Popular Summary

Quantum computation is focused on processing information quantum mechanically for solving problems that are difficult or impossible to investigate using a classical computer, such as factoring integers in polynomial time. Of the many approaches to quantum computing, topological quantum computation is particularly appealing because it stores and manipulates information non-locally, thereby drastically reducing susceptibility to the environmentally induced errors that afflict conventional quantum-computing systems. Quantum information can be encoded in the nonlocal state space of non-Abelian quasiparticles, which are particle-like objects with exotic exchange statistics such as Majorana fermions occurring in topological superconductors. The quantum operations necessary for processing can be implemented in such systems by exchanging the positions of these quasiparticles, forming braids of their world-line trajectories in 2+1 D spacetime.

However, the environment is watching the quantum processor, which in turn results in relaxation and decoherence. Even a topological quantum processor is not immune to such effects. In particular, the environmental effects are ignited by the dynamical process of braiding, even if absent for a static system. Loosing information to the environment equally implies that by measuring it we can learn about the system itself. In this project, I propose to turn the tables, and harness its surrounding environments, such as photons in cavity quantum electrodynamics setups, magnetic excitations in magnetic materials, or nuclei in semiconductors, in order to monitor and control the dynamics of Majorana fermions and beyond. Braiding relies on the highly non-local character of the quasiparticles: they do not need to overlap and the ground state manifold stays degenerate at all times. On the other hand, the electromagnetic field in microwave cavities, for example, extends over distances of the order of centimetres. Thus, the Majoranas appear local on the scale of the cavity field. This simple fact is at the core of this project.

There are a series of theoretical challenges that the project will undertake. First will be developing a general theoretical framework for the combined dynamics of topological systems and the environments, indifferent of the specific implementations. This top-bottom up approach, if successful, will prove useful for a wide range of implementations. Currently, nature provides us with several viable Majorana fermions implementations, among which semiconducting nanowires stand out as some of the most promising. Recent controversies on their experimental observation carried at Microsoft calls for novel approaches in order to push the field forward. For this purpose, the second part of the project will explore how by gently shaking and measuring their natural environments, such as photons or magnetic excitations, it is possible to reveal and manipulate Majorana fermions dynamics, and establish experimental signatures that are invisible in conventional electronic transport measurements. It will require developing new theoretical methods, employing numerical calculations, and propositions of novel experiments. The same environments will be exploited in the last part to evaluate the possibly long-range geometrical/topological correlations, and to construct quantum gates. While braiding alone is not sufficient for universal quantum computation, environments will allow to integrate Majorana-based topological quantum processors with conventional quits, which will facilitate universality, and immensely enhance their functionality. On the long run, understanding how Majorana fermions interact with environments should allow for efficient scaling of topological Majorana fermion qubits.