Extreme QCD Matter and Heavy-Ion Phenomenology

The theory describing the strong interactions in the Standard Model is Quantum Chromodynamics (QCD). One of its fundamental predictions is quark confinement and the spontaneous breaking of chiral symmetry. This theory predicts that for a certain critical value of the energy density, strongly interacting matter undergoes a transition from the hadronic phase to a new state of matter, the so-called quark-gluon plasma (QGP). In the hadronic phase, quarks appear in bound states, and the chiral symmetry is spontaneously broken, which implies, among other things, differences in the masses of hadronic chiral partners. In the QGP phase, chiral symmetry is dynamically restored and the quarks are deconfined. The deconfinement of color and the recovery of chiral symmetry leads to the phase diagram of QCD matter presented schematically in the figure. So far, there are different scenarios for a phase diagram that takes into account a phase transition or assumes that the phase change is a continuous crossover. The properties of QCD matter at high temperatures T and low values of the baryon chemical potential have already been well described by the solutions of the QCD within the framework of lattice field theory (LQCD). The region of low temperatures and high densities is a real challenge for physicists because it is not available for LQCD and requires a theoretical approach. Dense QCD matter is produced under experimental conditions during ultra-relativistic heavy ion collisions (HIC) and is also present in the interior of compact stars. Data analysis of HIC experiments at CERN, BNL in the USA, and GSI in RFN, as well as data from astrophysical observations of neutron stars and their mergers, provide information on the structure of QCD matter.

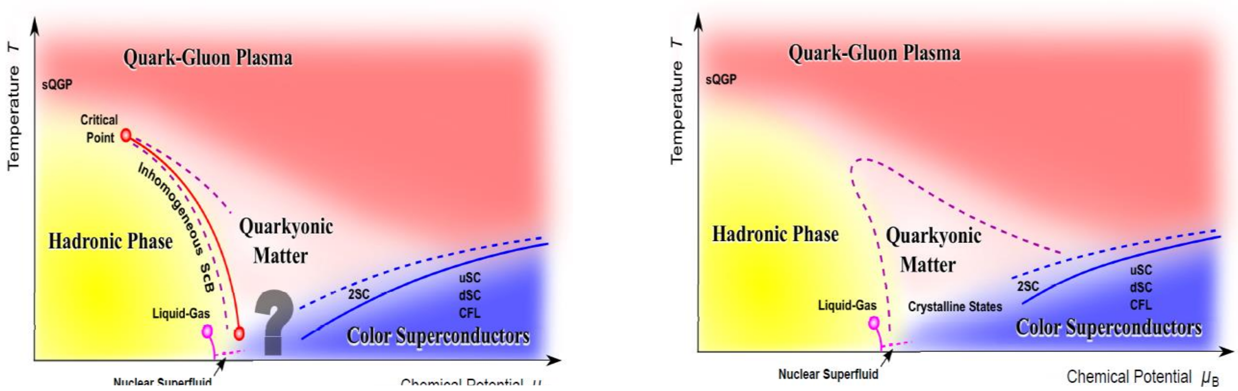

Figure: *Two possible scenarios for a QCD phase diagram in the temperature and chemical potential plane: (Left) The phase transition is the 1st order ending with critical points. (Right) Continuous phase change. From: F. Fukushima, C. Sasaki Prog. Part. Nucl. Phys. 72, 99 (2013).*

The main goal of this project is to deepen our fundamental understanding of the structure of dense QCD matter within the theoretical description and based on HIC experimental data and astrophysical observations. It is especially important to find and verify the signatures of QCD chiral symmetry restoration and color deconfinement. In this context, we will present, inter alia, calculations of the equation of state, hadronic, and electromagnetic spectral functions accounting for collective in-medium effects, as well as fluctuations and correlations of conserved charges. We will calculate yields and spectra of the produced hadrons, photons, and di-leptons in HIC. The results of theoretical research will be verified by comparison with data and astrophysical observations. The realization of this project will be a significant step towards the understanding of empirical data in the search for non-perturbative critical effects at the QCD phase transition.