PhD **Open Days**

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Quantum Mechanics in Curved Spacetime

PhD in Physics

Gonçalo Martins Quinta (goncalo.quinta@tecnico.ulisboa.pt)

Quantum Mechanics and General Relativity

The universe can be divided into two main realms: the microscopic world of particle physics, described by quantum mechanics; and the macroscopic world of gravity, governed by general relativity. Although the ultimate goal would be a theory merging these two, a definite answer has not been given yet. A different approach to the challenge is to find some hints that might lead to a full theory of quantum gravity by considering the framework of quantum mechanics in the presence of a curved spacetime. Since the dynamics of the microscopic world is contained in a very small region of space, the curvature of spacetime can usually be negligible, i.e. spacetime can be considered flat, meaning gravity plays no role in this limit. However, in the presence of very strong gravitational fields, such an approximation cannot be considered anymore. In this case, calculations of quantum effects must be performed in a curved spacetime; an area of physics which is called Quantum Field Theory in Curved Spacetime (QFTCS). It is not a regime so strong that the dynamics of spacetime and particles become interwined, as a theory of quantum gravity would contemplate, but rather a case where a fixed curved background must be taken into account. Despite not being the final theory, QFTCS predicts a plethora of new effects that such a theory must necessarily incorporate.

Vacuum polarization in flat spacetime

A particularly important quantum effect which brings new physical insights when considered in conjunction with curved spacetimes is called vacuum polarization. This effect is a consequence of one of the variants of the Heisenberg uncertainty principle, which states that any amount of energy can be created in vacuum but only during a very short time. This opens the possibility of creating a particle and corresponding antiparticle out of nothing, provided they annihilate each other shortly after. This cannot be directly observable, but the short duration of the particles existence is enough to induce observable consequences. For example, if the particles are charged, there will be an electric field generated by them, where previously there was none. Since this pair production will be constantly happening, there will be a measurable average effect, called vacuum polarization. In flat spacetime, the particular example of an average electric field being present in vacuum originates the so called Casimir effect, where two metal plates are attracted to each other due to the electric field of the vacuum, provided they are close enough.

Vacuum polarization in curved spacetime

By studying vacuum polarization in curved spacetimes, new effects arise which couldn't be predicted in the absence of gravity. One of the most prominent results is the fact that black holes have temperature. Black holes are the most compact objects in nature, consisting in a region of spacetime with a singularity, a point of infinite curvature, in the centre. From the singularity there is a certain distance, called horizon radius, from which nothing can escape, not even light. The surface that encompasses the black hole is called horizon, and everything that crosses it will never be able to come out again. Classically, therefore, one would not expect such an object to have an associated temperature, since that would mean it emitted radiation, when in reality nothing could come out of it. However, if we combine vacuum polarization with the concept of a black hole as a one-way membrane, the notion of black hole temperature naturally arises.

