Letter of Intent

Acronym and title: EOS@FAIR, Constraining Neutron Star Matter with Heavy Ion Collisions

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1. Research objectives

The objective of EOS@FAIR is to advance our understanding of QCD matter and the nuclear equation-of-state in the high baryon density regime as it can be explored in Heavy Ion Collision at moderate collision energies (explored at GSI/FAIR and RHIC-BESII) and in Neutron Stars and their mergers. Various phenomena are expected in this region of the phase diagram, including the restoration of chiral symmetry and quark deconfinement. These transitions may occur as a cross-over or a first order phase transition with a critical endpoint associated with it. The planned studies are therefore relevant for the understanding of QCD matter at high baryon densities, and consequently related to the emission of gravitational waves in supernovae and neutron star mergers.

Advancements in the overall description of the QCD phase diagram are planned using lattice QCD methods, as well as FRG and Dyson Schwinger approaches. These will be complemented by effective field theory models (e.g. chiral EFTs) that allow to connect the calculated thermodynamic properties to transport simulations of heavy ion reactions. Then relativistic transport and hydrodynamic simulations connect the properties of dense QCD matter to experimentally accessible observables (particle spectra, dileptons, fluctuations, clusters, polarization).

The project builds on substantial progress achieved by the Chart_QGP networking activity within STRONG-2020, which established close scientific collaborations between the theoretical and experimental communities across Europe and partner countries. Progress has been achieved, but still many of the properties and of the (thermo-)dynamics of QCD matter at high baryon densities remain only partially understood or not yet accessible. EOS@FAIR aims to accelerate the progress in the field.

This will be achieved by coordinating activities, with special focus on theoretical ab-initio approaches, phenomenological model building and theoretical interpretations, relevant for the Transnational Access infrastructure GSI/FAIR, by sharing models, analysis tools and data repositories, and harmonizing theoretical interpretation frameworks. A major goal is the training of the next generation of scientists in joint workshops for the community and especially for the ECRs of the networks. This will ensure the long-term sustainability and innovation capacity of the European community in the field.

2. Connection to Transnational Access infrastructures (TAs)

The project is centered around the GSI/FAIR facility, with special emphasis on the HADES and CBM physics program at GSI and FAIR. It will intertwine ab-initio methods with state-of-the-art simulation tools to pin down the properties of dense baryonic matter. The activities are structured around three scientific focus areas, each linked to a specific science question addressed by HADES/CBM at GSI/FAIR:

<u>1.) Structure of the QCD phase diagram, EoS and the CEP</u>: The work program aims to advance the understanding of the QCD phase diagram by integrating lattice QCD, functional methods, and effective chiral models. Lattice QCD results at low baryon chemical potential will be used to extract Taylor coefficients and susceptibilities, providing key constraints for effective models and functional approaches. Functional Renormalization Group and Dyson-Schwinger methods will explore the QCD phase structure at higher densities, yielding predictions for order parameters, phase boundaries, and critical behavior. These results will be used for the development of chiral mean-field models that incorporate both hadronic and quark degrees of freedom in a thermodynamically consistent framework. The final goal is to produce unified equations of state, with and without critical phenomena, for use in heavy-ion collision simulations, and to identify observables sensitive to the critical point for guiding CBM data analysis especially in the direction of fluctuation studies.

2.) Development and unification of transport and hydrodynamic simulations: To connect the theoretical developments to experimental observables at CBM, the results from lattice QCD, functional methods, and effective chiral models will be systematically implemented into state-of-the-art transport and (hybrid-)hydrodynamic models such as UrQMD, SMASH, and PHSD/PHQMD. These models serve as essential tools for simulating the dynamical evolution of heavy-ion collisions and translating theoretical input into experimentally measurable quantities. The unified equations of state, including versions with and without a critical point, will be incorporated into hydrodynamic and hybrid frameworks to study their impact on flow observables, particle yields, and fluctuation signatures. Critical-point sensitive inputs, such as susceptibilities and cumulants, will be used to model event-by-event fluctuations and non-equilibrium effects near the phase transition. In transport approaches like PHSD, modifications of the partonic and hadronic interactions informed by the QCD EoS will allow for a more realistic modeling of the system evolution under FAIR conditions. This integration ensures a consistent link between theory and experiment, enabling the identification of robust signals of the QCD phase structure and guiding the interpretation of CBM data, especially on flow observables and dileptons.

3.) Predictions for measurements: Finally, such frameworks provide a connection between the QCD equation of state (EoS) and critical phenomena to a broad range of observables relevant to the CBM experiment and beyond. Particle spectra and dilepton yields are directly sensitive to the temperature, collective flow, and medium properties governed by the EoS; thus, incorporating state-of-the-art theoretical inputs allows for a more accurate reproduction and interpretation of these observables. Event-by-event fluctuations of conserved charges, key signatures of the critical point, can be modeled more realistically using inputs such as susceptibilities from lattice QCD and functional methods. While cluster formation, particularly light nuclei and hypernuclei, is sensitive to the density and isospin dependence of the EoS, and can be studied within these transport frameworks with appropriately implemented freeze-out and coalescence dynamics. Hyperon polarization, which is driven by the gradients of the hydrodynamic fields, provides unique insight into the evolution of the QCD medium and on quantities influenced by the EoS and the presence of phase transitions. Moreover, connections to neutron star physics emerge naturally through the high-density EoS. The same effective models, constrained by lattice and functional QCD inputs and applied in heavy-ion simulations, can be extrapolated to describe neutron star matter, where they impact predictions for maximum mass, radius, and tidal deformability, quantities directly measurable via gravitational wave observations. This multi-disciplinary consistency strengthens the broader relevance of the work, linking FAIR-CBM physics with astrophysical observations and enhancing the synergy between nuclear theory, heavy-ion phenomenology, and astrophysics. Finally, the new high precision data and improved models, based on QCD interactions can be used for quantitative inference with state-of-the-art machine learning methods.

3. Estimated budget request

- Organization of an annual workshop and support for travel - 30.000 € p.a.
- Training activities for ECRs - 25.000 € p.a.
- Outreach and science communication activities - 5.000 € p.a.
- Indirect costs - 15.000 € p.a.

Thus, the total budget estimate is 75.000 € p.a. or 300.000 € for the full period of 4 years.

4. Participating and partner institutions

Florence University, Italy, Wroclaw University, Poland, Goethe-University, Germany, GSI, Germany, Justus-Liebig University, Germany, University Claude Bernard, France, CTU, Czech Republic, INFN Florence, Italy, ICE, Barcelona, Spain, U Banska Bystrica, Slovakia, Wigner Research Center, Hungary, SUBATECH, France