Master in Quantum Science and Technology
2016/17

Topics for Master's theses

The following is a (non-exclusive) list of possible topics supervisors, together with a generic title and a short description. The list will be presented in alphabetical order in family name.

- **Igor Bandos** (igor.bandos@ehu.eus)
  Supersymmetric multiparticle systems in String/M-theory String theory, presently also known under the name of M-theory, is the most promising (if not unique) candidate on the role of quantum theory of gravity and of unifying theory of all fundamental interactions. Its necessary ingradients are supersymmetry, an unusual symmetry mixing fermionic and bosonic particles (this is to say matter with interactions and the recently discovered Higgs particle) and the presence of additional spacetime directions ($D = 10$ and/or $D = 11$ instead of $D = 4$). The special role in String/M-theory is played by supersymmetric extended objects, super-p-branes (superstrings for $p = 1$, supermembranes for $p = 2$, supeprparticles for $p = 0$,), and multiple super-p-brane systems (mMp-branes and mDp-branes). The proposed research is aimed to investigate the properties of simplest $p = 0$ representative of these, mM0-brane, and of its lower dimensional ($D = 3, 4$) counterparts.

- **Jose Juan Blanco Pillado** (josejuan.blanco@ehu.es; with other members of the cosmology group. See also `http://tp.lc.ehu.es/earlyuniverse/`)
  Cosmology in String Theory The last few years have witnessed an impressive development of cosmology but there are still important problems to resolve. String Theory cosmology is a line of research that tries to look for novel solutions of cosmological problems within the String Theory context finding at the same time observational handles on String Theory. We propose to the student the study the impact in cosmology of one of the most fundamental properties of String theory; the existence of multiple 4d vacua of the theory. We propose to explore the Statistical distribution of these vacua in realistic models as well as to model the existence of multiple vacua in a statistical manner. We will also study the implications of this complicated structure of vacua for the theory of cosmological inflation.

  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.

- **Mariam Bouhmadi–López** (mariam.bouhmadi@gmail.com)
  Quantum Cosmology and the late Universe: Despite the huge advancement in cosmology, we still face enormous theoretical problems like finding a suitable explanation of the current dark energy (DE) era; i.e. we know that the Universe started speeding up recently as predicted by SnIeA observations more than a decade ago, and afterwards confirmed by several types of cosmological and astrophysical observations, but we do not know from a well grounded theoretical framework what is causing this acceleration. A possible explanation to explain the late-time acceleration of the universe is to invoke a 3-form field but it might come at the expense of a potential abrupt event in the future named the Little Sibling of the Big Rip. In this project, we will consider a quantum cosmological model where the 3-form field is living in a homogeneous and isotropic Universe. The quantisation will be carried on the framework of quantum geometrodynamics. We will then look for the possible avoidance of the Little Sibling of the Big Rip on the quantum realm.

- **Tom Broadhurst** (tom.j.broadhurst@gmail.com)

Quantum Dark Matter. The unsolved nature of Dark Matter remains one of the most outstanding puzzles in physics. The student should understand and appreciate the motivations for the standard WIMP particle case and the new stringent limits on this from the LHC and LUX experiments. The most viable dark matter candidate may now be light axions, in a Bose-Einstein state, motivated by string theory, and the student will take as a basis for his or her work the first simulations that have been made in this context with predictions that are being tested via Pulsar timing, using LOFAR and also the gravitational bending of light by condensate interference within distant galaxies using the Hubble Space Telescope. (See for context `http://www.nature.com/nphys/journal/v10/n7/abs/nphys2996.html`)

- **Alfonso García–Parrado Gómez–Lobo** (alfonso@math.uminho.pt):
Classical general relativity: formulation of the Einstein equations as an initial value problem and construction of special initial data (black hole initial data). This is relevant in the study of numerical simulations of black hole space-times and the study of their asymptotic evolution. The understanding of the initial value problem in general relativity is also important to understand the physics of the gravitation.

- **Maia García Vergniory** (maiagv@gmail.com)
Topological invariants implementation for bulk and thin films for topological matter by means of Wilson loops, and its application to real materials. The field of topological insulators has grown tremendously over the last 8 years. It has, undoubtedly, become the hottest, largest, and most dynamic field in condensed matter physics. Theoretically, it combines the intricacies of high-level field theory, anomalies and topology with the predictive power of ab initio and density functional theory calculations. In this project the student will implement a program based on tight binding model to calculate the topological invariants in orther to differentiate trivial from topological phases, and induce transitions between them. This method applies to bulk systems and thin films, such as chern insualtors, Weyl and Dirac semimetals, and non-symmorphically protected systems.