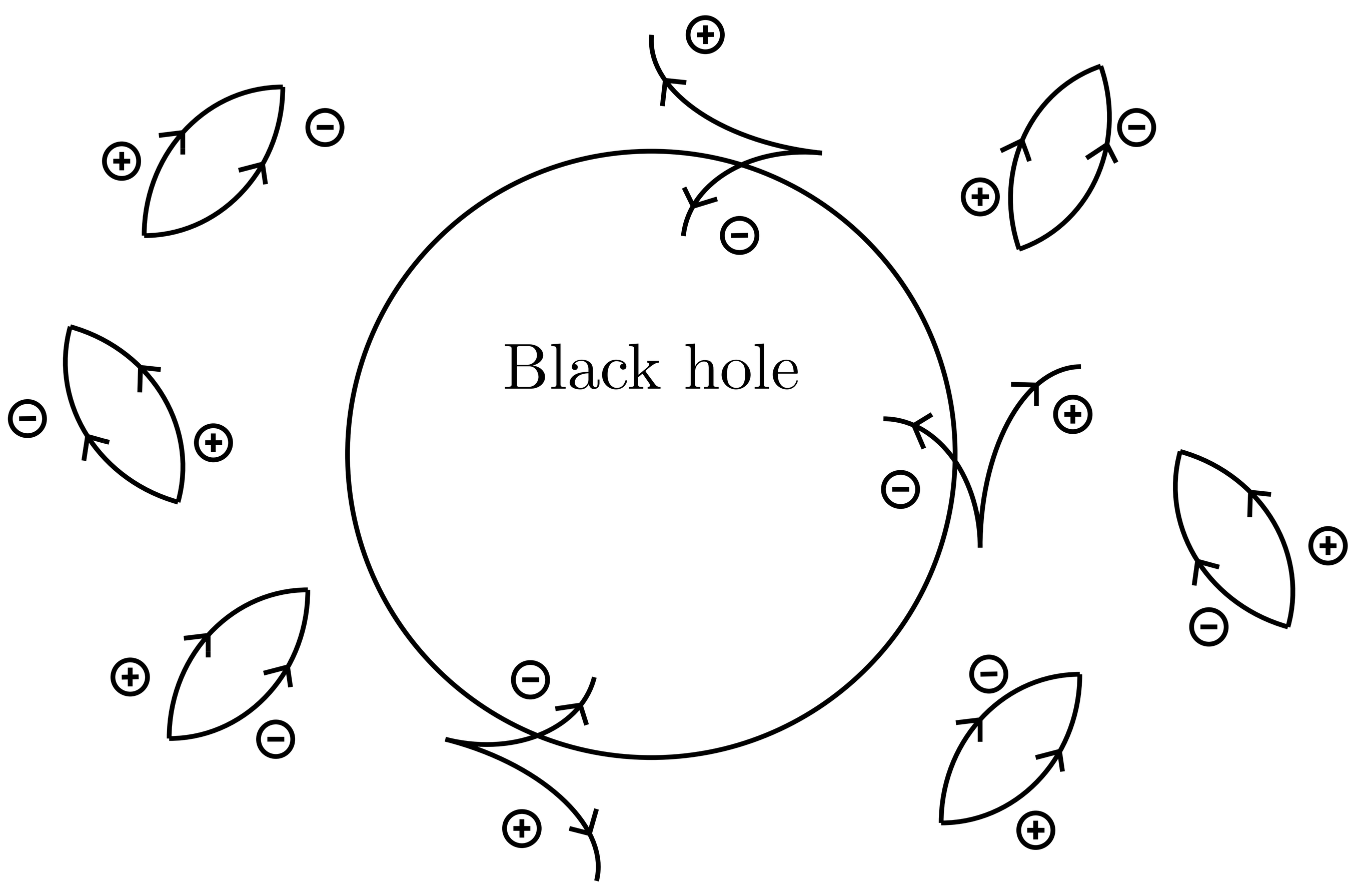

Figure 1: Example of interplay between vacuum polarization and a black hole. Pairs of particle/antiparticle are constantly being created and destroyed around the black hole. In some cases, one of the particle falls into the black hole while the other is scattered away from it. From the outside, this is equivalent to black hole radiation, to which a temperature is associated.

Considering the pair production of particles very close to the horizon, the case might arise where one of the created particles crosses the horizon while its antipartner does not (Figure 2). Thus, the annihilation of those particles will never occur, meaning that for an outside observer all he sees is a particle being radiated away from the horizon of the black hole. It is then possible to show that the emition spectrum of this radiation is that of a black body with a well defined temperature, called Hawking temperature.

The goal of this PhD project is to study problems which are already well understood in flat space quantum mechanics but in a context which includes gravity. In particular, it's intended to further the study of vacuum polarization in the context of different curved spacetimes, searching for new effects not yet explored. Particular emphasis will be given in higher dimensional spacetimes, where some consequences may be derived with some impact for unifying theories requiring multidimensional universes, like string theory for example. By considering the scenario where spacetime can be curved, we are also opening the possibility to simplify the mathematical problem while at the same time keeping the richness in physical consequences. For example, instead of charged particles, which are mathematically more intricate, one can consider uncharged scalar particles. Since all forms of energy induce curvature in spacetime, the simple fact that a pair of particles emerges from empty space will have a direct effect in the gravitational field, even though they are uncharged and characterized solely by their mass.