charged black holes that support a gauged, self-interacting, and minimally coupled scalar field with a Q-ball type potential. These solutions have been argued to form dynamically from a sort of non-linear superradiance in spherical symmetry. We perform full 3+1 numerical relativity simulations, providing new insights into their dynamical behavior, in particular that non-spherical dynamics may play a crucial role in their fate.

9. **Non-linear stability analysis of ℓ-Proca stars**

   Claudio Lazarte

   Abstract: Vector boson stars, also known as Proca stars, exhibit a remarkable dynamical robustness, making them strong candidates for exotic compact objects. They challenge the traditional black hole paradigm when interpreting data related to strong gravity and may also play a role like dark matter in the universe. Building on our previous work, which introduced a $(2\ell + 1)$-multi-field extension of the spherical Proca stars termed ℓ-Proca stars, we conducted a stability analysis of these stars for the case of $\ell = 2$. This analysis utilized fully non-linear three-dimensional dynamical simulations without imposing any symmetry constraints. Our main finding is that 2-Proca stars are unstable throughout their entire domain of existence. The instabilities that arise, aside from being dependent on the compactness of the system, are significantly influenced by the dynamical properties of the five constitutive Proca fields, which are characterized by their multipolar structure with m = 0, |1|, and |2|. Specifically, we found that: (i) the most compact configurations collapse radially into black holes. (ii) For less compact configurations, the fields with m = 0 and |1| experience a migration of angular momentum from $\ell = 2$ to $\ell = 1$, while those with $m = |2|$ maintain their multipolar structure. As a result, the new configurations correspond to multi-ℓProca stars. This newly formed star is either radially or non-axisymmetrically unstable, leading to collapse into black holes or, in the case of non-axisymmetric instability in the most dilute configurations, fragmentation into a binary Proca star.

10. **Stability of Hairy Black Holes with scalar or Proca hair**

    Jordan Nicoules

    Abstract: We present some preliminary results about the stability of the Kerr Black Holes with Scalar Hair (KBHsSH) and with Proca hair (KBHsPH), introduced by Herdeiro and Radu in 2014, and Herdeiro, Radu and Rúnarsson in 2016. These black holes admit a massive scalar (resp. vector) hair, minimally coupled to gravity and solution to the Klein-Gordon (resp. Proca) equation, which has a harmonic dependence in time and in the azimuthal angle. This allows the metric sector to be stationary and axisymmetric. The KBHsSH can coexist with traditional Kerr Black Holes in a region of the parameter space, and should be entropically favored. On the other hand, spinning scalar Boson Stars have been shown to be unstable dynamically (Sanchis-Gual

et al. 2019), which begs the question of the stability of the KBHsSH close to that limit. Motivated by the qualitatively different behavior between spinning scalar and Proca Bosonic Stars, we also evolve different configurations of Kerr Black Holes with Proca Hair. We thus perform fully non-linear 3D numerical evolutions to test the stability of these systems, using the Einstein Toolkit numerical suite. We discuss the first results obtained for the two types of matter fields, for very hairy and not very hairy configurations.

11. **Dynamical formation of multi-state boson stars**

Alejandro José Florido Tomé

Abstract: Dark matter is today one of the most fascinating mysteries in astrophysics, cosmology and theoretical physics. Its nature is still unknown, so different theoretical models have been proposed to explain it. In this work we have studied the dynamical formation of the solutions of the Einstein-Klein-Gordon system of equations, which correspond to compact objects composed of scalar fields describing a potential type of dark matter. These are multi-field boson stars formed by two massive complex scalar fields coupled to gravity. It is analogous to the study of two self-gravitating boson stars interacting only through gravity. If the fields are in different excited states, we have a multi-state boson star. Using numerical methods we have solved the above system of equations to study the formation and stability of multi-state boson stars under different circumstances.

IV. THURSDAY 22TH MAY

12. **Hypershadows: Imaging five dimensional black holes**

    João Pedro de Araújo Novo

    Abstract: What does a black hole look like? In 1 + 3 spacetime dimensions, the optical appearance of a black hole is a bidimensional region in the observer's sky often called the black hole shadow, as supported by the EHT observations. In higher dimensions this question is more subtle and observational setup dependent. Previous studies considered the shadows of higher dimensional black holes to remain bidimensional. We argue that the latter should be regarded as a tomography of a higher dimensional structure, the hypershadow, which would be the structure "seen" by higher dimensional observers. As a case study we consider the cohomogeneity-one Myers-Perry black hole in 1 + 4 dimensions, and compute its tridimensional hypershadow.

