Hessisches Kompetenzzentrum
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Bayesian Inferences of the Nuclear Equation of State



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Clusters
Lichtenberg II Cluster Darmstadt

Additional Software
NEoST, ChiralEOS

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Introduction

The dense matter equation of state (EOS), which describes the properties of matter at very high densities, plays a key role in the theoretical description of neutron stars, and provides a link between microscopic nuclear theory and macroscopic properties of neutron stars, such as their masses and radii. Constraining the EOS is therefore of central importance. Unfortunately, computing the EOS from first principles is highly computationally demanding, requiring significant resources in particular for inference problems where repeated calculations with different inputs are necessary. In addition, the calculation of neutron star properties based on EOSs becomes computationally demanding when repeated to the degree required in Bayesian inference frameworks. In this project we have so far addressed two different problems related to the EOS: (i) constraining the EOS based on neutron star observations and new nuclear theory input from first principles using chiral effective field theory (EFT), and (ii) direct determination of three-nucleon couplings from neutron star observations.

Methods

We use many-body perturbation theory to calculate the EOS in a first-principles manner from chiral EFT. In (i), calculations like these constrain the low-density part of the EOS, while we use two different agnostic parametrizations of the EOS in the less known high-density regime relevant to the core of neutron stars. Given an EOS, we solve the so-called Tolman-Oppenheimer-Volkoff (TOV) equations, which yield the neutron star mass and radius, and calculate the neutron star tidal deformability.

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Employing these computational techniques we use Bayesian inference to constrain the EOS with neutron-star observations from NASA's NICER (Neutron Star Interior Composition Explorer) telescope using the open source software NEoST [1], which samples the EOS parameters through so-called nested sampling. In (ii), we vary two parameters, called c_1 and c_3, governing the long-range three-nucleon force in neutron matter and compute the EOS 100 times from in the nuclear density range where chiral EFT is applicable. Based on the output of these high-fidelity results we train accurate emulators that are able to mimic the high-fidelity results at a tiny fraction of the computational cost. We train further emulators, based on neural network techniques, to solve the TOV equations. This allows us to perform Bayesian inference to infer c_1 and c_3 from neutron star radii and masses as well as tidal deformabilities given by gravitational wave observations.

Results

In (i), we find that the available data prefers higher pressures inside neutron stars. We find that the most probable radius for a 1.4-solar-mass neutron star is 12.01 (+0.56, −0.76) km within 95 % probability, and the corresponding radius for a 2-solar-mass neutron star is 11.55 (+0.94, −1.09) km, though these results depend somewhat on the parametrization of the high-density part of the EOS. In (ii), we find no constraints on the parameter c_1. However, with currently available data, we constrain c_3 to−2.52 (+2.21,−3.63) GeV^{-1} with uncertainties given at the 90 % level. Using one year's worth of pseudo-data from the upcoming next-generation gravitational-wave observatories Einstein Telescope and Cosmic Explorer, we find that we can constrain c_3 much better, to a level nearly comparable to the best currently available results from laboratory experiments. Our work represents the first time parameters in chiral EFT have been inferred from observations of macroscopic objects.

Discussion

We have studied the impact of recent neutron star observations from NICER and observations of gravitational waves from binary neutron star mergers on the neutron star EOS. Combined with new chiral EFT inputs, we find that the EOS posteriors become significantly tighter compared to previous works, and that the most likely radius of a 1.4-solar-mass neutron star is about 12 km. We have also developed a framework to infer three-nucleon couplings directly from neutron star observations and find that with projected results from upcoming telescopes we can potentially constrain c_3 to a level comparable with today's best results from laboratory experiments

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Publications

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Reference

[1] NEoST https://github.com/xpsi-group/neost

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