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Nuclear Pasta and Neutron Star Dynamics

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Neutron stars (NSs) comprise the most extreme matter in the universe, existing on the precipice between ordinary matter and black holes. Their immense density, gravity and magnetic fields offer a unique insight into the nature of matter under extreme conditions that cannot be replicated on Earth.
My PhD and presentation focus on the crust-core transition region of NSs, where neutron-rich nuclei exist in a sea of superfluid neutrons. In this dense region, attractive nuclear forces and Coulomb repulsion compete, preventing the system from minimising its total energy. Matter becomes frustrated, and a complex arrangement emerges featuring many local minima. This results in the formation of mesoscopic structures known as 'nuclear pasta', taking various forms ranging from spaghetti-like strands to lasagne-like sheets, depending on the most energy-efficient configuration at a given density. The material and transport properties of these pasta structures remain poorly understood, yet they play a crucial role in crust-core interactions. These interactions influence several NS observables, such as gravitational wave (GW) i-modes and resonant shattering flares from tidal resonances, expected to be detected by next-generation GW detectors and telescopes. Understanding nuclear pasta is thus key to advancing our knowledge
of NSs and dense matter physics.
My research employs a computational technique known as the the Lattice-Bolztmann Method (LBM) to model nuclear pasta. Derived from the Boltzmann equation, the LBM captures the mesoscopic behaviour of fluids, bridging microscopic particle interactions and macroscopic fluid dynamics. While the LBM has been widely used in complex terrestrial fluid simulations, its astrophysical application remains unexplored. Although there are many conceptual similarities between terrestrial applications of the LBM and nuclear pasta, the challenge lies in adapting the method to incorporate the extreme conditions inside NSs. Successful implementation of the LBM to model nuclear pasta will enable predictions of NS observables, improving our interpretation of future GW detections.

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