The beginnings of quantum mechanics had brought some headache to the greatest brains of that time. Even though the world seemed to be comprehensively described by the existing classical physics, beyond the chaos was revealed. It turned out that the micro-world is governed by randomness and contains unbeatable limitations. More than a hundred years passed, and we are still thrilled to discover details and prospects of quantum mechanics. A lot of the discoveries were possible because of the so-called ultracold physics. Since the development of the first lasers, scientists have learned how to cool and trap atoms, and now they can reach temperatures as little as 100 nK. It is seven orders of magnitude colder than any naturally existing place in the universe. We bother reaching so low temperatures because then particles stop their chaotic and complex motion. They reveal their quantum nature and become controllable. Ultracold systems provide remarkable possibilities to examine quantum many-body physics, quantum information, and simulations. We benefit from cold studies on a fundamental level and on an everyday basis – they make GPS possible, help predict earthquakes, and serve as a platform for quantum computers. Today we are capable of cooling many species of atoms, ions, and molecules. We can study them separately or as thermal gases, lattices, or condensates. In particular, the project author conducts fundamental studies of Rydberg molecules.

Rydberg atom is something between a regular atom and an ion - its electron is highly excited. Despite the energetic electron, the whole atom remains in the ultracold regime. Rydberg atoms exhibit a lot of unique properties. It can be large, and the larger (more excited) it gets, the longer its lifetime and polarizability. Those properties brought Rydberg atoms to physicists' attention since they make them relatively easy to manipulate and a promising platform for realizing quantum computation and many-body set-ups. In the experiment, strong excitation of the electron results in interactions with distant background atoms. Thus the natural next step is consideration of a molecule composed of a Rydberg and a regular atom – the so-called ultralong-range Rydberg molecules. They have giant dipole moments and exhibit unique oscillatory behavior of the potential energy spectrum and a complex spatial pattern of the wavefunction. In this project, I aim to marry the entity of an ultralong-range Rydberg molecule with highly magnetic atoms.

Highly magnetic atoms (like erbium or dysprosium) are newbies in Rydberg physics. The first observation of the atomic Rydberg state in Er is a matter of last year and suggests prospects in the field. Lanthanides possess a much more complex structure than any previously examined element. For example, Er has fourteen valence electrons, allowing for an imbalanced magnetic moment. Current working platforms like Rb and Sr have one and two valence electrons respectively. Lanthanides are also promising when comes to experimental tunability and manipulation, and they allow for various novel transitions.

In our work, we first examine the energy spectrum of a single Rydberg molecules (homonuclear of Er and heteronuclear of Er and Rb) and search for unique magnetic properties. We use state-of-the-art theoretical methods (Green's functions treatment, multichannel quantum defect theory) and construct a novel microscopic model to describe those complex systems. We expect to encounter possibilities for simulating quantum magnetism, so in the following steps, we focus on many-body systems. These are Rydberg composites – one excited Rydberg atom in a bath of ground-state atoms, and arrays or lattices of magnetic molecules. This field of research is very young, but the proposed tasks will also be realized experimentally.