Cosmology, Relativity, Fields and Particles

Director: **David Brizuela**

One choice among these two:

Title: **Relativistic effects in the Schroedinger-Newton equation.**

The complete quantization of general relativity has shown to be a very difficult task. Therefore, one could think about different approximations that might provide certain insight on the expected physical effects. In particular considering the Newtonian potential, that describes the non-relativistic gravitational interaction, and performing the usual quantization, one ends up with a quantum theory described by the so-called Schroedinger-Newton equation. In scenarios where the velocities of the particles are relatively small, this quantization should provide trustable results. The goal of this master thesis would be to generalized this approach by considering, instead of the non-relativistic Newtonian potential, post-Newtonian potentials which encode relativistic effects as a power series in the ratio between the particle velocity and the speed of light. The quantization of this system should be performed, which would lead to a Schroedinger-Newton equation with relativistic corrections. And this equation should be numerically solved to obtain quantum-gravity effects in different situations of interest.

Title: **Black holes in loop quantum gravity: the propagation of gravitational waves.**

Loop quantum gravity is an attempt to quantize the gravitational interaction. One of the main properties of this theory is that in semiclassical domains it shows different evolution to that given by general relativity because there are two main corrections to the classical Einstein equations: the so-called holonomy and inverse-triad corrections. In particular in cosmological scenarios, due to these corrections, the initial (big-bang) singularity is resolved and replaced by a quantum bounce. The goal of this master thesis would be to study perturbations of black holes with holonomy and inverse-triad corrections to analyze the effects that they produce on the propagation of gravitational waves. The idea would be to add these corrections to the linearized constraints of general relativity and obtain a deformed Poisson algebra.

Director: **Francesco Hautman**

Title: **DGLAP Equations and Branching Monte Carlo Solutions**

This is a project in the area of quantum chromodynamics, the quantum field theory of the strong interaction. The Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations are quantum evolution equations and constitute a central part of the theory. In this project the Masters candidate will gain a basic knowledge of quantum chromodynamics and of the physical meaning and mathematical structure of DGLAP equations, and will work on a particular approach, based on branching Monte Carlo techniques, to finding solutions of the evolution equations in specific scenarios of physical interest. Upon completion of this project, the candidate will be well placed both to continue the study of quantum fields and to apply computational Monte Carlo methods to problems in different areas of quantum physics, from condensed matter to high-energy and astro-particle physics.

Director: **Gunar Schnell**

Title: **The strange shape of transversely polarized protons**

The Sivers effect, characterized by the preference in the transverse momentum direction of quarks in a transversely polarized hadron, has become one of the major topics in hadron physics. It can be accessed among others through the distribution of unpolarized final-state hadrons produced in deep-inelastic scattering of high-energy leptons by transversely polarized nucleons, which has been the most utilized way so far to study the Sivers effect. The dominance of the contributions from up and down quarks to this process makes it difficult, though, to probe anything but those quark flavors without currently overwhelming uncertainties. However, due to the apparently opposite signs of up and down Sivers effects as well as the high sensitivity to strange quarks, a different process—-namely hyperon polarization—-might shed light on the difficult-to-measure strange-quark Sivers effect. In this work, the quark-parton model formalism for polarized hyperon production in deep-inelastic scattering will be reviewed and current parametrizations for parton distribution and fragmentation functions be used to make predictions for measurements at various facilities in order to estimate the feasibility of such measurements at existing and future experiments, and thus the possibility of accessing the shape of the strange-quark momentum distribution in transversely polarized protons.

