Dynamic correlations functions of quantum integrable models: in and beyond the equilibrium

Popular Science Summary

The world is complex. Whether we look into predicting the performance of financial markets or outcomes of elections, whether we want to understand the organization of ant colonies, human immune systems or gene regulatory networks in cells, what we see is a complicated web of connections, dependencies and interactions that lead to emergent and complex phenomena. A single molecule of water is not wet, though billions of molecules together acquire this characteristic. A single ant is a rather non-intelligent insect, an ant colony fascinates us with efficient skils of harvesting and transporting food to its nest. This complexity often arises by putting together many relatively simple objects and turning on interactions between them. For example, investors on financial markets just try to optimize their profits and the market communicates to them the actions of the other players. Still, these ingredients are enough to cause large-scale phenomena like market crashes.

Studying complex systems is difficult because they challenge our comprehension and mathematical description. Physics is an area of science that can help us with this task. The importance of interactions between the particles and the emergence of new features are typical challenges that modern physics faces. From the physics of quark matter through condensed matter systems with strongly correlated electrons and high T_C superconductors we see that putting many particles together lead to fascinating new phenomena such like superfluids, superconductors, spin-charge separation or fractional charges. These are all examples of emergent behaviour, like the wetness of water, that no single particle exhibit. Also in physics, thanks to the great development of experimental methods, we can test complex theories, look for their limitations and provide insights for further developments. The experiments are precise and reproducible to the degree difficult to achieve in other sciences. However, unlike the complex systems appearing in different fields, the physical ones are a bit simpler. Usually, the complex systems have to adapt to the ever-changing environment, just like the immune system trying to adapt to a new mutation of influenza every autumn. However, in physics, the rules of the game, the laws of physics, do not change. This provides a great opportunity to study complex systems in a slightly simpler form, without the adaptation part, but still with other crucial aspects including the important role of interactions and the emergence of new features.

Integrable models are a special class of physical models. They describe systems of interacting particles and they are just enough complicated to reach the complexity of more general models, and at the same time, they can be studied with a great mathematical precision. They offer us a unique opportunity to trace how the complexity arises. And the best way to understand systems in which particles are strongly correlated is to study their correlations. The aim of this research project is to develop new techniques of computing dynamic correlation functions in integrable models. This will provide us with a new way of understanding complex systems and of the emergence of a macroscopic picture (like the wetness of water) from microscopic properties (like properties of water molecules and their interactions). Dynamic correlation functions of integrable models can nowadays be also measured experimentally, for example, with cold-atomic gases. This makes the result of this project directly testable. Integrable models have yet another interesting feature. We can ask questions about a system in various, sometimes wild, circumstances. Usually, the toolbox of a quantum physicist is limited and mainly developed to tackle problems when a system is in a thermal equilibrium with an environment. Here, with integrable models, we can tackle more general situations. This allows exploration of many new exotic states of matter and understanding the complexity thereof. The aim of this research is to start charting the world of strongly correlated quantum systems beyond the equilibrium.