Master in Quantum Science and Technology
Topics for Master's theses
(2017-18)

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Classical and quantum description of non-Abelian multiwaves

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 super- 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-branes are known.

The proposed work will be devoted by studying the properties of the so-called non-Abelian multiwaves in D=3 and D=4 dimensions. These are the lower dimensional counterparts of the 11-dimensional multiple M0-brane system (multiple self-interacting M-theory waves). It is planned to investigate the symmetry properties of non-Abelian multiwave actions, to search for their curved (super)space generalizations, to quantize these models and to study the properties of the corresponding quantum systems. Actually, while the D=11 mM0-brane action and its D=3 cousin have been constructed, the action of D=4 non-Abelian multiwaves is not known yet and is planned to be the first result in this master thesis.

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Cosmic strings

Cosmic strings are one-dimensional stable concentrations of energy (topological defects) that may have been created in the Early Universe. They are predicted in many extensions of the Standard Model, therefore finding evidence for them would open up a new understanding at energies higher than we could ever probe on Earth. In order to obtain their observational consequences we need to understand the evolution of these strings. Recent field theory simulations of these objects have uncovered the existence of a possible new mechanism of energy loss for strings. In this project, we want to investigate the origin of this mechanism and study its relevance in the evolution of cosmological scale strings. This is a very important issue since it has a direct impact on the observational signatures of these models. More information on our group can be found at (tp.lc.ehu.es/earlyuniverse).

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The late-time acceleration of the Universe

The recent acceleration of the universe is by far the biggest and deepest problem in theoretical physics nowadays. Such an acceleration was inferred 20 years ago through measurements, of supernovae and corroborated by several observations, it lead also to the Nobel prize in physics in 2011. The goal of this project is to construct a phenomenological model to describe the current acceleration of the universe and work out its behavior at the perturbative level obtaining the expect matter power spectrum. We will as well compare our results with the available data of f*sigma_8. For appropriate scales, these two quantities can be sensitive to the current expansion of the universe and can be used to characterize whatever is driving our current expansion.

David Brizuela (david.brizuela@ehu.eus)

Back-reaction in models of loop quantum cosmology and application to inflation

Loop quantum cosmology is a set of symmetry reduced models of the theory of loop quantum gravity. These models have been very successful during the last years. One of the great results obtained in this context, is the resolution of the initial singularity. In these models, the big bang is replaced by the so-called big bounce. Led by the gravitational attraction the universe is contracted but, when quantum effects become relevant, gravity turns out to be repulsive. Thus, the collapse is overcome and the universe undergoes a bounce which leads it to an expansive branch. On the other hand, it has been proposed that the inflationary epoch of the universe might work as a magnifying glass for tiny quantum gravity effects. This would make the cosmic microwave background one of the few places to look for evidence of quantum gravity. In fact, during the last years there have been a number of proposals in order to compute quantum-gravity effects in the CMB in the context of loop quantum cosmology. Nonetheless, all these proposals neglect completely the quantum back reaction and essentially assume a classical trajectory of the system. In this work we propose to construct a formalism, based on a decomposition of the wave function in its corresponding moments, to systematically compute the effects of the back reaction in different loop quantum cosmological models. Once the formalism is under control, its application to inflationary scenarios will also be considered.

Tom Broadhurst (tomie325@gmail.com)

Axionic Dark Matter

The project is to compare the first axionic simulations of cosmic structure formed by dark matter that we have made with unique Hubble and JWST observations that are guaranteed to members of our group. This new subject is already of wide interest by the astronomy community based on the many unique predictions we have published in our recent Nature and PRL papers. This form of dark matter is motivated by string theory and forms an interference pattern of a self gravitating Bose Einstein Condensate of light axions with many advantages over the conventional heavy particle interpretation of dark matter - of fundamental importance for physics and cosmology.

Neutrinos and Large Scale Structure

We have a unique opening to join our team to measure the density of "relic" neutrinos that are predicted to be generated in vast numbers at the birth of the Universe and liberated just 1 second after the Big Bang, using data from the Sloan Digital Sky Survey and the Subaru Hyper Suprime-Cam in Hawaii. We have made the first detection of the sum of all 3 predicted flavors using the most massive clusters of galaxies in the Universe whose formation is delayed by the smoothing effect of these neutrinos as they have streamed relativistically away from the initial Gaussian field of density perturbations that cause structure to form in our Universe. This result, together with the Laboratory detection of neutrino oscillation allows us to define the mass Eigenstate hierarchy of the neutrino sector - of fundamental importance to physics, with implications for the unsolved major question of why matter dominates over antimatter in the Universe.

