Bayesian analysis of nuclear theory and astrophysics constraints for the dense matter equation of state

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Constraining the Dense Matter Equation of State with New NICER Mass–Radius Measurements and New Chiral Effective Field Theory Inputs

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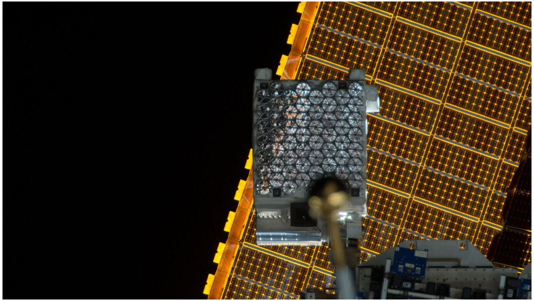
Goal: to infer posterior probability distributions (PDFs) for the mass-radius (M-R) and pressure-density (P-ε) of neutron stars using chiral effective field theory (χEFT) and astrophysical data

With data from . . .

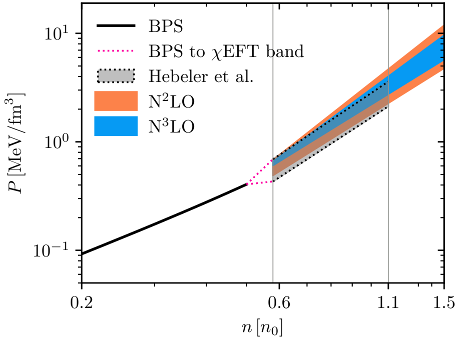
Gravitational wave data from neutron star mergers from LIGO/VIRGO

Mass-radius data of 3 neutron stars from NICER:



NASA's Neutron Star Interior Composition Explorer (NICER) aboard the ISS (image from NASA, obviously)

Nuclear physics constraints at low densities

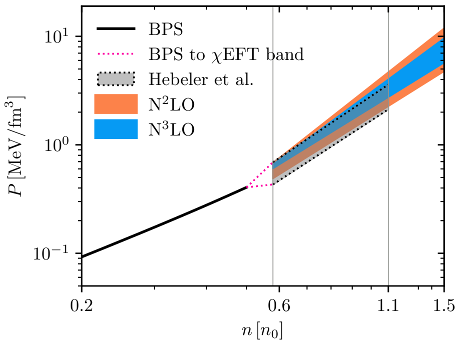


- Up to $0.5n_0$ (saturation density): Baym-Pethick-Sutherland (BPS)[a] crust
- From $\approx 0.6n_0$ to 1.1 or $1.5n_0$: χEFT at N^{2}LO and N^{3}LO[b]
- High-density parametrizations at higher densities

[a] Baym et al., ApJ **170** (1971)

[b] Keller et al., Phys. Rev. Lett., **130** (2023)

Nuclear physics constraints at low densities

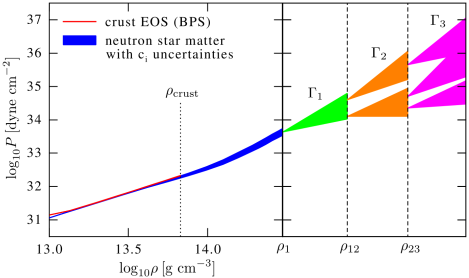


The new χEFT bands:

- New bands calculated directly in β-equilibrium; Hebeler bands use an empirical parametrization
- We trust χEFT to higher density ($1.5 n_0$)
- Include muons in addition to electrons and neutrons/protons

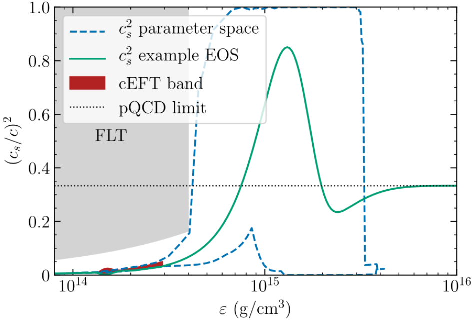
High-density parametrizations, ≈ 5 unknown parameters

Piecewise polytropes (PP): 3 independent polytropes with parameters Γ_{1-3}, ρ_{12}, and ρ_{23}



Hebeler et al., arXiv:1303.4662, ApJ **773** (2013)—also the reference for the "Hebeler et al." χEFT band

