1 Objectives and Expected Significance

Neutron stars are the unique natural laboratory to study quantum chromodynamics (QCD) at finite density and low temperature. Our understanding of the densest matter in the observable universe has been driven by X-ray observatories such as *RXTE*, *Chandra*, and *XMM*, γ-ray satellites such as *Integral* and *Swift*, proposed instruments such as the *International X-ray Observatory*, and the promise of gravitational wave detectors such as *LIGO*. To quote the 2010 Decadal Survey [1] *New Worlds, New Horizons in Astronomy and Astrophysics*: "Measuring neutron star masses and radii yields direct information about the interior composition [of neutron stars] that can be compared with theoretical predictions." In the past few years, a number of recent observational, theoretical, and experimental developments have led to a new understanding of, and new questions about, the internal constitution of neutron stars. Of especial interest are the following.

1) The short crust cooling timescale of quasi-persistent transients [2, 3, and references therein] suggest that the neutron star crust has a high thermal conductivity [4, 5] and is relatively cold. This is potentially at odds with observations of long X-ray bursts [6, 7, 8].
2) Measurements of the Eddington limiting flux and the flux normalization from bursting neutron stars with well-measured distances have been used to construct a mass-radius relations for neutron stars [9, 10, 11, 12].
3) The recent discovery of a two solar mass neutron star [13], which has strong implications for the presence of exotic matter [14].
4) Ongoing and planned experimental and theoretical efforts in nuclear physics [for a brief overview, see 15, and references therein] such as the lead radius experiment (PREx) at Jefferson Lab, are leading to better constraints on the equation of state (EOS) of neutron-proton symmetric nuclear matter at densities 0.4–4 ρ_0, where $\rho_0 \approx 3\times 10^{14}$ g cm^{-3} is the nuclear saturation density (the density of matter within a nucleus).

These efforts depend on the EOS and transport properties of matter over a range of densities, from sub-nuclear to several times saturation, and from nearly symmetric (roughly equal neutron and proton abundances) to nearly pure neutron matter. Our proposed work advances the frontier of neutron star physics by combining observational constraints on the neutron star mechanical structure (masses and radii) and observational constraints on the neutron star thermal structure (interior temperatures and cooling timescales) to form a new picture of neutron star structure and the EOS of dense matter. Along the way, this work will address what surface phenomena (X-ray bursts, superbursts, and cooling transients) imply about the physics of nuclear matter.

- What is the nature of matter at several times nuclear density? Is there a transition to an exotic phase of matter in the cores of some neutron stars?
- What is the nature of matter at at sub-saturation densities? Does the composition depend on the accretion history of the source?

It is essential that these two questions are tackled in concert. The EOS at super-nuclear densities dictates the mass and radius, and hence the surface gravity and crust thickness, as well as the efficiency of cooling via neutrinos. Both of these affect the temperature in the neutron star crust. The observations of crustal cooling, in addition to constraining matter at sub-saturation densities, also offer a complementary constraint on matter at higher densities.

Combining laboratory experiments and astronomical observations to determine the cold EOS for bulk nuclear matter from sub- to super-nuclear densities is an exciting possibility within a few years. This proposal describes a directed theoretical effort towards this goal.