Abstract for the general public

Nearly 100 years ago, Albert Einstein, using the insights of the Hindu physicist Satyendra Bose, proposed the existence of a new state of matter. This state, today called Bose-Einstein's condensate, appears in gas under extreme conditions – at temperatures billions of times lower than room temperature, in gases with densities hundreds of thousands of times lower than the air density around us. Two decades have passed since we received the Bose-Einstein condensate in the laboratory. Today, Bose-Einstein condensate is routinely obtained in hundreds of laboratories around the world and is entering the application phase: we already use it to measure very precisely the gravitation and magnetic field strengths.

Four years ago, it seemed that at least the basic properties of gases at low temperatures were known to a satisfactory degree. Nothing could be further from the truth. Physicists working in this field have recently experienced a real scientific shock. Well, the experimental group of Tilman Pfau performing quite a standard experiment, in which the attraction between atoms caused the condensate to shrink first and then explode, gave a completely unexpected result. Instead of a spectacular explosion, a group of stable droplets was obtained. Soon it turned out that the experiment created another, completely unexpected state of matter. Stability and properties of this new state result from quite subtle effects, described in quantum mechanics of many bodies. At the same time the analogous state of matter, now called quantum drops, was created in cooled clouds consisting of two different elements. In turn, this year, three experimental groups, in Stuttgart, Insbruck and Florence, created a fluid almost without viscosity, but also having properties of a solid with regularly spaced atoms, like in a crystal. This state, appearing at the border of parameters separating the phase of the Bose-Einstein condensate and quantum droplets, is a candidate for the so-called "supersolid", which has been sought for decades.

Bearing in mind this unexpected twist of action, it must be admitted that ultracold matter still hides a lot of puzzles. The lesson from this story is the need for more detailed research, preferably based on fundamental descriptions with as few approximations as possible. On the one hand, it requires difficult numerical calculations for quantum multi-body systems, on the other hand, it requires construction and solution of carefully selected mathematical models, taking into account the effects that have been omitted so far.

During this long-term project I intend to set up a group which will carry out such research, in order to find and study new phases of matter at low temperatures. The search will be carried out in a wide class of systems in which there are two types of interactions - short range and non-local interactions. I will focus on areas close to instability when these two types of interactions almost cancel each other out and quantum corrections enter the game. The study will include specific physical systems that have been implemented in laboratories for years: dipole gases, in which new phases of matter have already been observed, as well as gases trapped in resonant cavities, in which such phases have not yet been searched for. One of the hypotheses is the existence of new phases, in this second physical system, studied for decades, but in a different context. The result of the research will be the preparation of phase diagrams, characterization of types of phase transitions and analysis of excitations and stability of these new phases.