Director: **Igor Bandos**

Title: **Classical and quantum description of supersymmetric non-Abelian multiwaves.**

String theory, now also known under the name of M-theory, is the most promising candidate on the role of quantum theory of gravity and Unified theory of all fundamental interactions. Multidimensional supersymmetric extended objects, strings, membranes and higher 'p-branes', and multiple p-brane systems, play important role in string/M-theory. The actions and equations of motion for single p-branes are known (with a few exceptions). This cannot be said about multiple p-brane systems. Although some progress in this direction can be witnessed, only few complete actions for relatively simple multiple p- brane systems are known. The proposed work will be devoted to studying the properties of the so-called non- Abelian multiwaves in D=4 dimensional spacetime. This is a lower dimensional counterpart of the 11-dimensional multiple M0-brane system (self-interacting system of multiple M-theory waves). It is planned to construct and to investigate the symmetry properties of the D=4 non-Abelian multiwave action, to search for its curved (super)space generalizations, to develop the generalized Hamiltonian formalism, and finally to quantize this model and to study the properties of the corresponding quantum systems (which can be called D=4 Matrix model field theory).

Directors: **Jeremy Wachter** and **Jose Juan Blanco Pillado**

Title: **Quantum Tunneling in Quantum Field Theory**

Quantum tunneling is a hallmark of quantum phenomena in physics. In this project we will study the different approaches that are currently available in the literature to address similar processes in Quantum Field Theory and apply these techniques to the computation of vacuum decay in a cosmological setting.

Directors: **Joanes Lizarraga** and **Jon Urrestilla**

Title: **Lattice simulations of Superconducting Cosmic Strings**

Superconducting strings, as predicted by Witten, can be formed in systems with U(1)xU(1) symmetry when only one of the U(1) symmetries is spontaneously broken. This symmetry breaking leads to the formation of stable vortices or strings. The field associated to the unbroken symmetry condensates at the core of those vortices and formes superconducting flux tubes. The formation of superconducting strings is predicted in many supersymmetrical and inflationary cosmological scenarios, thus they could be relevant in some early universe models. Even though they have been studied from different perspectives, e.g. using field theory or approximating to Namgu-Goto strings, the full dynamics of networks of superconducting strings has not been simulated yet. Lattice simulations bring the possibility to explore a wide range of interesting and fundamental properties such as intercommutation, formation of stable superconducting loops… In addition the student will be able to study the evolution of superconducting string in cosmological backgrounds, where some cosmological observables can also be computed. The project will be developed exclusively from a numerical point of view and the student will acquire valuable skills in advanced numerical methods and lattice simulations.

Director: **Jose Senovilla**

Title: **Gravitation and General Relativity**

Description: All classical, theoretical and mathematical aspects of General Relativity and other theories of gravitation based on Lorentzian geometry.

Supervisors: **Mariam Bouhmadi-López** and **Diego Sáez-Gómez**

Title: **Quantum cosmology of the late Universe**

The search for a consistent theory of quantum gravity is among the main open problems in theoretical physics. One aspect is the fate of the singularities which are prevalent in the classical theory of general relativity and its extensions. The hope is that a consistent quantum theory of gravity is free of such singularities. This aspect can most easily be investigated in the framework of quantum cosmology: the application of quantum theory to the Universe as a whole. Within this context, some of the dark-energy models are particularly suitable as they might induce future singularities. On this thesis project we will tackle the possible quantum resolution of some of those singularities and if time allows we will constrain them as well observationally. More information about our research can be found by checking our list of publications at inspirehep.

Director: **Tom Broadhurst**

Title: **Black Hole superradiant interaction with coherent Bosonic Dark Matter**

Description: TBA

Quantum matter, simulations, and technologies

Director: **Aran Garcia-Lekue**

Title: **Electronic characterization of nanoporous graphene (NPG)**

Recently, a new multifunctional material has been reported [Science 360. 199 (2018)], which is composed of a graphene membrane with pores whose size, shape and density can be tuned with atomic precision at the nanoscale. These nanopore sizes can turn semimetallic graphene into a semiconductor and, from being impermeable, into the most efficient molecular-sieve membrane. In this project, the unique electronic and transport properties of NPG will be further investigated, by means of powerful computational tools based on density functional theory (DFT). Besides, a strong collaboration with experimental groups experts in the field is envisioned.

