Quantifying uncertainties for the neutron star equation of state from chiral effective field theory

PRC 113 (2026) and arXiv:2605.18560

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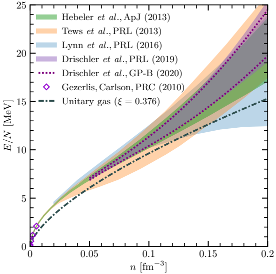
in collaboration with Luis Hoff, Melissa Mendes, Isak Svensson, Kai Hebeler and Achim Schwenk

The nuclear equation of state (EOS)
from nucleons to neutron stars

- connect microscopic calculations of dense matter to astrophysical observations

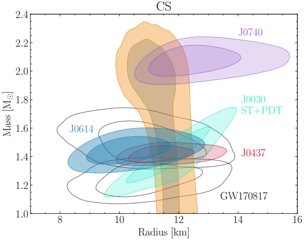


Huth et al., PRC (2021)

The EOS is ...

... pressure as a function of density, temperature, and composition

... key to neutron stars and mergers

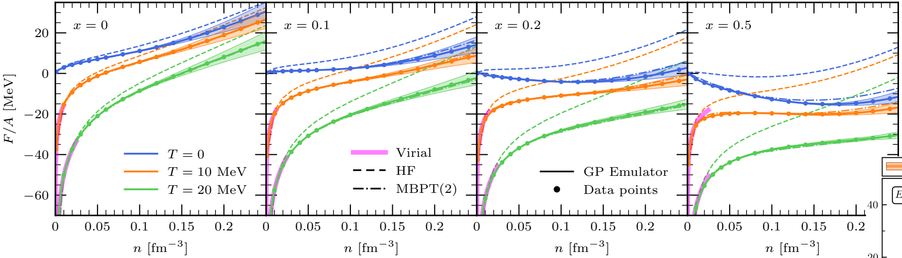


from I. Svensson, M. Mendes, N. Rutherford

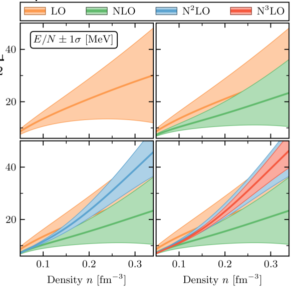
goal: provide microscopic information with quantified uncertainties

EOS developments and uncertainties

- nucleonic matter results for different proton fractions (x) and temperatures (T)



Keller et al., PRL (2023)



- order-by-order corrections from effective field theory (EFT)
- quantify truncation uncertainties with Gaussian processes (GP)

Drischler et al., PRC (2020)

goal: expand GP uncertainties to arbitrary *x* and finite *T*

GP uncertainty quantification

following Melendez et al. PRC (2019)

- collection of random variables: $f(x) \sim GP[m(x), \kappa(x, x'; \theta)]$
- kernel: $\kappa(x, x'; \theta) = \bar{c}^2\, exp\left[-\frac{1}{2}(x - x')^T L (x - x')\right]$

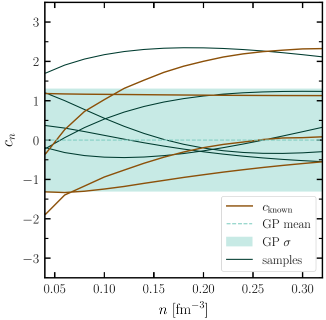
2D correlations

$$L = \begin{pmatrix} \ell_n^{-2} & 0 \\ 0 & \ell_x^{-2} \end{pmatrix}$$

- consider EFT expansion for observable

$$E(x) = E_{\text{ref}}(x)\left[\underbrace{\sum_{i=0}^{k} c_i(x) Q^i(x)}_{\text{known}} + \underbrace{\sum_{i=k+1}^{\infty} c_i(x) Q^i(x)}_{\Delta E(x)}\right]$$

$\rightarrow$ reference energy E_{ref} and expansion parameter $Q = \frac{k_F}{\Lambda_b}$

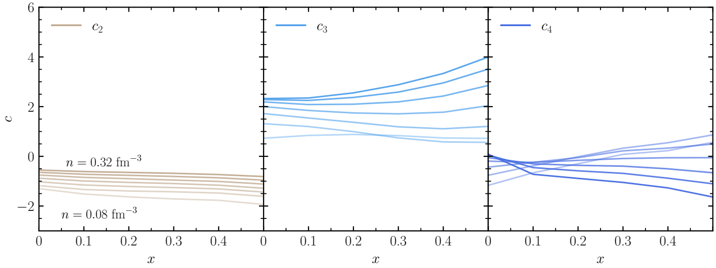


$\Rightarrow$ **hyperparameters $\bar{c}^2, \ell$ are determined from expansion coefficients**

