Neutron-rich matter from chiral effective field theory

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Nuclear thermodynamic equation of state

The equation of state of neutron-rich matter from sub- to supra-nuclear densities directly influences neutron star structure and evolution, the dynamics of core-collapse supernovae, r-process nucleosynthesis, as well as features of gravitational waves produced during the late inspiral and post-merger phases of binary neutron star coalescence. The major challenge is to model the free energy $F(n, T, Y_p)$ of baryonic matter over approximately eight orders of magnitude in density ($n \sim 10^8 - 10^{15}$g/cm^3), temperatures up to $T \sim 5 \times 10^{11}\, K$, and proton fractions $Y_p \leq 0.6$. Under this range of conditions (well below the chiral symmetry breaking scale of $\Lambda_\chi \approx 1$ GeV) effective field theory methods [1-3] are expected to provide a suitable framework for the description of strongly interacting matter. In anticipation of new observational campaigns of neutron stars (e.g., NICER) and additional discoveries from gravitational wave observations of binary neutron star mergers (Advanced LIGO), present efforts in our research group are focused on reducing theoretical uncertainties in the nuclear thermodynamic equation of state and refining phenomenological energy density functionals by imposing microscopic constraints from chiral effective field theory (chiral EFT).

Microscopic many-body calculations based on chiral EFT are now able to provide reliable predictions for the homogeneous matter equation of state through a multi-channel analysis of theoretical uncertainties. In the past year we constructed a class [4] of equations of state for homogeneous matter at finite temperature that simultaneously satisfy constraints from microscopic many-body theory [5-7], nuclear experiments, the model-independent virial expansion, and observed neutron star radii. The different regimes are smoothly joined, resulting in a thermodynamically stable hot and dense matter equation of state. In the upcoming year we will work toward full supernova equation of state tables that include the inhomogeneous mixed phase at low temperatures and densities.

Neutron star tidal deformabilities constrained by chiral effective field theory

Gravitational wave and electromagnetic signals from binary neutron star mergers offer a unique probe for studying the properties of ultra-dense matter. The recent observation of gravitational wave event GW170817 [8] and the associated electromagnetic counterpart [9] suggest the source to be a merger of two neutron stars with combined mass $M_{\text{total}} = 2.74^{+0.04}_{-0.01}\, M_\odot$ that left behind a relatively long-lived hypermassive neutron star remnant.

Measurement of the late inspiral gravitational waveform from GW170817 was sufficient to place a conservative upper bound of $\Lambda < 800$ on the tidal deformability of a $1.4\, M_\odot$ neutron star, competitive with bounds [10] deduced from current neutron star mass and radius measurements. In a recent work [11] we constructed a large class of over 72,000 energy density functionals constrained by the neutron matter equation of state from chiral effective field theory and the known saturation properties of homogeneous nuclear matter in order to place theoretical constraints on the neutron star tidal deformability, shown in Fig. 1. We found that the tidal deformability of a $1.4\, M_\odot$ neutron star lies in the range $350 < \Lambda < 540$,

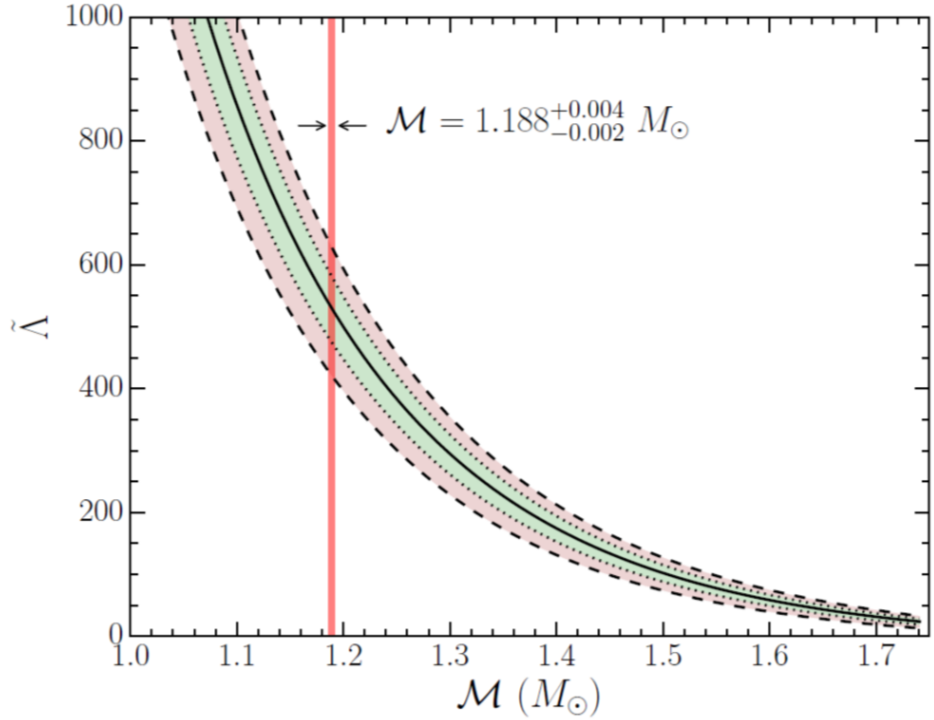

FIG. 1. Neutron star chirp tidal deformability as a function of chirp mass from chiral nuclear forces.