Iñaki Garay (inaki.garay@ehu.eus)

Loop Quantum Gravity: U(N) framework and spinorial techniques

The so called U(N) framework for Loop Quantum Gravity (LQG) is a relatively new formalism that provides a different viewpoint to study the approach to quantum gravity given by LQG. Using this framework it is possible to construct simple models to study the dynamics on them and gain intuition about the implementation of the dynamics in the general case (still one of the main open problems of the theory). Related with this, a spinor representation of LQG was also developed and it was shown that it is possible to recover the U(N) framework by quantizing a classical system written in terms of spinors. This project consists in studying the Loop Quantum Gravity theory, the U(N) framework and the spinorial techniques in order to, eventually, propose a new simple model to implement the dynamics and study its physical consequences.

Francesco Hautman (francesco.hautman@desy.de)

TMD Distributions at Hadron Colliders

Quantum Chromodynamics (QCD) is the gauge field theory of the strong interactions. The Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations constitute an essential part of QCD at high energies, and describe the behavior of quark and gluon distribution functions in hadrons. They are central to the understanding of the physics of scattering processes at the Large Hadron Collider (LHC) as well as at future colliders such as the planned Electron Ion Collider (EIC). The purpose of this project is to gain a basic knowledge of the physical meaning and mathematical structure of DGLAP equations, to learn a particular approach to solving the equations which has been recently proposed based on the so-called parton branching technique, and to explore the application of this new approach to LHC/EIC processes which are sensitive to transverse momentum and polarization degrees of freedom encoded in the so-called “transverse momentum dependent” (TMD) distributions. These processes are relevant, for instance, for spectra of lepton pairs produced by Drell-Yan mechanism in proton-proton collisions, for di-photon and multi-lepton final states produced from Higgs decays, for single-particle inclusive production in electron-hadron collisions.

Lucas Lamata (lucas.lamata@gmail.com)
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Quantum reinforcement learning with quantum photonic systems

The thesis will consist on proposing and analyzing an implementation of protocols for quantum reinforcement learning (one of the main kinds of quantum machine learning, in the context of quantum artificial intelligence) in the platform of integrated quantum photonics. A first part of the thesis will consist on the analysis of basic few-qubit building blocks of this protocol with quantum photonics, and a later development of how to couple these building blocks to build a network of quantum reinforcement learning units with quantum photonics.

Juan Luis Mañes (wmpmapaj@lg.ehu.es)
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Group theory analysis of interacting electrons: the case of CuBi2O4

Double Dirac fermions have recently been identified as possible quasiparticles hosted by three-dimensional crystals with particular non-symmorphic space group symmetries. However, the paramagnetic phase of CuBi2O4 does not obey the non-interacting group theory predictions from the dimensions of several irreducible representations: it should be a symmetry protected semimetal, instead it has a gap of 2 eV. This project consists of two parts, the first one related to material design. The strong correlation between Cu and Bi electrons can be screened by doping the Bi site with Sn: CuBi1-xSnxO4. This new compound will be studied for different Sn concentrations (from x=0 to x=1.5) by means of Dynamical Mean-Field Theory (DMFT), a method to determine the electronic structure of strongly correlated materials. On the other hand, the electronic band structure will give us an insight to develop an interacting group theory for this particular space group and perhaps open a new way to study Mott insulators.

Michele Modugno (michele.modugno@ehu.eus)

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, superfluidity, 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.

Gonzalo Muga (jg.muga@ehu.eus)

Shortcuts to adiabaticity (STA)

Currently the flagship of the group. Adiabaticity is the ability of physical systems to keep certain properties (adiabatic invariants) constant when the external control parameters are changed slowly. In quantum mechanics it is mostly associated with the absence of transitions among instantaneous levels when the Hamiltonian is changed slowly in time and no level crossings occur. Adiabaticity is often used in research and industrial processes to prepare states but it takes by definition a long time, which is not always available or desirable. STA are methods to speed up slow, adiabatic processes that we have lead and pioneered since 2009. Decoherence is the main obstacle to develop scalable quantum information processes and in general quantum technologies. Designing fast processes that keep quantum coherence and do not produce spurious excitations is a major route to suppress or mitigate decoherence. Due to the widespread use of adiabatic processes, STA are applied to a broad range of systems in Atomic, Molecular, Statistical and Optical Physics, condensed matter, and even beyond the quantum world, in Optics (where STA are used to produce compact devices such as waveguide connectors), or mechanical engineering (e.g. to control operation of robotic cranes). STA is currently a hot topic with exponentially growing publications and experiments. The master student would join one of the lines currently active in the group after considering his/her interests

