Beyond General Relativity: Black Holes and Gravitational Waves

Project Description:

This PhD project aims at exploring some successful and hot topic alternative theories of gravity in what concerns black holes and compact objects, and gravitational waves, specifically from inflation. In particular, one aims at further analyse non-minimal coupling gravity theories with a Weyl connection, which was shown to have interesting properties, namely that the metric field equations are of second order in the derivatives, i.e., free of ghost instabilities. This model has a stable space-form ground state and its vector field can be identified with the electromagnetic vector potential. In its turn, the hybrid metric-Palatini gravity and its generalisation have a rich lore of interesting physical features, in particular, it encompasses a triple unification scenario of inflation, dark matter and dark energy that deserves to be further explored and compared with inflation data from Planck mission. Therefore, these main classes of alternative theories of gravity constitute relevant theories to assess whether spacetime can be described with more than solely the metric field: with a non-metricity vector field or with an additional affine connection, respectively. Thus, studying its implications for black holes, or compact objects such as gravastars, or its compatibility with data from inflation and gravitational waves, as well as its mathematical stability and existence of solutions pose a quite challenging and crucial research that shall be pursued in this PhD project. Moreover, it is expected that some outreach activities take place throughout this plan, which will strengthen the Azores Strategy for Space. It will reinforces the collaborations between the University of the Azores, the Astronomical Observatory of Santana-Azores and the schools. This will give visibility of the project at the same time that raises awareness on hot research topics in Physics and Astronomy which are the basis of Space Science and Technology.

State of Art:

Despite the mathematical beauty and simplicity of Einstein's General Theory of Relativity, and its success at Solar System level and the prediction of gravitational waves, black holes and black hole shadows, among others, there are some problems in what concerns very high and very low energy regimes. In the first case, there is the incompatibility with Quantum Mechanics, and the existence of singularities; and on the second case, the observational need of dark matter and dark energy, which have not been directly found so far.

Therefore, several Alternative Theories of Gravity have been proposed in the literature. One of such models rely on generalising Einstein' theory through a generic function of the scalar curvature in the action functional, the so-called f(R) theories [1,2]. Another model resort the latter gravity model and include a non-minimal coupling through another generic function of the scalar curvature multiplied by the matter Lagrangian density [3]. This model has a rich lore of implications both theoretical and observational, namely it accounts for the dark matter profile mimicking at galaxies and clusters of galaxies [4,5], and for the late time acceleration of the Universe [6], it is stable under cosmological perturbations [7], it is compatible with inflation and gravitational wave data [8,9], it possesses black hole solutions with dressed physical quantities [10], it passes the Cassini and extra force constraints from the Sun [11], and it allows for a seeding mechanism for cosmic magnetic fields during the early expansion stage of the Universe - inflation [12,13].

In fact, this model can accommodate a Weyl connection, leading to a theory based on the metric field and its non-metricity through a vector field [14]. This model was shown to be free of Ostrogradsky instabilities, even when the vector field is dynamical, where some additional conditions arise [15].

Another class of gravity theories extend Einstein's one by introducing, in addition to the scalar curvature term, a function of a scalar curvature built from an independent connection, and is dubbed as hybrid metric-Palatini gravity [16]. This scenario was further explored in the generalised hybrid metric-Palatini gravity [17], which was shown to include a natural triple unification scenario for inflation, dark matter and dark energy [18].

Both non-minimal coupling with Weyl connection and the hybrid metric-Palatini models deserve further analysis and have many avenues not studied so far, both resorting to analytical and mathematical studies of stability and robustness, and resorting to observational data, namely from Planck mission for inflation and primordial gravitational waves [19]. In particular, black holes solutions are fundamental, as their shadows have been directly observed, as well as gravitational waves produced from the collision of pairs of black holes by LIGO and Virgo collaborations. However, and given the recent detection of astrophysical compact objects lying in the lower mass gap between neutron stars and stellar black holes [20], it poses an additional question on whether there exist further objects in the Universe. In particular, it is crucial to study the gravitational vacuum stars, known as Gravastars, which are hypothetical objects alternative to black holes,

and that have formed from stellar collapse which in the presence of quantum effects lead to a phase transition responsible for an object with physical boundary and no event horizon. Furthermore, these models should have some interesting physical bearings on inflationary Dynamics that should be constrained with Planck mission data, namely in what concerns to scale invariance and primordial Gravitational waves.
Thus, this proposal aims at pursuing these lines of research which will certainly lead to relevant insights on the nature of gravity.

