Snowmass2021 - Letter of Interest

Discovering quark-matter cores in massive neutron stars

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) TF02, TF06, EF07

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Abstract:
The prospect of discovering quark matter cores inside massive neutron stars constitutes one of the grand challenges of nuclear astrophysics. Research revolving around this question combines in a unique way two very different subfields of physics: to achieve optimal progress, one needs to take advantage of recent results from both particle and nuclear theory and from astrophysical measurements of neutron star properties. In this Letter of Interest, we highlight the fact that the eventual discovery of quark cores in neutron stars may result from gradual progress utilizing such advances in a model-independent way, rather than from one dramatic smoking-gun detection. This observation highlights the importance of pushing research efforts on multiple fronts, including neutron-star mass and radius measurements, gravitational-wave detections, as well as theoretical Equation of State determinations in both the nuclear and quark matter phases.

Background: The underlying quantum field theory of the strong nuclear force, Quantum Chromodynamics (QCD), is known to present formidable challenges in the limit of high baryon densities. On the theory side, lattice Monte-Carlo simulations are hampered by the Sign Problem, and observational information is similarly scarce due to ultrarelativistic heavy-ion experiments being limited to probing the hot and relatively dilute Quark-Gluon Plasma (QGP) phase, where quarks and gluons surpass hadrons as the effective degrees of freedom of the system. The possible existence of the high-density analogue of this exotic phase of matter – cold Quark Matter (QM) – inside massive neutron stars (NSs) has been theorized a long time ago, but due to a combination of theoretical and observational challenges, this assertion has not been verified yet, but remains one of the grand challenges of nuclear astrophysics.

Recent years have witnessed unprecedented progress in the astrophysical observations of NSs, ranging from the famous observation of a gravitational-wave signal from a binary NS merger and its electromagnetic counterparts [1,2] to more traditional X-ray and pulsar timing observations [3], providing insight into the macroscopic properties of NSs, such as their masses and radii [4] This progress has opened a new window to ultra-dense matter and may even allow for a convincing detection of exotic phases of matter in NSs in the near future. However, in order to fully exploit the recent and upcoming observational data, a commensurate theoretical advances are also required.

Rationale and discovery potential: In the absence of a smoking-gun observation that could only be explained by the presence of quark cores in NSs, a recent approach to the problem has been to combine all available ab-initio theoretical results from nuclear and particle theory to robust observational information on NSs in an effort to model-independently constrain the properties of matter in the centers of NSs of various masses [5]. A recent Nature Physics article from 2020 [6], co-authored by several signatories of this Letter of Interest (LoI), showed that together with state-of-the-art observational data for the masses and tidal deformabilities of NSs, current results for the Equation of State (EoS) of nuclear and quark matter [7,8] suffice to provide very stringent limits to how QCD matter needs to behave in order for quark cores to be absent even inside maximally massive NSs. This article also identified several physical quantities, the constraining of which would play a major role in a future tightening of the current results, including:

- EoS of nuclear matter at 1-2 nuclear saturation densities and of quark matter at 20-40 saturation densities,
- Speed of sound of dense nuclear matter beyond saturation density
- Order of the deconfinement transition at small temperatures and high densities, and the magnitude of the related latent heat,
- Radii and tidal deformabilities of NSs with accurately known masses,
- Resolved ringdown-phase observations of gravitational wave detections from NS merger events, and
- Electromagnetic observations of the NS merger remnants and the subsequent kilonova explosions.

While the current state-of-the-art ab-initio results for the EoS are clearly challenging to improve upon, there are several avenues, where even dramatic progress is possible. One of these, pioneered by some of the authors of this letter, is related to the use of high-loop-order perturbative QCD calculations, where recent efforts are bringing the state of the art to the Next-to-Next-to-Next-to-Leading order [8]. Similarly, while current radius measurements of compact stars still contain sizable uncertainties, the NICER mission is expected to provide improved radius estimates for stars with accurate known masses in the near future [9,10], which alone could have a dramatic effect on analyses of the type presented in [6] (note that this analysis contained no input from radius measurements).

Objectives and conclusions: In light of recent advances in the field of nuclear astrophysics, it is plausible that the eventual discovery of QM cores in massive NSs will not occur via a single dramatic observation, but rather through multiple theoretical and observational advances that work together in gradually eliminating the possibility of all NSs being composed of nuclear matter. Given the general importance of this question, improving the status of the aforementioned related results is a top priority in the field, and will hopefully receive considerable attention from all relevant research communities.

References

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