Nuclear astrophysics theory progress

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Nuclear forces up to fifth order in the chiral expansion

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) chiral effective field theory [Wei79, Epe09, Mac11] is expected to provide a suitable framework for the description of strongly interacting matter. In the previous year we have extended [Sam18] the modeling of the nuclear equation of state to include contributions from nucleon-nucleon interactions up to next-to-next-to-next-to-next-to-leading order (N4LO) in the chiral expansion with several values of the momentum-space cutoff $\Lambda = 450, 500, 550$ MeV. The parameters of the leading three-body force were refitted in each case to the triton binding energy and lifetime. The new set of chiral potentials leads to reduced uncertainties in the nuclear equation of state at and below normal nuclear densities $n < 0.16\,\mathrm{fm}^{-3}$, and saturation in symmetric nuclear matter is qualitatively reproduced at the correct binding energy and density.

Correlations among the nuclear symmetry energy, slope parameter, and curvature

The nuclear isospin-asymmetry energy, which characterizes the energy cost of converting protons into neutrons in an interacting many-body system, is an important organizing concept linking the properties of atomic nuclei to the structure and dynamics of neutron stars. In particular the isospin-asymmetry energy governs the proton fraction of dense matter in beta equilibrium, the thickness of neutron star crusts, and the typical radii of neutron stars. Modeling the isospin-asymmetry energy at several times normal nuclear densities is theoretically and experimentally challenging but crucial for linking upcoming neutron star observations to fundamental properties of the nuclear equation of state. Recently [Hol18] we have investigated correlations among the nuclear symmetry energy (J), its slope parameter (L), and curvature (K_{sym}) that parameterize the density dependence of the isospin-asymmetry energy S_2:

$$S_2(n) = J + L\left(\frac{n-n_0}{3n_0}\right) + \frac{1}{2}K_{sym}\left(\frac{n-n_0}{3n_0}\right)^2 + \cdots,$$

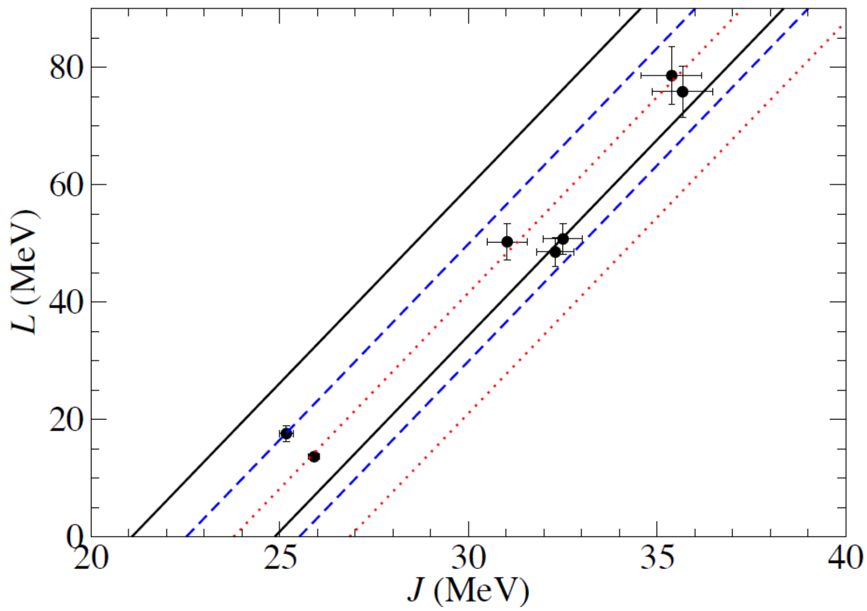

FIG. 1. Correlation [5] between $\boldsymbol{L}$ and $\boldsymbol{J}$ from explicit chiral effective field theory calculations (dots) and from a general Fermi liquid theory analysis (lines).

where n_0 is the saturation density of symmetric nuclear matter. In particular, starting from a Fermi liquid theory description of nuclear matter based on chiral two- and three-body forces, we found a relatively strong linear correlation between L and J, and between K_{sym} and J. In addition, certain features of the correlations, such as their slopes, were found to be insensitive to detailed properties of the nuclear force. In Fig. 1 we show the L vs. J correlation obtained from Fermi liquid theory (lines) as well as from explicit calculations from chiral two- and three-nucleon forces. These correlations were then employed in a new Bayesian framework [Lim18a] for deriving neutron star radius and tidal deformability probability distributions.