13. **Observing boson stars in binary systems: The case of Gaia BH1**

    Pedro Alexandre Ferreira Passos

    Abstract: The Gaia experiment recently reported the observation of a binary system composed of a Sun-like star orbiting a dark compact object, known as Gaia BH1. The nature of the compact object remains uncertain. While the Gaia mission identifies it as a black hole candidate, the absence of X-ray or radio detections challenges that interpretation, and alternative exotic compact objects such as boson stars have also been suggested. In this paper, we study whether a boson star could account for the observed properties of the source. To do so we compute the X-ray luminosity of the central dark object as a result of spherically symmetric (Bondi-Michel) accretion of matter, comparing our results for the cases in which the dark object is a Schwarzschild black hole or a non rotating boson star. Our model incorporates realistic interstellar medium properties, ranging from hot ionized gas to dense molecular clouds. By solving the governing equations numerically, we calculate mass accretion rates and derive the resulting Bremsstrahlung X-ray luminosities. Black holes and boson stars fundamentally differ by the absence of an event horizon in the latter, which directly impacts accretion dynamics as there is an accumulation of mass in regions closer to the boson star, which will significantly change the observed X-ray emission. For the Gaia BH1 system we find that accretion onto a black hole yields luminosities of $\sim 10^{27}$ erg cm^{-2} s^{-1} which corresponds to an X-ray flux undetectable by Chandra sensitivity. On the other hand, boson star accretion can produce observable luminosities in the order of 10^{27} to 10^{41} erg cm^{-2} s^{-1}. We argue that X-ray observations could help in discriminating the nature of the dark companions in binary systems like Gaia BH1 and test the possibility of boson stars as alternatives to black holes.

14. **Proca stars as black hole imitators: the story so far**

    Ivo Sengo

    Abstract: In April 2019, the Event Horizon Telescope (EHT) collaboration announced to the world the first photograph of a black hole. A peculiar image whose striking feature is a central dark region surrounded by a bright orange ring (due to hot matter accreting into the black hole). The central dark region is what we call the shadow of the black hole, and it is a consequence of the extreme light bending in the vicinity of the hole. From a theoretical point of view though, black holes might not be the only objects capable of such extreme distortion of light. Some families of exotic stars can also be sufficiently compact to alter light trajectories and produce images that resemble the ones of black holes. Here we once again tackle this question bringing fresh inputs from GRHMHD simulations.

15. **Collisions of excited spherical boson stars: glimpses of chains and rings**

    Marco Brito

    Abstract: We study the dynamical stability of spherically symmetric scalar excited boson stars in a full 3+1D evolution and we show that they remain stable if such was the case considering only spherical perturbations. We also perform the head-on collision of equal boson stars resulting in both a black hole remnant or a boson star remnant. We see that when colliding stars are in the fundamental state we obtain a highly perturbed

spherical boson star, whereas in the excited case, the end result is a dynamical superposition of bosonic chains and rings similar to the ones found as static states in Liang et al (JHEP 03, 119 (2025)). This suggests that there is a crucial difference between the excited cases and the fundamental state, since it seems that excited states cannot be formed dynamically via head-on collisions, unlike their fundamental counterparts.

16. **Binary Proca stars: dynamics and gravitational wave emission from eccentric mergers**

Gabriele Palloni

Abstract: Boson stars are theoretical exotic compact object which are considered as a possible explanation of dark matter. In this talk, I will discuss the dynamics and gravitational wave (GW) emission of binary rotating vector boson star (known as Proca stars) mergers in eccentric orbits. We have investigated configurations with different masses and compactness, varying the parameters of the binary (initial velocity and phase difference), and finding how these parameters can affect the outcome of the mergers and the gravitational waveforms. In particular, the initial relative phase of the two complex vector fields forming the stars can drive the merger in a plethora of different outcomes, affecting the GW energy emitted and its mode structure. Furthermore I will also review these peculiar dynamics: from the formation of transient short-living hypermassive Proca star to the formation of a Kerr black hole with a faint Proca field remnant around the horizon.