Astrophysics & Cosmology Journal Club 2023 (CFisUC, University of Coimbra)

Tuesday, 28 February 2023 - Tuesday, 25 July 2023

Book of Abstracts

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Mergers of Dark Matter Admixed Neutron Stars

We investigate mergers of neutron stars consisting of two non-interacting fluids minimally coupled to the gravitational field using the numerical relativity code BAM. The first fluid represents baryonic matter, whereas the second fluid models dark matter, which we describe using the equation of state of a degenerate Fermi gas. We consider two different scenarios for the distribution of the dark matter. In the first scenario the dark matter is confined to the core of the star, whereas in the second scenario the dark matter extends beyond the surface of the baryonic matter forming a halo around the baryonic star. We show how the dark matter impacts the binary dynamics and merger waveforms.

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Modeling Late-Time Tails for Scalar Perturbations of Quantum Corrected Black Holes

Author: Scott Shaw[1]

[1] *University of Massachusetts Dartmouth*

Corresponding Author: sshaw1@umassd.edu

The main goal of this research is to obtain a clear and accurate model of the late-time behavior of a quantum-corrected black hole's radiative emission wave. Specifically, the focus is on late-time tail waveforms, which appear after the exponentially damped signal originating from the ring down phase of a perturbed black hole. This project focused on interpreting the effects of loop quantum corrections on black hole quasi-normal modes and radiative tails. We began with the scalar wave equation and solved for the Regge-Wheeler scalar field potential, which captures the physics of a standard Schwarzschild black hole. This solution allowed us to generate waveforms with different initial variables, such as multipole numbers and radial epsilon exponents. Next, we analyzed the divergent characteristics, oscillatory behavior, and decay rates of the late-time tails for the quantum-corrected black hole and performed a comparison with the Schwarzschild case. This research is part of an ongoing project on gravitational wave emission from quantum-corrected black holes, and how they can be modeled. It is a bid to make detection and recognition of such waveforms possible in future gravitational wave observatories.

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Revisiting the Thermal Evolution of Neutron Stars

Corresponding Author: rnegreiros@id.uff.br

The cooling of neutron stars has proven to be a fantastic way of probing the interior of these objects. Many works were dedicated to investigating several aspects of this rich and complicated phenomena. Our current understanding of the thermal evolution of these objects tells us that they cool down mainly due to two mechanisms: neutrino emission from their interior, and photon emission from the surface. Initially, the neutrino emission from the interior dominates the cooling. After this neutrino dominated era, when the interiors are cool enough that neutrino emission becomes less relevant, the cooling is driven by photon emission from its surface. Furthermore, the significant differences between the structure of the star's core and crust (the former is composed of a degenerate interacting gas, whereas the latter is mostly crystalline) lead to a thermal decoupling between them for the first (approximately) 100 years of thermal evolution - known as the thermal relaxation time. In this presentation I will revisit the thermal relaxation process for neutron stars. I will show that differently than what was previously thought possible, neutron stars under specific conditions may exhibit abnormally high thermal relaxation times. In order to understand under which conditions such phenomena may take place we will thoroughly discuss the physics of neutron star cooling and energy transport.

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Thermal curvature perturbations in thermal inflation

Corresponding Author: j.m.gomes@liverpool.ac.uk

We compute the power spectrum of super-horizon curvature perturbations generated during a late period of thermal inflation, taking into account fluctuation-dissipation effects resulting from the scalar flaton field's interactions with the ambient radiation bath. We find that, at the onset of thermal inflation, the flaton field may reach an equilibrium with the radiation bath even for relatively small coupling constants, maintaining a spectrum of thermal fluctuations until the critical temperature T_c, below which thermal effects stop holding the field at the false potential minimum. This enhances the field variance compared to purely quantum fluctuations, therefore increasing the average energy density during thermal inflation and damping the induced curvature perturbations. In particular, we find that this inhibits the later formation of primordial black holes, at least on scales that leave the horizon for T > T_c. The larger thermal field variance also reduces the duration of a period of fast-roll inflation below T_c, as the field rolls to the true potential minimum, which should also affect the generation of (large) curvature perturbations on even smaller scales.

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Nearly model-independent constraints on dense matter equation of state in a Bayesian approach

Authors: Arunava Mukherjee[1]; B. K. Agrawal[1]; N. K. Patra[None]; Sk Md Adil Imam[1]; Tuhin Malik[2]

[1] *Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700064, India.*

[2] *CFisUC, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal*

Corresponding Author: p20190033@goa.bits-pilani.ac.in

We apply the Bayesian approach to construct a large number of minimally constrained equations of state (EOSs) and study their correlations with a few selected properties of a neutron star (NS). Our set of minimal constraints includes a few basic properties of saturated nuclear matter and low-density pure neutron
matter EOS, which is obtained from a precise next-to-next-to-next-to-leading-order ($\mathrm{N^3LO}$) calculation in
chiral effective field theory. The tidal deformability and radius of NS with mass $1-2M_\odot$ are found to be strongly correlated with the pressure of β-equilibrated matter at densities higher than the saturation density ($\rho_0 = 0.16$ fm^{-3}) in a nearly model-independent manner. These correlations are employed to parametrize the pressure for β-equilibrated matter, around $2\rho_0$, as a function of neutron star mass and the corresponding tidal deformability. The maximum mass of a neutron star is also found to be strongly correlated with the pressure of β-equilibrated matter at densities $\sim 4.5\rho_0$.

