One of the most puzzling features of quantum mechanics is nonlocality. The existence of the so-called entangled states forces us to describe two particles, even very distant from each other, as one strongly correlated system. Quantum nonlocality cannot, however, be utilised for any superluminal information transfer. In other words, quantum entanglement does not violate the relativistic causal structure implied by the theory of relativity. On the other hand, the discovery of quantum entanglement has ignited a new field of quantum information that enables, inter alia, completely secure cryptographic protocols and computational algorithms, much faster than standard ones.

The strength of quantum correlations can be quantified using Bell-type inequalities: in the simplest case of two particles and two possible detector settings, a certain quantity S cannot exceed the value of 2 when the classical description is used. On the other hand, quantum mechanics allows for a maximal value of $S = 2\sqrt{2}$ - the so-called Tsirelson's bound. The quantity S can theoretically reach even greater values - up to $S = 4$. In the late 1990s, it was discovered that there are possible theories (so-called "PR-boxes") that saturate the maximum value of S - and are therefore “even more nonlocal" than quantum mechanics - but still do not lead to superluminal information transfer.

The project aims to investigate the information-theoretic properties of various theories beyond standard quantum mechanics. The demand of compatibility with the relativistic causal structure, assuring the absence of logical paradoxes, will be adopted as the basic axiom. In the light of the latest research it turns out that this principle allows for the existence of even more general theories (the so-called "RC-boxes") than the aforementioned PR-boxes. They can lead to strange effects such as a nonlocal change in correlations between distant objects. One of the difficult and unresolved problems is whether it is possible to establish secure cryptographic protocols within such theories. While the answer to this question is positive in quantum mechanics and also - at least partially - for PR-boxes, preliminary research suggests that this property breaks down in the general RC scheme.

Recent theoretical research also suggests that quantum field theory - used to describe fundamental interactions in nature - might lead to correlations that cannot be realized in ordinary quantum mechanics. The project will attempt to construct a physical model, in which these mysterious correlations could reveal themselves. We will also study the information-theoretic properties of such models from the RC-box perspective.

The realisation of the project will allow to understand the fundamental limitations of information processing in nature. This is important not only from the perspective of discovering the fundamental laws of physics, but also in the context of potential applications in cryptography or communication in space.