-Quantum thermodynamics: Quantum engines and refrigerators benefit from STA to improve efficiency. Fundamental questions remain, such as the true cost of shortcuts, the quantification of the third principle, or the best way to apply STA to implement prototypes.

-Beyond quantum: Technologically relevant STA in optics or mechanical engineering

-Interferometry: Explore the use of STA to develop compact detectors and interferometers.

Asymmetric devices in quantum technologies

Diodes or valves are well known macroscopic asymmetric devices, with preferential directionality for flows of currents or particles. Microscopically, building asymmetric devices for heat or particle flow would have a huge technological impact for energy control or to develop quantum circuits. This is challenging though, because certain symmetries of the interaction potentials such as time-reversal invariance, or PT symmetry preclude certain asymmetrical devices. The group has a long experience in this field. In 2004 we proposed the "atom diode", a laser device that lets atoms pass only one-way. It was later implemented experimentally and used for atom cooling.

Enrique Rico (Enrique.rico.ortega@gmail.com)

Quantum simulation of topological quantum matter

We will simulate symmetry protected topological phases of matter, which are known to have non-trivial edge modes. We will describe the experimental setup and the measurement protocol of the edge physics where we will analyze how to realize chiral modes on the lattice by a higher-dimensional embedding, through the domain wall construction, which will require new tools from quantum technologies to be developed. We will need both the numerical aspect of the quantum technologies toolbox and the quantum simulation from different experimental setups to have a complete and successful understanding of this task. The development of the new methods used during these studies will be easily transferred to the simulation of new emerging phases of matter (e.g. topological phases) in condensed matter physics that are currently under study and have a direct impact in quantum technologies as a potential candidate for quantum memories.

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Quantum Machine Learning with Quantum Memristors

Gunar Schnell (gunar.schnell@ehu.eus)

The Sivers effect

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 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.

Evgeny Sherman (evgeny.sherman@ehu.eus)

Development of chaos in systems of spins

The aim of this project is to look numerically and analytically at development of various kinds of chaos determined by spin-related properties of condensed matter. We are going to study semirelativistic systems with so called spin-orbit coupling, where particle spin is strongly coupled to its momentum. The systems we are going to investigate in detail are hot excitons in solids and very cold Bose-Einstein condensates.

Jens Siewert (jens.siewert@ehu.eus)

The Bloch representation and the geometry of quantum states

The Bloch representation is a powerful tool to solve problems in (non-relativistic) quantum mechanics, in particular for discrete systems with dimension higher than 2. This is because its language is deeply rooted in geometry and therefore its concepts are amenable to geometric intuition. Potential topics for master projects are related to generators of SU(d), entanglement of bipartite and multipartite states, questions touching upon monogamy constraints for various quantum correlations, the existence of absolutely maximally entangled states, and others. (Please contact me personally for more detailed description of projects).

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Mutation Detection with Electron Transport in DNA

Francesca Vidotto (vidottof@gmail.com)

Entangled states in quantum gravity: applications to cosmology and black holes

In Loop Quantum Gravity it is possible to write quantum states of the geometry, and compute transition amplitudes between them. While the basic states of the theory are pure states, is of particular interest to construct states that carry entanglement. In fact, those states are of particular physical relevance, in the description of the state of the geometry in the early universe and in the physics of black-hole horizon. Different proposal for those states have recently appeared in the literature. The project aims at understanding and comparing these proposals, and possibly studying a concrete phenomenological application.

Lianao Wu (lianao_wu@ehu.eus)

Trotterization to simulate adiabatic evolution and adiabatic quantum computation

Our 2002 BCS simulation paper was the first to propose Trotterization to simulate adiabatic evolution of a time-dependent driving Hamiltonian, which now is known as the Trotterized (or digitized) adiabatic quantum computation and was implemented experimentally. We will apply the Trotterizations to Boson sampling using photonics chip system, which will be more robust than time-dependent dynamical systems.

Bilbao, Oct. 26th, 2017