- **Matthias Kleinmann** (matthias_kleinmann001@ehu.eus)
Complex or real Hilbert space? Quantum theory is based on the structure of the complex Hilbert space generated by all wave functions. The fact that this space is complex rather then real is absolutely essential to the theory. However, an interesting question is whether this is more a matter of mathematical convenience or whether there is direct experimental evidence for this complex structure. Indeed, arguments have been brought forward that no such direct experimental evidence is possible. The topic of the Master thesis is to investigate the assumptions behind these no-go results and explore several approaches how they could be bypassed. This will lead either to a stronger no-go result or exhibit a way to show that quantum theory cannot be based on a real Hilbert space.

- **Lucas Lamata** (lucas.lamata@gmail.com)
Quantum Simulations of General Dicke Models with Trapped Ions. Quantum simulations consist in the intentional reproduction of a quantum model in a controllable quantum platform. In this Master Thesis project, the student will analyze the possibility to realize a quantum simulation of the prototypical Dicke model, a many-body quantum model consisting of N spins coupled to a quantized bosonic mode, and its extensions to many photons, inhomogeneities, time-dependent couplings, and additional dynamical terms, with digital, analog, and digital-analog techniques. While digital quantum simulators are based on decomposing the dynamics into elementary gates, analog quantum simulators rely on a continuous evolution with a similar Hamiltonian to the simulated system. Digital-analog quantum simulators combine both, via the use of large analog blocks, providing scalability, with flexible digital steps. A prominent quantum platform, namely, trapped ions, will be considered for this purpose, studying in detail the feasibility of experimental realizations with state-of-the-art trapped-ion technologies.

- **Aritz Leonardo Liceranzu** (aritz.leonardo@ehu.eus)
Direct calculation of exciton binding energies with the time-dependent density-functional theory: Excitons are electron-hole (e-h) pairs appearing below the band gap in insulators and semiconductors. The theoretical calculation of the binding energies is computationally challenging due to the long-range

interaction of the bound (e-h) pair. The student will have to adapt/implement the Casida equation formalism for molecular excitations to (infinite) periodic solids and test this computational approach with available experimental data.

- **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.

- **Gonzalo Muga** (jg.muga@ehu.es)
  The main and pervasive obstacle towards fully functional new quantum technologies (QT) is decoherence. The solution proposed in this Project is to develop and apply **Shortcuts to Adiabaticity (STA)**, so as to enhance the basic operations and devices on which QT are built. As well, STA allows to create novel devices with technological impact. Preliminary work and test cases have been worked out by the IP, who has pioneered and leads this emerging field.

- **José Ignacio Pascual** (ji.pascual@nanogune.eu)
  Quantum Materials: fabrication and atomic-scale investigation of spin chains in graphene nanoribbons. Graphene nanoribbons are semiconducting 1D carbon materials inheriting some of the properties of grahene. They can be created with atomic precision on a metal surface by chemical reactions. In this project, the candidate will develop an strategy to embed transition metal atoms inside nanoribbons, using a low temperature scanning tunneling microscope as experimental set up. Once created, the student will study the magnetic and electronic properties of the spins chains in the interior of nanoribbons, with the aim of resolving their magnetic coupling and collective spin-order states.

- **Enrique Rico** (enrique.rico.ortega@gmail.com)
  Quantum simulation of topological many-body quantum systems with superconducting circuits. (Key-fields involved: FIELDS AND PARTICLES; THEORETICAL CONDENSED MATTER; QUANTUM INFORMATION; QUANTUM SIMULATIONS; QUANTUM TECHNOLOGIES) The topic of this research project will show the master student the application of several frontier fields of physics in the study, description and manipulation of many-body systems with singular topological properties that appear in condensed matter or high energy physics. We will consider simple models that characterize some topological phases of matter and we will use quantum simulators from superconducting circuits to build these phases of matter in the lab.

- **Gunar Schnell** (gunar.schnell@ehu.eus)
  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, in particular for systems with dimension higher than 2, 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. Potential topics for master projects are related to generators of SU(d), entanglement of bipartite states, questions touching upon the monogamy of entanglement, and others.

- **Raül Vera** (raul.vera@ehu.eus; together with JJ Blanco-Pillado)

Field theory description of double layers in quadratic gravity. The aim is to obtain a field theory description of double layers in quadratic theories of gravity. To that end we focus on a smooth description via the study of the a scalar field that makes up the layer and take the limit of a thin transition.

- **Lianao Wu** (lianaowu@gmail.com)

My 2002 BCS simulation paper (PRL 89, 057904 (2002)) was the first to use Trotterization to simulate adiabatic evolution, in particular initial state preparation which now is known to be equivalent to universal adiabatic quantum computation. A student may be interested in the **"Trotterized adiabatic quantum computation"** and works out an example.