Objectives:
This PhD project aims to explore alternative theories of gravitation to General Relativity, namely Non-minimal Coupling Weyl Gravity and Generalised Hybrid Metric-Palatini Gravity. For the former, it is intended to study Black Holes solutions and their alternatives, namely Gravastars, in the context of this theory, as well as to explore the inflationary Dynamics of the model in comparison with Planck mission data. As for the latter, it is intended to study the Gravastars solutions and inflation with Planck mission, based on this generalised theory. As a byproduct of this research proposal, several outreach activities (talks, scientific dissemination articles) for the general public and for school students.

References:
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Actions:
1) **Study of Nonminimally Coupled Weyl Gravity 1: Black Holes;**

1. Objetivos: In this task, we shall analyse black hole solutions in this theory, and their departure from GR counterparts. In particular, given the Weyl vector field, we shall expect that the solutions may include a “charge-like” term, specially if this vector is to be identified with the electromagnetic vector potential.

2. Tarefas: Analysis of spherically symmetric solutions of the theory, and departure from this symmetry, in order to account for the Weyl vector field. Comparison with General Relativity and Non-Minimal Coupling Model (without the vector field).

3. Derivables: a paper in an international journal of reference (high impact) is expected as a result of this analysis. An outreach article i salso expected in what concerns black holes, and these solutions in more general theories of Gravity.

2**) Study of Nonminimally Coupled Weyl Gravity 2: Gravastars;**

1. Objetivos: In this task, we shall explore the alternative scenario to black Holes, namely the gravitational vacuum stars, or Gravastars, which have undergone a physical phase transition during their collapse and not reached the black hole ultimate scenario.

2. Tarefas: Analysis of the gravastar solutions of this theory, namely the study of the inner, Shell and outer regions of the spacetime, and the Israel junction conditions, as well as the physical properties of entropy, proper length and equation of state.

3. Derivables: a paper in an international journal of reference (high impact) is expected as a result of this analysis.

3) **Study of Nonminimally Coupled Weyl Gravity 3: Inflation with Planck.**

1. Objetivos: In this task, we shall explore this scenario in what concerns inflation and data from Planck mission, namely in the scalar scale invariance and the amount of early time Gravitational waves.

2. Tarefas: Extension of the analysis of inflation that was done in the context of the NMC gravity model (without non-metricity), taking special care to the introduction of the vector field, adapting the numerical code to be able to compare the observational quantities (scale invariance, scalar-to-tensor ratio), that shall also be derived, with the Planck data.

3. Derivables: a paper in an international journal of reference (high impact) is expected as a result of this analysis.

4) **Study of Generalised Hybrid Metric-Palatini Gravity 1: Gravastars;**

1. Objetivos: In this task, we aim at looking into the gravastar solutions of this theory and to compare with the analysis that was done by other authors to black Holes.

2. Tarefas: Given the analysis of Gravastars in NMC Weyl Gravity, it shall be analysed the Generalised Hybrid Metric-Palatini Gravity model, with the particular attention that in scalar-tensor representation there is one scalar field responsible for the dark energy/varying cosmological constant that is a natural candidate for the inner region of the gravastar.

3. Derivables: a paper in an international journal of reference (high impact) is expected as a result of this analysis. An outreach paper and a public talk are also expected to introduce the Gravastars scenario as alternative to black holes.

5) **Study of Generalised Hybrid Metric-Palatini Gravity 2: Inflation with Planck.**

1. Objectivos: In this task, we shall explore the inflation paradigm in these theories, and special attention shall be draw to the subclass of the model which admits the triple unification of inflation, dark matter and dark energy. In particular, this scenario in the scalar-tensor formulation gives a natural candidate for the inflation scalar field, which can be scrutinised and whose implications can be compared with data.

2. Tarefas: Extension of the analysis of inflation that was done in the context of the NMC gravity model (without non-metricity), taking special care to the introduction of the vector field, adapting the numerical code to be able to compare the observational quantities (scale invariance, scalar-to-tensor ratio), that shall also be derived, with the Planck data. This shall be done resorting to the scalar-tensor formulation of these theories.

3. Derivables: a paper in an international journal of reference (high impact) is expected as a result of this analysis.

<u>Timeline:</u>

1-12 months : Task 1 (12 months)
13-20 months : Task 2 (8 months)
21-30 months : Task 3 (10 months)
31-38 months : Task 4 (8 months)
39- 48 months : Task 5 (10 months)