Cosmology, Relativity, Fields and Particles

Director: **David Brizuela** (david.brizuela@ehu.eus) - *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: **Igor Bandos** (igor.bandos@ehu.eus)

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).

Director: **Iñaki Garay** (inaki.garay@ehu.eus)

Title: **Loop quantum gravity: implementation of dynamics in simple models**

Loop quantum gravity (LQG) is a well established proposal for the quantization of spacetime. Among its main results we find the description of the microscopic origin of the black hole entropy and, within the cosmological version of the theory (known as loop quantum cosmology), the avoidance of the initial singularity. Nevertheless, the implementation of the dynamics and the semiclassical limit are still open problems of the theory. In this project, we will explore the mathematical structure of LQG in order to explore these issues. More concretely, we will make use of the so-called spinorial formalism for LQG in order to propose dynamics for carefully constructed simple models with physical interpretation.

Director: **Jose Juan Blanco Pillado** (josejuan.blanco@ehu.eus)

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** (joanes.lizarraga@ehu.eus), **Jon Urrestilla**(jon.urrestilla@ehu.eus)

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, etc. 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** (josemm.senovilla@ehu.eus**)**

Title: **Gravitation and General Relativity**

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

Quantum matter, simulations, and technologies

Director: **Adolfo del Campo** (adolfo.delcampo@gmail.com)

Title: **Super-Adiabatic Quantum Computation**

Adiabatic quantum computing is a formed of quantum computing at the forefront of quantum technologies. Cutting-edge prototypes of quantum annealing devices have by now been commercialized (e.g. by D-wave) and explored by Google, NASA and LANL, among other companies and institutions. In essence, adiabatic quantum computing exploits the application of the quantum adiabatic theorem to find the ground state of many-body Hamiltonians that encode the solution to an optimization problem of interest. Realistic annealing schedules in finite-time often lead to nonadiabatic dynamics and formation of excitations. In this context, the understanding acquired from the nonequilibrium dynamics across quantum phase transitions provides useful heuristics to design strategies for efficient quantum annealing. Much of the required understanding is encapsulated in the Kibble-Zurek mechanism that predicts that the density of excitations scales as a universal power law with the annealing time. This paradigm can however be extended to account as well for the full counting statistics of defects, i.e., the distribution of the number of quasiparticles generated as a result of the breakdown of adiabatic dynamics in finite-time quantum annealing. The project aims at characterizing this distribution and design super-adiabatic schemes to suppress the formation of excitations, achieving efficient adiabatic quantum computing in finite time.

Director: **Aran Garcia-Lekue** (wmbgalea@ehu.eus)

Title: **Novel electronic properties of graphene nanostructures**

Graphene nanostructures exhibit unique properties and hold a great promise for developing new nanoelectronic devices. Interestingly, it has been recently demonstrated that graphene nanoribbons (narrow strips of graphene) may exhibit topological electronic states, which could be of relevance for many technological applications, such as quantum computing. In this project, state-of-the-art computational tools will be employed to investigate the electronic properties of graphene nanoribbons doped with heteroatoms, with special emphasis on the emergence of topological phases. Besides, a strong collaboration with experimental groups experts in the field is envisioned.

Director: **Asier Eiguren** (asier.eiguren@ehu.eus), **María Blanco** (maria.blanco@ehu.eus)

Title: **Kondo physics with realistic Fermi surfaces using Numerical Renormalization Group**

The objective of this project is to solve the Anderson impurity problem considering a realistic Fermi surface calculated by means of ab-initio methods. Hitherto, Numerical Renormalization Group (NRG) studies on Kondo screening were typically restricted to s-wave scattering models. i.e. a spherical Fermi surface with constant matrix elements were assumed. In this Master Thesis the student will include the details of the electronic structure of the embedding crystal using ab initio wave functions.

Directors: **Aitor Bergara** (a.bergara@ehu.eus), **Aritz Leonardo** (aritz.leonardo@ehu.eus)

Two proposals are available:

Title: **Pressure induced topological transitions**

Pressure strongly modifies atomic structures of materials, resulting in highly complex physical behavior. For example, even though under normal conditions alkalies crystallize in simple compact structures, phase transitions to complex and low coordinated structures have been reported to emerge under pressure. Correlated to these transitions, a number of exotic phenomena arise under high pressure. For example, it has been shown that pressure enhances the superconducting transition temperature. Actually, last year two experimental groups observed that LaH10 superconducts at 260 K and 200 GPa, becoming the highest Tc ever measured. On the other hand, topologically non-trivial materials (insulators, semimetals and metals) have become a hot topic in recent condensed matter physics research. Their electronic structures exhibit nontrivial band crossings near the Fermi energy. In this PhD project we propose to analyze possible pressure induced topological transitions even in simple systems, as a result of the already observed enhanced electronic complexity under pressure. The study of the eventual connection between the topological transition and superconductivity will also be part of the research project.

