# Snowmass2021 - Letter of Interest

# *Determining the Equation of State of Cold, Dense Matter with Electromagnetic Observations of Neutron Stars*

**Thematic Areas:**
☐ (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) *[Please specify frontier/topical group]*

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**Abstract:**
The unknown state of matter at ultra-high density, large proton/neutron number asymmetry, and low temperature is a major long-standing problem in modern physics. Neutron stars provide the only known setting in the Universe where matter in this regime can stably exist. Valuable information about the interior structure of neutron stars can be extracted via sensitive electromagnetic observations of their exteriors. There are several complementary techniques that require different combinations of high time resolution, superb spectral resolution, and high spatial resolution. In the upcoming decade and beyond, measurements of the masses and radii of an ensemble of neutron stars using these techniques, based on data from multiple proposed next-generation X-ray space telescopes, can produce definitive empirical constraints on the allowed dense matter equation of state.

The lack of knowledge about the physical properties at ultra-high density ($\rho_s > 2.8 \times 10^{14}\,\mathrm{g\,cm^{-3}}$), large proton/neutron number asymmetry, and low temperature ($\lesssim 10^{10}$ K) remains one of the principal outstanding problems in modern physics, owing to a number of challenges both in the experimental and theoretical realms [see, e.g., 44, for a review]. A multitude of plausible theoretical predictions for the state of matter in this regime exist, ranging from normal nucleonic matter, to particle exotica such as hyperons, deconfined quarks, color superconducting phases, and Bose-Einstein condensates. Matter in this extreme regime is known to only exist stably in the cores of neutron stars (NSs). This makes NSs tremendously valuable for nuclear and particle physics as they serve as important natural laboratories where we can investigate the constituents of matter and their fundamental interactions under conditions that cannot be reproduced in any terrestrial laboratory, and we can explore the phase diagram of quantum chromodynamics (QCD) in a region that is presently inaccessible to numerical calculations [10]. Determining the dense matter equation of state (EoS) has far-reaching implications for astrophysics as well. The detailed physics and the accompanying electromagnetic, neutrino, and gravitational wave signals of some of the most energetic phenomena in the Universe, such as black-hole/NS and double NS mergers [27, 20, 1, 3, 4] as well as core-collapse supernovae, are highly sensitive to the interior structure of NSs [18].

Since we cannot directly sample the matter in the core of a NS, we must rely on indirect inference using sensitive observations of their exteriors. Because the mass-radius ($M$-$R$) relation of NSs is strongly dependent on the EoS of the dense matter in their interior [see, e.g., 23, 24, 33, 37, 16], measurements of the mass and radius of several NSs to a precision of a few percent using astrophysical observations can provide insight into the state of matter in their interior (Figure 1). This has motivated the development of a host of observational and data modeling techniques for inferring the mass and radius of NSs using electromagnetic observations. A large subset of such methods rely on observations in the X-ray range (≈0.1–30 keV) of the surface thermal radiation from NSs , because the properties of the observed photons are greatly effected by the immense gravity in the vicinity of the star [e.g., 17, 28, 34, 8, and references therein], which in turn, is determined by the stellar $M$ and $R$.

The current *Neutron Star Interior Composition Explorer* (*NICER*; see [11]) NASA X-ray timing mission is starting to produce $R$ and $M$ measurements of a few radio millisecond pulsars (MSPs) that produce thermal radiation by fitting model pulse profiles to the observed X-ray pulsations [14, 29, 39]. Other promising avenues towards constraining the EoS with electromagnetic observations include: i) the detection of one or more NSs with spin rate $\gtrsim$1 kHz, providing limits on the maximum spin rate before break-up [15]; ii) detection of photospheric absorption lines from a NS, enabling a measure of the stellar compactness $M/R$ [9, 34]; iii) modeling of so-called photospheric radius expansion thermonuclear bursts in accreting NSs due to super-Eddington accretion [42, 25], which can yield a measurement of $M$ and $R$ separately [see, e.g., 32]; iv) spectroscopy of quiescent NSs in low-mass X-ray binaries (LMXBs) with well-measured distances radiating uniformly from the entire surface [40, 13, 7, 41]. Thus, observations at X-ray energies offer various means for obtaining strong constraints on the allowed dense matter EoS, providing unique insight into the low temperature-high density region of the QCD phase diagram.