which is consistent with the upper bound from the observed neutron star merger event. We also examined the neutron star mass-radius relation and determined the radius of a 1.4 $M_\odot$ neutron star to lie in the range 11.6 km < R < 12.9 km. As future neutron star merger events are observed, the framework developed in [11] will enable stronger constraints on the equation of state and nuclear force

Tensor Fermi liquid parameters in nuclear matter from chiral EFT

Fermi liquid theory is widely used to describe the transport, response, and dynamical properties of nuclear and neutron matter in terms of interacting quasiparticles. In recent work [12] we have calculated for the first time the full decomposition of the quasiparticle interaction in symmetric nuclear matter into its central, relative tensor, center-of-mass tensor, and cross-vector interaction components. Realistic two- and three-body forces derived within the framework of chiral effective field theory were employed, and we estimated theoretical uncertainties by varying the resolution scale and order in the chiral expansion. The work is expected to provide microscopic guidance for the tensor forces employed in modern mean field effective interactions and nuclear energy density functionals. Work to derive the quasiparticle interaction in asymmetric nuclear matter with applications to neutrino diffusion in proto-neutron stars is underway.

Proton pairing in neutron stars from chiral effective field theory

Neutron superfluidity and proton superconductivity play an important role in the thermal evolution of neutron stars and the large-scale dynamical phenomenon of pulsar glitches. In a recent work [13] we studied the 1S0 proton pairing gap Δ as a function of density in beta-equilibrated neutron star matter within the BCS approximation starting from realistic two- and three-body chiral nuclear forces. We find that three-body forces suppress proton pairing and lead to a transition to the normal state at a density around twice that of saturated nuclear matter. The peak in the proton pairing gap occurs close to the crust-core interface where the density is about one-half that of saturated nuclear matter. We estimate the critical temperature for the onset of proton superconductivity to be $T_c = (3.7 - 6.0) \times 10^9 K$, which is consistent with previous theoretical results in the literature and marginally within the range deduced from a recent Bayesian analysis [14] of neutron star cooling observations.

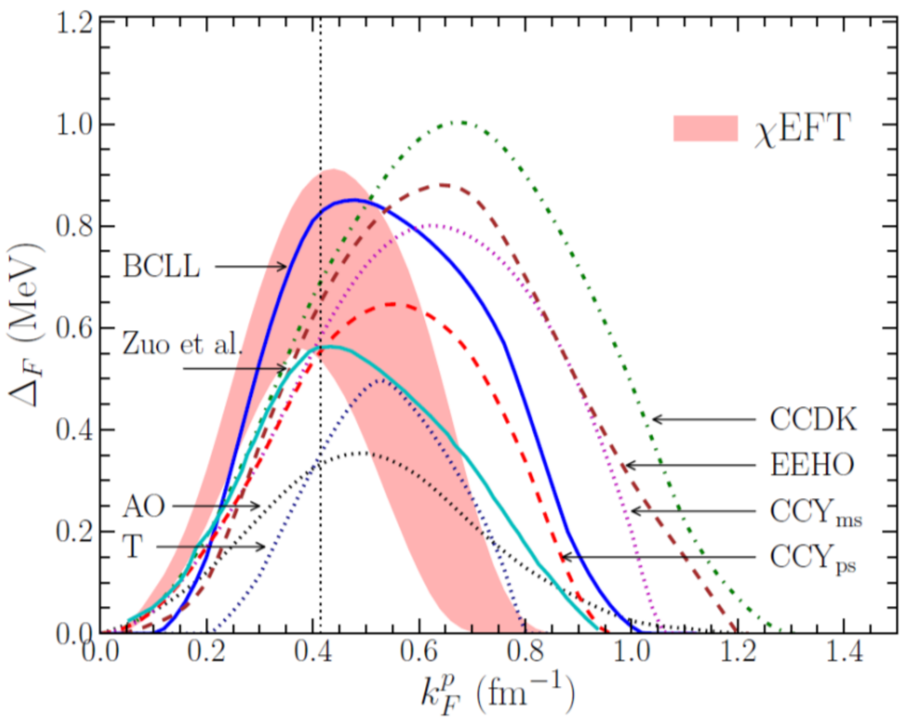

FIG. 2. Proton pairing gap as a function of the proton Fermi momentum in beta-equilibrated neutron star matter.

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