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Causality, Superfluid Dark Matter, and Modified Gravity

Author: Jacob Litterer[None]

Corresponding Author: jakelitterer@gmail.com

Superfluid dark matter is a novel way of reconciling the apparent discrepancy between galactic phenomenology and {\Lambda}CDM. The success of these models is that on cosmological scales they can play the role of CDM, while on galactic scales there is a phase transition to a superfluid, and the nontrivial dynamics in this regime can reproduce the observed Tulley-Fisher relation. However, in general, these models exhibit a breakdown of causality, which indicates they would resist having any UV completion in the usual sense of Wilsonian field theory. Constructing a class of theories of this form that are explicitly causal, instead of dark matter we can consider these as scalar modifications of gravity, which in very dense environments can become stronger than ordinary gravity. We find various observational constraints in this class of modified gravity theories, where the strongest constraint comes from the stability of neutron stars.

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NLO QCD Corrections to (pseudo)Scalar and Chiral to quark pair Vertices using IReg

Author: Ricardo Jorge Carvalho Rosado[None]

Corresponding Author: ricardojcrosado@gmail.com

The improvement of experimental results as led to the need of equally precise, and practical, theoretical approaches to the Standard Model. The Implicit Regularisation (IReg) framework sets itself apart of more conventional dimensional schemes as it works purely in the physical 4 dimensions, which eases some problems of the aforementioned, like the need for evanescent fields. In this work we test the implementation of IReg onto the decay rate of the Z0 boson as well as a scalar and pseudo-scalar bosons into a quark anti-quark pair at NLO in QCD.

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Constraining the properties of strongly interacting matter with the multi-messenger observations of compact stars

Author: Violetta Sagun[1]

[1] *University of Coimbra*

Corresponding Author: violetta.sagun@uc.pt

Compact stars are the most exotic and dense laboratories in the Universe to test the properties of strongly interacting matter. Understanding the complex phenomena observed in neutron and hybrid stars requires profound knowledge in a wide range of scientific disciplines. In addition to the experimental data on nuclear and hadron matter, the realistic equation of state (EoS) should be consistent with the astrophysical, and gravitational wave observations. While details of the phase transitions and properties of quark matter are traditionally investigated in the accelerator experiments on heavy-ion collisions, compact astrophysical objects recently gained a big interest since observational data on their radii, masses, rotational frequencies, etc. significantly constrain the properties of strongly interacting matter. Another source of information comes from the binary neutron star mergers. Thus, the LIGO-Virgo interferometers detection of gravitational waves emitted during the binary neutron stars merger, GW170817, set the major limit on the tidal deformabilities of the stars involved in the collision and, therefore, on the EoS at the super-high baryonic densities.
I will present the astrophysical and gravitational wave constraints on the EoS of strongly interacting matter as well as the smoking gun signals of the deconfinement phase transition in compact stars and their mergers. As regards observations of gravitational waves, it has been recently reported

that phase transition from hadron to quark matter is expected to have a dramatic impact on the frequency of gravitational waves emitted during neutron star mergers, which provides a fresh and continuously updating ground for testing the formulated equation of state. Finally, I will briefly mention how the next generation of gravitational wave telescopes will probe the existence of the deconfinement phase transition in compact stars.

Using an example of the recently announced lightest compact star HESS J1731-347 I will demonstrate how the multi-messenger observations could shed light on the interior composition of the star.

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Observing high-energy and very-high-energy gamma-rays from compact binary mergers

Corresponding Author: biswajit.banerjee@gssi.it

The physics governing the production of the early emission of gamma-ray bursts (GRBs) is still poorly understood. The early emission is usually caught by a wide field of view gamma-ray instruments in the range of 10 keV-10 MeV, but to date, at higher energies (above 100 GeV) it has not been detected yet. I will discuss the multi-messenger observational strategies to detect the early emission of short GRBs at very-high-energies (VHE; E > 30 GeV) in the era of the third-generation gravitational wave detectors Einstein Telescope (ET) and Cosmic Explorer (CE). We evaluate the joint detection efficiency by the Cherenkov Telescope Array (CTA). We take into account the expected capabilities to detect and localise gravitational wave events in the inspiral phase of the compact binaries and to provide an early-warning alert for upcoming short GRBs, thanks to the proposed low frequency response of ET. I will discuss possible VHE components from the synchrotron self Compton components in the leptonic GRB model, high energy tail of the hadronic GRB model as well as external inverse Compton emission as viable candidates in the energy band of 30 GeV - 10 TeV. I will also discuss the discovery of the GeV emission from a compact binary merging event which opened a window for probing the MWL emission with an extended emission. This further increases the possibility of detection of the mergers in high-energy and VHE gamma-rays.