While current space-borne observatories have made important headway, they lack the required capabilities to fully exploit the information about the dense matter EoS encoded in the observed X-ray emission from NSs. Therefore, accomplishing this important undertaking requires a new generation of space telescopes with at least an order-of-magnitude improvement in sensitivity across the soft and hard X-ray bands relative to existing observatories, while also maintaining fast timing capabilities required for effective studies of rapidly spinning NSs. Such missions currently under development or consideration in the next decade and beyond include *STROBE-X* [36], *AXIS* [30], *Athena* [31], and *Lynx* [43]. Table 1 summarizes the various techniques and NS source classes that can be employed to provide constraints on the dense matter EoS using X-ray observations, and the future planned observatories with the capabilities to accomplish the desired measurements. The ability to target multiple NS varieties is crucially important, since it provides verification of the measurement techniques, allowing characterization and mitigation of systematic errors. For instance,

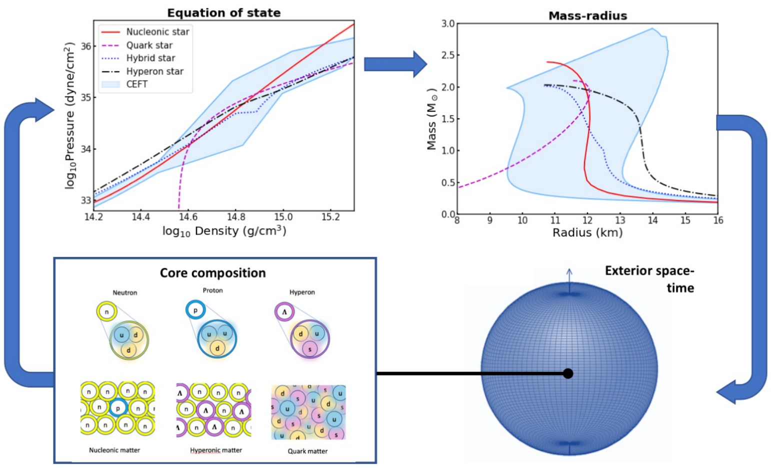


Figure 1: The particle content and their interactions in the high density – low temperature setting at the cores of NSs is highly uncertain. Our lack of knowledge about these microphysical aspects (lower left: uds = up down strange quarks) is encapsulated in the EoS (top left). A sampling of plausible theoretical EoS models is shown that includes a nucleonic star (red) [5], a quark star (magenta) [26], a hybrid star consisting of a nucleonic outer core and quark matter inner core (blue) [45], and a hyperon star with nucleonic outer core and hyperonic matter inner core (black) [6]. The light blue region represents the approximate range spanned by the set of currently viable models [16]. The different EoS govern the global properties of the star such as $M$, $R$ and oblateness for a given rotation rate, via their influence on stellar structure (top right). These determine the exterior space-time properties of the star, which measurably alter the properties of the radiation propagating from the NS surface, encoding in it information about the EoS and the associated microphysics. Figure adapted from [36].

a number of NSs exhibit both accretion-powered pulsations and thermonuclear burst oscillations, permitting pulse profile modelling for the same source using two different types of hot spot. Additionally, for the bursting sources, conducting spectroscopic modeling of the burst cooling tail can offer additional cross-checks of techniques [see, e.g. 32]. By targeting more NSs, it will be possible to sample the EoS across a wider range of core densities. This will map the EoS more fully, probing any potential phase transitions with finer resolution, and will move us out of the regime where EoS model parameter inference may be prior-dominated [see for example 12]. The Advanced LIGO and VIRGO gravitational wave observatories have now made the first direct detection of a binary NS merger [2]. With future runs, they may be able to constrain $R$ to $\sim$10% using a few tens of detections [38, 21]. Collectively, the resulting complementary electromagnetic and gravitational wave measurements hold the promise to provide definitive empirical constraints on the true nature of the densest matter in the Universe [29, 35, 19, 22].

| **Technique** | **NS source class** | **Observatories** |
|---|---|---|
| Pulse profile modeling | rotation-powered MSPs | *STROBE-X*, *Athena* |
| | accretion-powered MSPs | *STROBE-X* |
| | bursting NS LMXBs | *STROBE-X* |
| Extremely rapid rotation | accretion-powered MSPs | *STROBE-X* |
| Radius expansion bursts | bursting NS LMXBs | *STROBE-X* |
| Absorption line spectroscopy | bursting NS LMXBs | *Athena*, *Lynx* |
| Continuum spectroscopy | quiescent NS LMXBs | *AXIS*, *Athena*, *Lynx* |

Table 1: Summary of measurement techniques and NS source classes suitable for dense matter EoS constraints and the proposed X-ray observatories that have the capabilities to carry out these investigations.

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