Speed of sound (CS): constrained by FLT, causality, $c_s^2 \to 1/3$ from below at high densities



Greif et al., arXiv:1812.08188, MNRAS **485** (2019)

Bayesian posterior for EOS parameters $\boldsymbol{\theta}$ and central energy densities $\boldsymbol{\varepsilon}$

$$
\begin{aligned}
p(\boldsymbol{\theta}, \boldsymbol{\varepsilon} \,|\, \boldsymbol{d}, \mathbb{M}) \propto\ & p(\boldsymbol{\theta} \,|\, \mathbb{M})\ p(\boldsymbol{\varepsilon} \,|\, \boldsymbol{\theta}, \mathbb{M}) \\
& \times \prod_i p(\Lambda_{1,i}, \Lambda_{2,i}, M_{1,i}, M_{2,i} \,|\, \boldsymbol{d}_{\mathrm{GW},i}) \\
& \times \prod_j p(M_j, R_j \,|\, \boldsymbol{d}_{\mathrm{NICER},j})
\end{aligned}
$$

- $\Lambda_{1,i}$ and $\Lambda_{2,i}$ ($M_{1,i}$ and $M_{2,i}$): tidal deformabilities (source-frame component masses) given GW data $\boldsymbol{d}_{\mathrm{GW},i}$[1]
- $\boldsymbol{d}_{\mathrm{NICER},j}$: mass-radius NICER data (folds in highest-mass data from radio)
- $\mathbb{M}$: all modeling assumptions we make

[1] References to all data at the end of the presentation.

Software

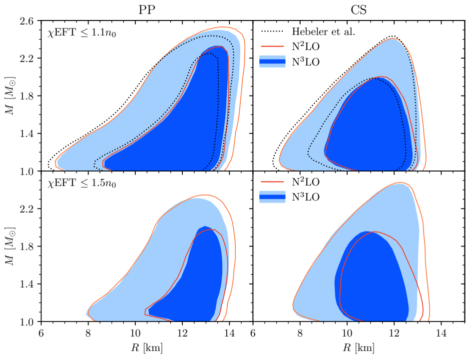
All calculations are performed with NEoST, which is publicly available:
`https://xpsi-group.github.io/neost/`

NEoST uses MultiNest as its sampler: Feroz et al., MNRAS **495** (2009), Buchner et al., A&A **471** (2014)

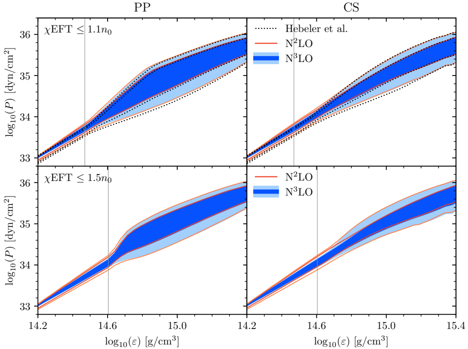
A full reproduction package for all our results is available:
`https://zenodo.org/records/10871354`

Priors

Mass-radius:

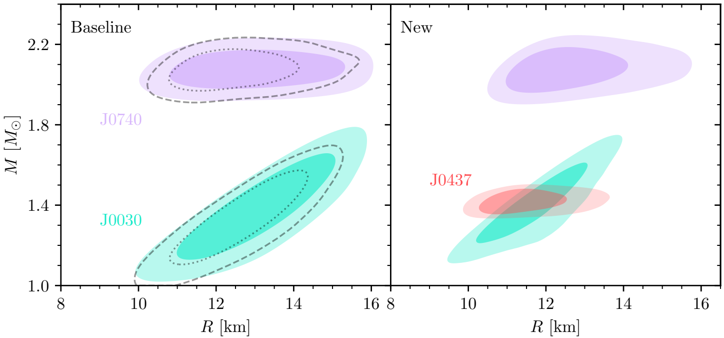


Pressure-energy density:



- PP and CS overall similar, CS is a bit more constraining
- Trusting χEFT to $1.5n_0$ yields less uncertainty
- New χEFT bands slightly more constraining than the Hebeler band
- Priors limits upper radius

