The aim of the proposed PhD project is to describe the systems of confined electrons or holes in a potential cavity defined by external electric fields in black phosphorous (BP).

Few-layer BP is a relatively novel material that is composed of layers held together by the van der Waals interaction similarly as graphite is formed by graphene layers. The separation of separate layers of BP down to the monolayer (so called phosporene) is now possible. The atomically thin systems are characterized by wide energy gap and high carrier mobility and for these reasons the BP has been under and extensive theoretical and experimental scrutiny by physicists, chemists and engineers since 2014.

The BP devices which are now produced and studied cover field-effect transistors for electronics and nanocrystals for optics and optoelectronics. The nanoscrystals support confinement of both electrons and holes by the mere finite size of the object. The object that confined the carriers in all the three directions is called ‘a quantum dot’.
For optical studies usually a large ensembles of nanocrystal quantum dots are used. Since each of the dot has a slightly different size the measurements of the optical lines are statistically broadened which excludes a precise determination of the spectra that contains the information on the kinetic energy of the confined carriers their interactions etc.

The PhD project will deal with a single electrostatic quantum dot that is defined by gating. These structures were studied previously in bulk semiconductors, carbon nanotubes or bilayer graphene with so called transport spectroscopy which observes switching on and off the current as a confined energy level falls into the transport window defined by electrochemical potentials of the source and drain. These experiments provide very precise measurements and can be used as a ultimate verification of the theories on the confined system.

The task of the PhD student will be to establish the properties of the system and indicate the spectral features the resulting charging spectra. The proposed topic contains new physics for quantum dot systems to be explored by the PhD student. A monolayer phosphorene is a strongly puckered lattice, with P atoms on two parallel planes. The crystal structure of monolayer and few-layer material is strongly anisotropic which is translated to the in-plane anisotropy of the electron stucture. The conduction and valence bands are strongly anisotropic near the gamma point with the effective masses along the zigzag direction are much larger than in the armchair direction. The anisotropy of the conductance and valence bands leads in particular to a nonregular structure of the Landau levels in the quantum Hall conditions. The heavy carrier masses – for the zigzag direction – should enhance the carrier-carrier interaction and produce strongly correlated phases. The orientation of QD in space – which can be tuned by gate voltages – will determine the relative strength of the interaction. The transport spectroscopy is precise enough to resolve the energy effects of the spin-orbit interactions. Moreover, due to the puckered lattice the vertical electric field can change or close the energy gap which produces further prospects for manipulation of the confined states by electric fields.

As far as the novelty of this PhD project proposal is concerned – so far there are neither experimental nor theoretical literature on electrostatical QDs in BP. We expect the experiment to appear soon since the technology for growth of these systems is available – since the advanced FETs prepared on BP are produced, extensive studies are carried in on material, and since the transport measurements on electron and hole systems will be crucial for determination of the interaction effects within the QD, spin-orbit coupling, confined Landau levels, etc.