In the grand cosmic theatre, the catastrophic ending of a star more massive than about 9 times the mass of our sun, known as gravitational stellar core-collapse supernova, is the most powerful energy outburst in the present universe. Such explosions take centre stage as mesmerising events that potentially reveal the intricate interplay between the yet to be discovered state of matter at extreme conditions and nuclear and particle physics. Here, a journey is embarked to explore the captivating connection between core-collapse supernovae and the fundamental physics that shapes the universe.

At the heart of core-collapse supernovae lies the high-density equation of state. It is a fundamental concept in physics that describes the relationship between pressure, density, and energy within the dense core of a collapsing massive star. Understanding this equation of state is crucial for unravelling the behaviour of matter under extreme conditions, such as those encountered during a supernova. To comprehend the intricacies of core-collapse supernovae, we must delve into the realms of nuclear and particle physics. The intense temperatures and pressures within the collapsing stellar core trigger nuclear reactions that drive the supernova dynamics.

One of the most intriguing aspects of core-collapse supernovae is the release of gravitational energy in form of gravitational waves and neutrinos. The former are a prediction of Einstein's theory of gravity, general relativity, which have been found to be correct thanks to the first gravitational wave observations of coalescing binary black holes and neutron stars, for which the Nobel Prize in physics was awarded in 2017. The latter are fundamental particles that travel nearly at the speed of light and have been observed from the last galactic event, SN1987A, which was awarded the Nobel Prize in physics in 2002. Both messengers, gravitational waves and neutrinos, originate from the deep interior of a supernova and hence provide information about the central supernova happenings, including the equation of state, that is otherwise hidden to us, since the supernova becomes optically visible only when the explosion reaches the stellar surface. This turns theoretical studies of massive star explosions into invaluable laboratories for probing the high-density equation of state and the laws governing nuclear and particle physics.

The goal of this project is the development of cutting-edge supernova models, which concerns large scale computer simulations and beyond state-of-the-art input physics. This is an ever-evolving field with ongoing research pushing the boundaries of our knowledge within both, computational general relativistic neutrino radiation fluid dynamics as well as the state of matter and fundamental interaction processes that give rise to the emission of neutrinos as part of the multi-messenger signal. The resulting improved computational models and simulations, incorporating the complexities of the high-density equation of state and nuclear and particle physics, will help to refine our understanding of these explosive events. Complementary are experimental efforts in nuclear and particle physics, including collider experiments as well as gravitational wave and neutrino detectors, contribute to the development of theoretical frameworks and validate our understanding of the fundamental physics at play.

Core-collapse supernovae offer a captivating platform to explore the interplay between the high-density equation of state and nuclear and particle physics. The quest to understand the behaviour of matter under extreme densities and temperatures drives scientific inquiry, leading to ground-breaking discoveries. As we continue to unlock the secrets of core-collapse supernovae, we inch closer to comprehending the fundamental physics that govern the cosmos and our place within it.