Director: **Aritz Leonardo and Aitor Bergara**

Title: **Ab-initio study of the role of electronic correlations in hydrides at high pressures**

50 years ago N.W. Ashcroft predicted that metallic hydrogen could be a superconductor at room temperatures. The main features required for this behavior are a high energy associated with the atomic movement and a strong interaction between the electrons and the crystal lattice. These features will remain present in several alloys in which the hydrogen atom is still the main component, so that the quest of new high temperature superconducting material based on hydrogen is ongoing. When any of these alloys crystallize, the hydrogen present in the compounds is already in a chemical pre-compression state which might lead to the necessity of a much lower external pressure for the required metallic transition. In 2015 it was observed that a compound formed with Hydrogen and Sulfur (H2S) had a superconducting transition temperature of 200 K at high pressures setting a record at that moment. More recently this August 2018, two independent experimental groups have arrived to the conclusion that the compound LaH10 exhibits a new record transition temperature of 260 K at 200GPa. The main purpose of this TFM will be to study the role of electron correlation in the above mentioned compounds close to the stabilization pressures, and to shed some light on whether the correlation enhances or not the formation of hydrogen dimers.

Directors: **D. Sokolovski and M. Pons Barba**

Title: **Investigation of a strongly interacting Bose-Einstein condensate, trapped in a double well potential**

The project investigates the dynamics of a strongly interacting bosons, able to tunnel across the potential barrier, separating two potential wells. In the Hubbard model, one would need to evaluate the tunnelling frequencies between the multi-particle states, and study the shape of the resonance curves as a function of the asymmetry parameter. The project involves both analytical and numerical work. Further information may be obtained from the Supervisors.

Director: **Diego Guérin**

Title: **Studies on conduction through putative ion channels in icosahedral viruses"**

In a recent report that employ both Classical and Quantum calculations*, we show that the icosahedral viral capsid of an insect virus, the solvent and structural ions can permit the proton conduction along the cavity that traverses the protein shell. This phenomenon was studied in Triatoma virus (TrV), seems to be present in all similar non-enveloped viruses, and could be associated to pH sensitization. In this project we aim to extend this study to analyze the capsid of vertebrate viruses like poliovirus and rhinovirus.

Director: **Enrique Rico**

Title: **Quantum Simulation: Gauge fields, Holography and Topology**

We will introduce a generalisation of conventional lattice gauge theory to describe fracton topological phases, which are characterised by immobile, point-like topological excitations, and sub-extensive topological degeneracy. They constitute a new class of quantum state of matter, which does not wholly fit into any of the existing paradigms, but which connects to areas including glassy quantum dynamics, topological order, spin liquids, elasticity theory, quantum information theory, and gravity. We will describe the basic properties of gapless fracton phases, and their connections to elasticity theory and gravity. To conclude, we will study the quantum simulation of fracton phases within circuit quantum electrodynamics.

Director: **Evgeny Sherman**

Title: **Spin-orbit coupling and development of chaos**

The aim of this project is to study analytically and numerically the development of chaotic behavior determined by spin-related properties of condensed matter. We will consider semirelativistic systems with spin-orbit interaction, where the particle spin is strongly coupled to its momentum. The systems we are going to investigate in detail are optically excited semiconductors and very cold Bose-Einstein condensates and Fermi gases.

Research lines: spintronics, cold atomic gases and Bose-Einstein condensates, quantum nonlinear dynamics, chaos theory, nanostructures.

Director: **Gonzalo Muga**

Title: **Control of quantum system dynamics and structure for quantum technologies**

Quantum *dynamics* offers a vast potential of applications but they are hindered by decoherence. A general way to mitigate decoherence is to implement “Shortcuts to adiabaticity” (STA), a set of techniques developed by the group to speed up the processes without residual excitations. STA work by inverse engineering the time-dependent external control. They have been applied to a broad range of systems such as qubits in different physical platforms (trapped ions, superconducting circuits, neutral atoms in optical lattices,…) to implement interferometry, or quantum information processing. STA extend as well beyond quantum mechanics to make optical or mechanical devices more compact and robust. Fundamental questions remain such as determining the “cost of the shortcuts'' in quantum engines; different techniques, such as variational approaches have to be developed for practical applications; connections with supersymmetry are also to be explored. As for the *structure*, different Hamiltonian types allow for different phenomena. We are in particular interested in asymmetrical devices such as “diodes'', “valves'', “Maxwell demons”, or “rectifiers'' at a microscopic scale. They will be key to develop new quantum technologies. Symmetry plays an important role in determining selection rules that tell us what (nonHermitian) Hamiltonians should be implemented to achieve these effects. Open research here would be both fundamental (to develop group theory for nonHermitian Hamiltonians) and applied (to work out specific devices with optical and/or quantum-optical realizations).