Data scenarios

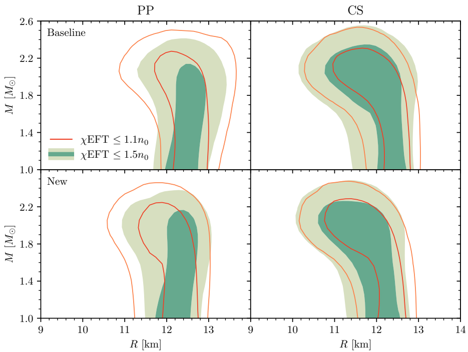


Two scenarios for comparison: "Baseline" with the (slightly updated) older NICER results, and "New" with the recent J0437 millisecond pulsar

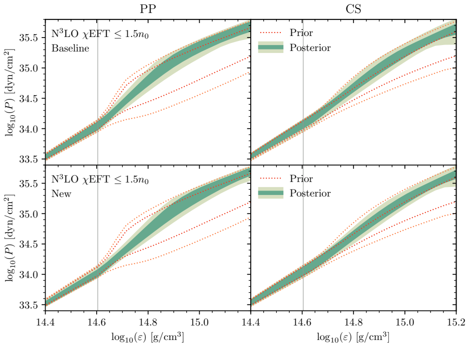
(In the paper we also consider two more scenarios, which I will not cover here)

Posteriors

Mass-radius:

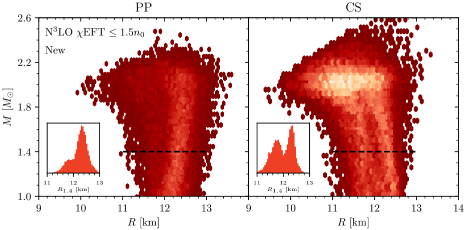


Pressure-energy density:



- The new NICER result favors smaller radii, especially for low-mass stars
- Trusting χEFT to higher densities disfavors high-mass, low-radius stars
- Data prefers high pressures

Bimodal-like structure

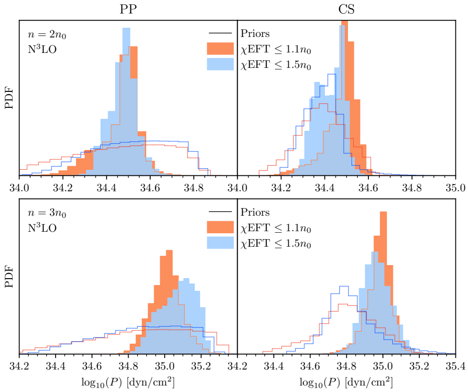


A **bimodal-like** structure appears in several posteriors, both at N^2LO and N^3LO, most clearly seen with the CS parametrization.

For masses below $\approx 1.4 M_\odot$, our results favor radii lower or higher than—but not equal to—12 km

Origin is not completely clear—tension between data points

Bimodal-like structure

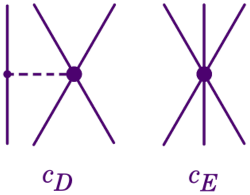


Also visible in the pressure posterior, but less pronounced

The data prefers higher pressures

Extended outlook: replace χEFT band with Bayesian results?

- χEFT: systematic expansion for low momentum
- all predictions **uncertain** due to (i) unknown low-energy constants (LECs), (ii) finite-order truncation (plus some other problems)
- Three-nucleon forces appear at N^2LO with two LECs c_D, c_E:



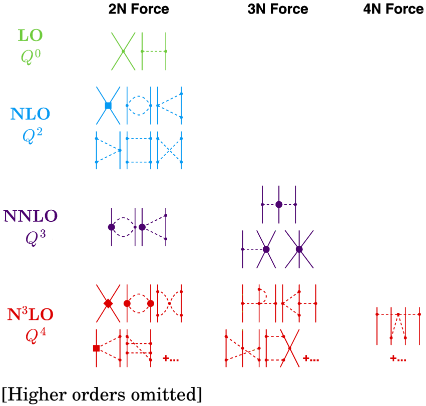
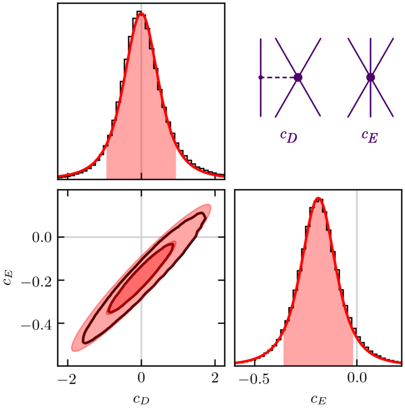


Figure adapted from Entem et al., Phys. Rev. C **96** (2017).

