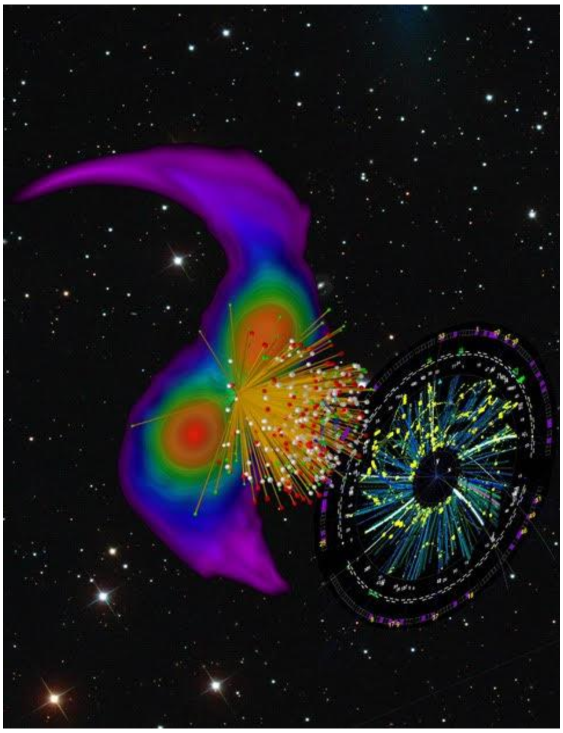
New insights into neutron star matter

Combining heavy-ion experiments, astrophysical observations, and nuclear theory

An international research team has for the first time combined data from heavy-ion experiments, gravitational wave measurements and other astronomical observations using advanced theoretical modelling to more precisely constrain the properties of nuclear matter as it can be found in the interior of neutron stars. The results were published in the journal "Nature".

Throughout the Universe, neutron stars are born in supernova explosions that mark the end of the life of massive stars. Sometimes neutron stars are bound in binary systems and will eventually collide with each other. These high-energy, astrophysical phenomena feature such extreme conditions that they produce most of the heavy elements, such as silver and gold. Consequently, neutron stars and their collisions are unique laboratories to study the properties of matter at densities far beyond the densities inside atomic nuclei. Heavy-ion collision experiments conducted with particle accelerators are a complementary way to produce and probe matter at high densities and under extreme conditions.

"Combining knowledge from nuclear theory, nuclear experiment, and astrophysical observations is essential to shedding light on the properties of neutron-rich matter over the entire density range probed in neutron stars," said Sabrina Huth from Institute of Nuclear Physics at Technical University Darmstadt, who is one of the lead authors of the publication. Peter T. H. Pang, another lead author from the Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, added: "We find that constraints from collisions of gold ions with particle accelerators show a remarkable consistency with astrophysical observations even though they are obtained with completely different methods."



Artist's rendering showing the simulation of two merging neutron stars (left) and the emerging particle tracks that can be seen in a heavy-ion collision (right) that creates matter under similar conditions in the laboratory. Credits: Tim Dietrich, Arnaud Le Fevre, Kees Huyser; background: ESA/Hubble, Sloan Digital Sky Survey

Recent progress in multi-messenger astronomy allowed the international research team, involving researchers from Germany, the Netherlands, the US, and Sweden to gain new insights to the fundamental interactions at play in nuclear matter. In an interdisciplinary effort, the researchers included information obtained in heavy-ion collisions into a framework combining astronomical observations of electromagnetic signals, measurements of gravitational waves, and high-performance astrophysics computations with theoretical nuclear physics calculations. Their systematic study combines all these individual disciplines for the first time, pointing to a higher pressure at intermediate densities in neutron stars.

The authors incorporated the information from gold-ion collision experiments performed at GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt as well as at Brookhaven National Laboratory and Lawrence Berkeley National Laboratory in the USA in their multi-step procedure that analyses constraints from nuclear theory and astrophysical observations, including neutron star mass measurements through radio observations, information from the Neutron Star Interior Composition Explorer (NICER) mission on the International Space Station (ISS), and multi-messenger observations of binary neutron star mergers.

Including data of heavy-ion collision in the analyses has enabled additional constraints in the density region where nuclear theory and astrophysical observations are less sensitive. This has helped to provide a more complete understanding of dense matter. “In the future, improved constraints from heavy-ion collisions can play a key role to bridge nuclear theory and astrophysical observations by providing complementary information,” said Prof. Dr. Chris Van Den Broeck, co-author from GRASP, Utrecht University and Nikhef.

“It is exciting to see that these studies bring together all these different scientific communities. Further down the line, it will become possible to understand and model not only the equation of state but also the transport properties of matter under the most extreme conditions. In particular, measurements from the upgraded ALICE experiment and observations with next-generation gravitational wave detectors such as Einstein Telescope are likely to play a significant role and contribute new insights,” said Prof. Dr. Raimond Snellings, Scientific Director of GRASP.

Further information
[Scientific Publication]