Title: **Molecular dynamics study of Calmodulin**

The complete resolution of the sequence of the human genome in 2016 has been a huge milestone that continuously reveals causal relations among pathologies and gene signaling. Moreover, the latest advances of experimental techniques, such as nuclear magnetic resonance, provide a direct access to 3D maps with atomic resolution of the proteins that form cell membranes. This new accessible structural information has become a revolution in biological sciences for the design of new drugs that improve the well-being of humans. Remarkably, 60% of the commercial drugs act precisely on the proteins located at the cell membranes. With this scenario in mind, physical models that mimic atomic interactions within the proteins and their posterior time evolution through molecular dynamics provide a very powerful tool for the prediction and comprehension of membrane phenomena. Theoretical simulations of proteins serve as a guidance for the design of new drugs and help understanding the enormous amount of experimental information available. In this Master Thesis we shall consider the Kv7.2 channel of neuron membranes — a potassium voltage-gated channel located in human neurons —whose functioning relies in a potential difference induced by calmodulin (CaM). By means of All-atom simulations, molecular dynamics and coarse grain models, we would like to validate two claims regarding the behavior of the secondary structure of the IQ motiv of the channel: 1) Both wild type and mutant can form stable helices without the ribosome; 2) Wild type can form an alpha helix at the ribosome whereas the mutant cannot.

Director: **Aurelia Chenu** (achenu@dipc.org)

Title: **Bath engineering in stochastic systems**

Any realistic description of a quantum systems asks for an open representation, where the system of interest interacts with a larger environment. In an operationalist view of open system, the system-bath correlations can be classified into classical and non- classical correlations, according to the existence or not of a representation of the reduced system in terms of an ensemble of Hamiltonian. Hamiltonian ensembles are typically used to described disordered systems, which interestingly provide a versatile framework and backbone representative of complex materials as diverse as photosynthetic light-harvesting antennae and photonic circuits. In particular, recent results show how disorder can be used to protect quantum properties of matter, such as long-range correlation, or many-body entanglement. Using the operational approach, this project aims at characterizing the dynamical impact of the disorder, through the structure of the resulting master equation, into coherent and incoherent contributions to the averaged dynamics. This project will harness the cutting-edge of quantum technologies, i.e. quantum simulation in a diversity of platforms, and is relevant for close collaborations with experimentalists.

Directors: **Diego Guerin** (diego.guerin@ehu.eus)

Title: **Quantum and Classical Dynamic Modelization of Immunogenic Proteins**

TBA

Directors: **D. Sokolovski** (dgsokol15@gmail.com), **M. Pons Barba** (marisa.pons@ehu.eus)

Title: **Quantum measurement theory and its applications**

The project will be an introduction to the field of measurement in Quantum Mechanics and the investigation of bosonic hybrid devices to monitor the evolution of a quantum system. Quantum Measurement Theory (QMT) is important to understand the quantum world, and it has, due to the technological progress, a large number of “quantum engineering” applications. The project involves both analytical and numerical work. Further information may be obtained from the Supervisors.

Director: **Enrique Rico** (enrique.rico@ehu.eus)

Title: **Quantum Simulation of Lattice Gauge Models**

We will study conventional lattice gauge theory and generalisations that realise topological phases. They constitute a class of quantum state of matter, which does not wholly fit into the existing paradigms, but which connects to areas including topological order, spin liquids, and quantum information theory. To conclude, we will study the quantum simulation of these models within circuit quantum electrodynamics.

Director: **Evgeny Sherman** (evgeny.sherman@ehu.eus**)**

Title: **Quantum mechanics with spin-orbit coupling**

The aim of this Master project is to study analytically and/or numerically quantum motion determined by spin-related properties of single particles and condensed matter. We will consider 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 electrons in solids or very cold Bose-Einstein condensates and atomic Fermi gases.

Director: **Gonzalo Muga** (jg.muga@ehu.eus)

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: **Íñigo Egusquiza** (inigo.egusquiza@ehu.eus), **Mikel Sanz** (mikel.sanz@ehu.eus)

Title: **Microwave quantum illumination and quantum radar**

Quantum Illumination is a novel technique which exploits quantum entanglement as a resource to detect the presence of an object with higher accuracy or smaller number of photons. The applications go from detection of trapped molecules to quantum radars, detection of cloaked objets and better weather forecasts. Here we will study existing protocols and try to adapt them to a realistic scenario in the microwave regime to try to implement it in collaboration with the Walther Meissner Institute in Garching (Germany) and the Ecole Polytechnique de Lyon (France).