Inferred posterior for c_D and c_E[2]

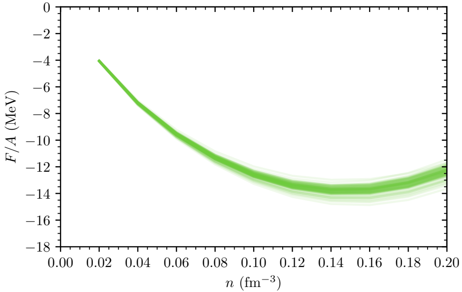


Posterior for the 3NF LECs.

- Infer c_D, c_E from data: mass and radius of ^{4}He, mass and β-decay rate of ^{3}H.
- Account for experimental errors and EFT truncation errors in the inference
- Truncation errors crucial

[2] Wesolowski, IS, et al., Phys. Rev. C **104** (2021)

Posterior predictive distribution (PPD) for **symmetric** nuclear matter



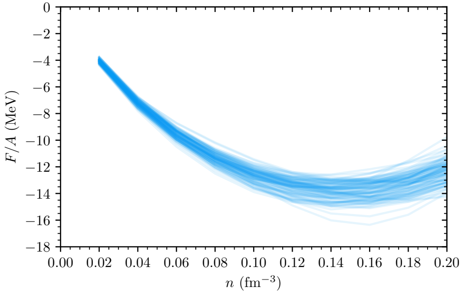
PPD based on the LEC distribution on the previous slide.

Calculation of the free energy per particle as a function of density.[a]

- Up to slightly above saturation density $n_0 = 0.16\ \mathrm{fm}^{-3}$, can be extended
- Relatively unknown 3NF strengths yield fairly uncertain predictions
- Straightforward extension to arbitrary proton fraction (and temperature), or matter in β-equilibrium as required by NEoST

[a]Performed using many-body perturbation theory with code from Jonas Keller+Yannick Dietz, TU Darmstadt.

With EFT truncation errors modeled with Gaussian processes



As before, but with correlated EFT truncation errors added on

PRELIMINARY:
We also model EFT truncation errors (correlated across density) using Gaussian processes[a]

[a] Melendez et al., Phys. Rev. C **100** (2019), Drischler et al., Phys. Rev. C **102** (2020).

Ongoing work with Hannah Göttling, Alex Tichai, Kai Hebeler, Achim Schwenk. We plan to also account for errors in the MBPT calculation.

Replace χEFT band in NEoST with distribution based on this work?

Inferring three-nucleon forces from astro data

In collaboration with (among others) Rahul Somasundaram and Ingo Tews, LANL

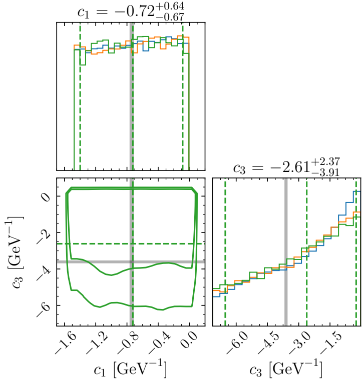
- The LEC c_3 appears in the πN part of χEFT potentials
- Influences both 2- and 3-nucleon forces; we focus on $3N$
- Typically fitted to πN scattering data

c_3 also contributes to the nuclear EOS in neutron matter, and can thus in principle be constrained by **neutron star observations**.

Until now, the computations have been prohibitively expensive, but new developments have overcome this roadblock.

We infer c_3 from **current and next-generation astro data**

Inferring three-nucleon forces from astro data



Constraints on c_1 and c_3 using **currently** available astro data.

- c_1 (another πN LEC) is unconstrained
- Current data is not enough to precisely determine c_3
- But: precise inference of c_3 becomes **feasible with next-generation GW data**

(paper is on its way)

Thank you & data references

PSR J0437, PSR J0030, PSR J0740:

- Choudhury, Salmi, Vinciguerra et al., ApJ Lett. **971** (2024)
- Vinciguerra, Salmi, Watts et al., ApJ **961** (2024)
- Salmi, Choudhury, Kini et al., ApJ (2024, in press)

GW:

- Abbott, B. P., Abbott, R., Abbott, T. D., et al., Phys. Rev. X **9** (2019)
- Abbott, B. P., Abbott, R., Abbott, T. D., et al., ApJ Lett. **892** (2020)

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