Neutron star moments of inertia constrained by nuclear theory and experiment

Neutron star observations are a promising tool to infer the properties of nuclear matter at several times normal nuclear densities. Radio timing observations of the relativistic double pulsar system PSR J0737-3039 are expected to produce in the next several years an estimate of the more rapidly rotating pulsar's moment of inertia. Recently, we have made theoretical predictions [Lim18b] for the mass and radius dependence of neutron star moments of inertia from a Bayesian analysis of the nuclear equation of state constrained by nuclear theory and experiment [Lim18a]. We have found that for pulsar J0737-3039A with mass $M = 1.338 M_{\odot}$, the moment of inertia lies in the range $0.98 \times 10^{45}\,\mathrm{g\,cm}^2 < I_{1.338} < 1.48 \times 10^{45}\,\mathrm{g\,cm}^2$ at the 95% credibility level. In Fig. 2 we show the strong correlation between the moment of inertia of PSR J0737-3039A and its radius R, demonstrating that a precise measurement of $I_{1.338}$ will enable robust predictions for its radius complementary to other astronomical observations, such as tidal deformabilities from gravitational wave detectors and direct radius measurements from the NICER X-ray telescope.

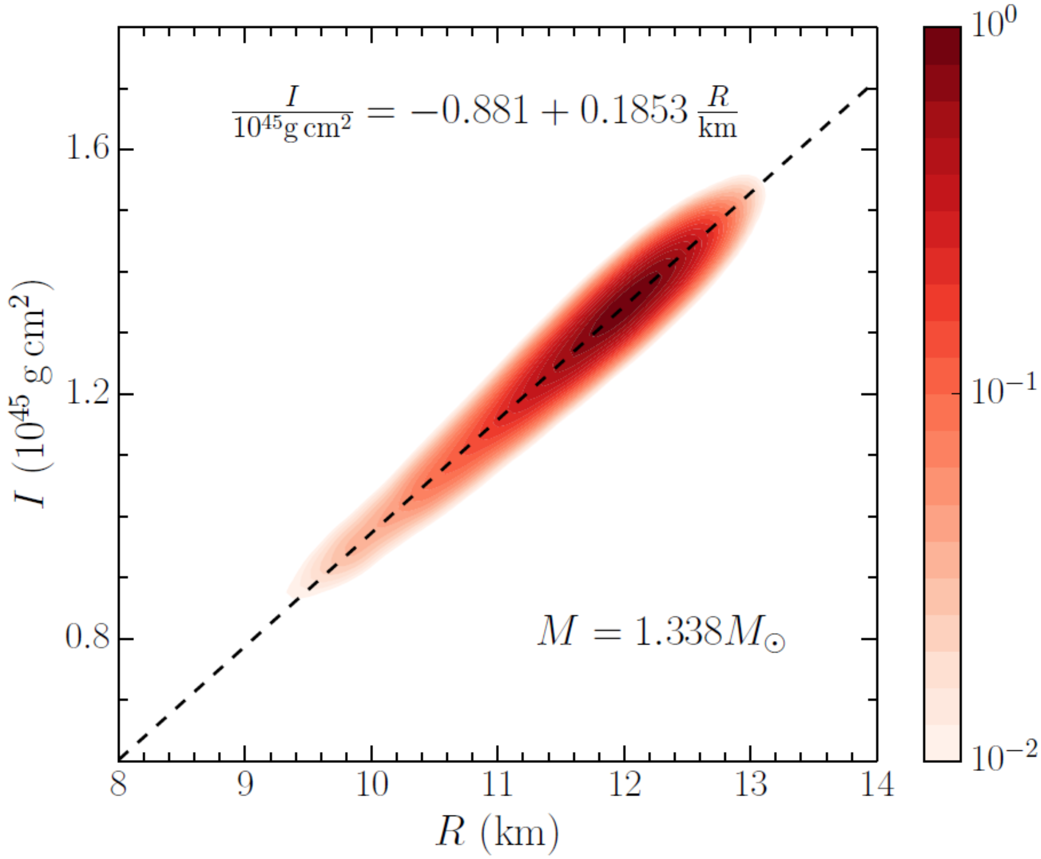

FIG. 2. Correlation between the moment of inertia of a $\boldsymbol{M = 1.338M_\odot}$ neutron star and its radius predicted from a Bayesian analysis of the nuclear equation of state.

We have also studied the fraction of the neutron star moment of inertia residing in the crust, which sets the ratio of the superfluid angular momentum to the total angular momentum in the neutron star. This angular momentum reservoir must be sufficiently large in order to support the observed glitch activity of the Vela pulsar [Cor88]. From our theoretical modeling we find that the crustal fraction of the moment of inertia is in the range 1-6% for typical neutron star masses, which is insufficient to explain glitches in the Vela pulsar under the scenario of strong neutron entrainment [Cha12, And12]. Additional theoretical modeling, such as the inclusion of pairing [Wat17] in the band theory calculations of neutron entrainment, may be needed to resolve the observed discrepancy.

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