Director: **Jens Siewert** (jens.siewert@ehu.eus**)**

Title: **Bloch Representation for Two-Qubit States: Entanglement versus Nonlocality**

The Bloch representation (that is, the mathematical description of quantum-mechanical density operators in terms of a matrix basis) is a powerful — yet far from fully developed — tool to solve quantum mechanics problems. Its language is deeply rooted in geometry and therefore its concepts are amenable to geometric intuition. Only recently, methods have been presented to adequately visualize higher-dimensional state spaces, such as the Bloch-sphere analog of a three-level system (qutrit) and also that of two two-level systems (i.e., two qubits), and there is much potential for further research. The goal of this master thesis project is to investigate the long-standing question whether an intuitive geometric understanding of the different types of correlations in a two-qubit system is possible. In particular we will study the difference between entanglement and nonlocality, that is, between states that do violate a Bell inequality, and others that do not. One may conjecture that the difference between mere entanglement and nonlocality is encoded in simple geometrical conditions. This idea will be studied by using Bloch-representation based schemes for visualizing the correlation part of two-qubit states.

Director: **Jorge Casanova** (jcasanovamar@gmail.com)

Title: **Nanoscale control of electron-spin-labels with nitrogen vacancy centers for molecular structure determination**

Electron-spin-labels have a large gyromagnetic ratio leading to a strong coupling with a quantum sensor such as the nitrogen vacancy center in diamond. At the same time, the fast spinning rate of electron spins posses serious problems to their coherent control. In this research work, we will design, and numerically demonstrate, the efficiency of dynamical decoupling methods to detect and position electron spin pairs attached to biomolecules for magnetic resonance imaging purposes.

Director: **Juan Luis Mañes** (juanluis.manes@ehu.eus), **Maia G. Vergniory** (maiagv@gmail.com)

Title: **Topological properties of metamaterials**

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 topology of non-electronic lattices, such as 3D phonons and photonic crystals, to reveal their topological mysteries.

Director: **Lianao Wu** (lianaowu@gmail.com)

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: **Michele Modugno** (michele.modugno@ehu.eus)

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** (mikel.sanz@ehu.eus), **Enrique Solano** (enr.solano@gmail.com)

Title: **Reinforcement Learning in Quantum Artificial Life**

The concept of artificial life in quantum technologies have already been introduced, studying the minimal system which show a basic behaviour associated with "life", i.e. quantum individuals which can be born, live, reproduce, and die. Here, we would like to go one step forward and introduce basic Darwinian predator-prey behaviour in these quantum individuals. This will be achieved by a quantum reinforcement learning protocol emerged from the interaction of a quantum individual with its predator/prey. Finally, we will try to implement this dynamics in a real cloud quantum computer.

Director: **Sebastian Bergeret** (fs.bergeret@csic.es)

Title: **Non-equilibrium properties of superconductors with spin-dependent fields**

The interplay between superconducting correlations and spin-dependent fields leads to striking phenomena as topological superconductivity, dissipation-less magneto-electric effects and non-conventional pairing. Studies in this field mainly focus on ground state properties under ideal equilibrium situations. The goal of this project is to provide a theoretical description of non-equilibrium properties in superconductors with spin-orbit coupling and induced exchange fields. In a first stage the student will derive the kinetic equations governing the charge, spin and heat transport of such superconductors and identify the non-equilibrium modes and their mutual coupling. In a second stage she/he will explore realistic setups , predict novel effects and propose experiments with different material combinations. Collaboration with international experimental groups is also expected.

Director: **Sofía Martinez Garaot** (sofia.martinez@ehu.eus), **Gonzalo Muga** (jg.muga@ehu.eus)

Title: **Fast and robust control of quantum systems**

Many quantum optical systems are employed to test and illustrate the fundamental concepts of quantum theory. They have also practical applications for communications, quantum information processing, metrology and the development of new quantum-based technologies. Controlling these systems accurately in order to implement all these technologies has become a major goal in contemporary Physics. Quantum adiabatic processes are useful to drive or prepare states because they are usually robust. However, they are prone to suffer noise and decoherence or loss problems due to the long times involved. This is often problematic because some applications require many repetitions or too long times. Shortcuts to adiabaticity (STA) are alternative fast processes that reproduce the same final populations, or even the same final state, as the adiabatic process in a finite, shorter time. Since adiabatic processes are ubiquitous, STA methods also extended beyond the quantum world, to optical devices, classical mechanical systems, and statistical physics. In this research work we will contribute to this field designing new STA methods or improving and applying the ones already developed in the group to different systems and conditions.