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Symbolic Regression (SR): an overview

Author: Felipe Demigio[None]

Corresponding Author: felipedemigio@protonmail.ch

Symbolic Regression (SR) is a type of regression analysis used to find the model which can best fit a dataset according to a specified condition by conducting a search on the space of mathematical expressions. This talk aims to give an introduction to this topic, to succinctly present a few popular and particularly Physics-oriented search algorithms, and to showcase examples of SR's application in research

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Resonant particle production during the inflationary epoch

Corresponding Author: diogo.s.gorgulho@hotmail.com

The usual inflationary paradigm places the reheating period strictly after the slow-roll regime of the inflaton field comes to an end. We develop and analyse a novel mechanism that allows for production of scalar particles during the slow-roll regime due to a narrow parametric resonance found in the equations of motion. It is shown that an appreciable number of particles can be produced through this mechanism without their energy density becoming dominant, thus breaking the underlying inflationary paradigm.

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What is the nature of the HESS J1731-347 compact object?

Author: Violetta Sagun[1]

[1] *University of Coimbra*

Corresponding Author: violetta.sagun@uc.pt

Once further confirmed in future analyses, the radius and mass measurement of HESS J1731-347 with $M = 0.77^{+0.20}_{-0.17}\ M_\odot$ and $R = 10.4^{+0.86}_{-0.78}$ km will be among the lightest and smallest compact object ever detected. This raises a lot of questions about its nature and opens up the window for different theories to explain the measurements. We use the latest data on the mass, radius, and surface temperature together with the multi-messenger observations of neutron stars to investigate the possibility that HESS J1731-347 is the lightest observed neutron star, a strange star, a hybrid star with an early deconfinement phase transition, or a dark matter admixed compact star. The nucleonic and quark matter models are modeled within the most up-to-date realistic EoSs with a self-consistent calculation of the pairing gaps in quark matter.

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The passage through the 5:3 resonance between Ariel and Umbriel with inclination

Corresponding Author: sergiogomes96@live.com.pt

Ariel and Umbriel have almost certainly passed through the 5:3 mean motion resonance in the past, owing to the tidal evolution of their orbits. However, the exact mechanism that allows the system to evade capture in this resonance is a great puzzle. For coplanar orbits (zero inclinations), the eccentricity of at least one satellite must be close to 0.01 at the time, which is unlikely because tides are expected to quickly damp the eccentricities to near zero. For non-coplanar orbits, the inclinations appear to grow to high values, which is unlikely because tides are very inefficient to damp the inclinations to the presently observed near zero values. Assuming circular orbits for both satellites, we show that, if the inclination of Umbriel was higher than 0.1° at the time of the resonance encounter, capture in the 5:3 mean motion resonance can be avoided. Moreover, after the resonance crossing, the inclination of Umbriel drops to a mean value around the presently observed one.

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Exotic Baryons in (Hot) Neutron Stars

Corresponding Author: marquezkauan@gmail.com

This presentation will provide an overview of two research papers. The first paper focuses on the calculation of baryon-meson coupling constants for spin-1/2 baryonic octet and spin-3/2 decuplet using symmetry arguments based on SU(3) and SU(6) group transformations. The coupling constants are determined by reproducing known potential depths for hyperons and Δ resonances. These constants are then applied to study neutron star matter with hyperons and deltas. The findings reveal that the Δ^- particle is crucial in the neutron star interior, consistently appearing and impacting the

astrophysical properties, potentially increasing the maximum mass reached. The second paper investigates the nuclear isentropic equation of state for stellar matter composed of nucleons, hyperons, and Δ-resonances in different stages of a neutron star's evolution. A relativistic model within the mean-field approximation is used, along with density-dependent couplings adjusted by the DDME2 parameterization. Baryon-meson couplings are determined based on SU(6) and SU(3) symmetry arguments. The dominant exotic particle in the star is found to be Λ at different entropies for both neutrino-free and neutrino-trapped stellar matter. The inclusion of new particles leads to a decrease in temperature, and increasing entropy per baryon results in larger stellar radii and lower mass due to neutrino diffusion. In neutrino transparent matter, radii decrease with entropy per baryon without significant changes in stellar mass.

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PNJL model at zero temperature: The three-flavor case

Corresponding Author: odilon.ita@gmail.com

We propose a three-flavor version of the Polyakov-Nambu-Jona-Lasino (PNJL) model at zero temperature regime, by implementing a traced Polyakov loop (Φ) dependence in the scalar, vector and 't Hooft channel strengths. We study the thermodynamics of this model, named as PNJL0, with special attention for the first-order confinement/deconfinement phase transition for which Φ is the order parameter. For the symmetric quark matter case, an interesting feature observed is a strong reduction of the constituent strange quark mass (Ms) at the chemical potential related to point where deconfinement takes place. The emergence of Φ favors the restoration of chiral symmetry even for the strange quark. We also investigate the charge neutral system of quarks and leptons in weak equilibrium.