Director: **Jens Siewert**

Title: **The Bloch representation and the geometry of quantum states.**

The Bloch representation (that is, the mathematical description of quantum-mechanical density operators in terms of a matrix basis) is a powerful tool to solve quantum mechanics problems. This is because its language is deeply rooted in geometry and therefore its concepts are amenable to geometric intuition. One of the long-standing problems is to extend the well-known Bloch sphere for spins 1/2 (or qubits) to higher-dimensional spins and, in particular, to composite systems. In this thesis project, we pursue questions that are closely related to new ideas in this field, which, at the same time, devise an alternative path to describe correlations in quantum systems. The focus of the project will be on the geometry of the state space of finite-dimensional systems with dimension > 2. Surprisingly, these topics have direct relations to monogamy of entanglement, the existence of quantum error correcting codes, and in general to the role of integer numbers in quantum mechanics.

Director: **Jorge Casanova**

Title: **Nanoscale control of electron-spin-labels with nitrogen-vacancy centres in diamond**

Brief description of the work: Electron-spin-labels have a large gyromagnetic ratio that leads to a strong coupling with a quantum sensor as the nitrogen vacancy center even at large distances. At the same time, their fast spinning rate poses serious problems to coherently control them. In this research work we will design different control schemes to detect and position electron-spin-labels attached to molecules of interest for the sake of nanoscale molecular magnetic resonance imaging.

Directors: **Juan Luis Mañes** and **Maia G. Vergniory**

Title: **Topological Quantum Chemistry**

Topological insulators and topological semimetals have caused a paradigm shift in our understanding of phases of matter. They exhibit a remarkable symbiosis between elegant mathematical theories, accurate material prediction and technological applications. The experimental discovery of many predicted topological materials seals the triumph of the predicting potential of ab initio calculations combined with symmetry analysis in solid state physics. A new field called Topological Quantum Chemistry has stablished that symmetry-based considerations complement chemical theories of bonding, ionization and covalence, redefining the concept of topology by means of elementary band representations. Our goal consists in extending this formalism to study the connectivity of phononic bands and the existence of edge modes within these systems.

Director: **Lianao Wu**

Title: **Online experiment on Leakage Elimination Operations with IBM quantum computer**

Research lines: theoretical studies on quantum computation and quantum control, including the first use of *Trotterization* in adiabatic quantum simulation and computation, pioneer proposals for creating decoherence space and leakage elimination operator using dynamical decoupling, conceptual initiative in quantum malware and self-protected quantum algorithm.

Director: **Lucas Lamata**

Title: **Quantum Artificial Intelligence with Superconducting Circuits**

The prospective student will study the field of quantum artificial intelligence with superconducting circuits, and analyze possible implementations of the existing protocols with cloud quantum computers. Among plausible issues to address, are the topics of quantum autoencoders with quantum adders, as well as quantum adaptation protocols with reinforcement learning for multipartite entangled states.

Director: **Michele Modugno**

Title: **Ultracold atomic gases: a toolbox for quantum physics**

Ultracold quantum gases represent one of the most fascinating research areas of modern physics. They are being employed in many laboratories around the world for investigating fundamental problems from disparate areas (including e.g. solid state physics, superfluids, non-linear and disordered systems), representing one of the current platforms for quantum simulations. The student can choose a project in any of the above areas, to be carried out with analytical and numerical methods. Collaborations with international experimental groups are also possible.

Director: **Mikel Sanz**

Title: **Quantum Simulation of Financial Markets**

We will try to extend the techniques developed during the last decades in quantum simulations and quantum machine learning to problems in financial markets and economics. We will consider analog, digital and digital-analog approaches.