Asymmetric matter
application of GP 2D to finite proton-fraction results

- consider asymmetry ($\alpha = 1 - 2x$) in reference scale

$$E_{\rm ref}^{\rm BQ+3B} = \underbrace{16\ \mathrm{MeV}\left(\frac{n}{n_0}\right)^{2/3}}_{\text{Drischler et al., PRC (2020)}} + \underbrace{4\ \mathrm{MeV}\left(\frac{n}{n_0}\right)^{6/3}(1-\alpha^2)}_{\text{3N informed}}$$



comparison

GP-1D:
individual $\bar{c}^2$

GP-2D:
one $\bar{c}^2$

choices

- stationary kernel
- inverse χ^2 prior for $\bar{c}^2$
- representative grid

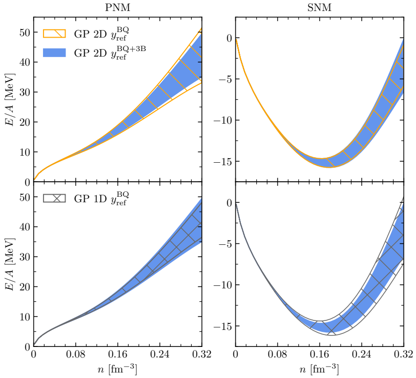
Asymmetric matter
comparison to GP 1D

GP-1D: individual $\bar{c}^2$

GP-ND: one $\bar{c}^2$

- pure neutron matter (PNM) bands are increased
- symmetric nuclear matter (SNM) bands are decreased

→ *x*-dependent reference scale counteracts this effect



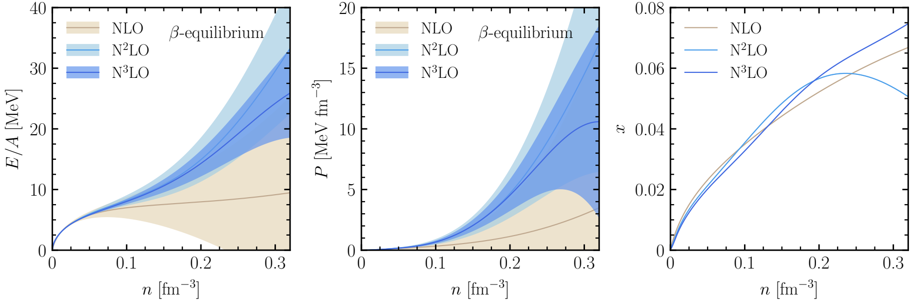
Neutron star matter

GP derivatives and uncertainty propagation

- constructed GP-2D kernel
  - $\rightarrow$ access uncertainties for arbitrary x
  - $\rightarrow$ access thermodynamic quantities $(P, \mu, ...)$

β-equilibrium:

- $\mu_n = \mu_p + \mu_e, \qquad \mu_{\nu,\bar{\nu}} = 0$
- $\mu_n - \mu_p \sim \partial_x E/A$



$\rightarrow$ **we provide the EOS of nuclear matter in β-equilibrium with quantified chiral uncertainties**

Göttling et al., PRC (2026)

Finite temperature
application of GP 3D to finite temperature results

$$F(n, x, T) = F_{\text{ref}}(n, x, T)\left[\sum_{i=0}^{\infty} c_i(n, x, T) Q^i(n, x, T)\right]$$

- reference scale

$$F_{\text{ref}} = max\{E_{\text{ref}}^{\text{BQ+3B}}, T\}$$

- relevant momentum scale

$$Q = \frac{max\{k_{\text{F}}^{(n)}, k_{\text{F}}^{(p)}\}}{\Lambda_b}$$

→ smooth max function

GP-3D

- correlation lengths

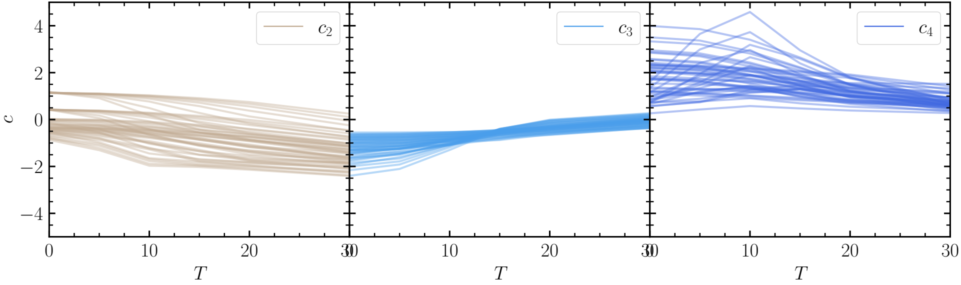
$$L = \begin{pmatrix} \ell_n^{-2} & 0 & 0 \\ 0 & \ell_x^{-2} & 0 \\ 0 & 0 & \ell_T^{-2} \end{pmatrix}$$

- constant $\bar{c}^2$

Finite temperature
application of GP 3D to finite temperature results

$$F_{\text{ref}} = max(E_{\text{ref}}^{\text{BQ+3B}}, T) \qquad Q = \frac{max\{k_F^{(n)}, k_F^{(p)}\}}{\Lambda_b}$$

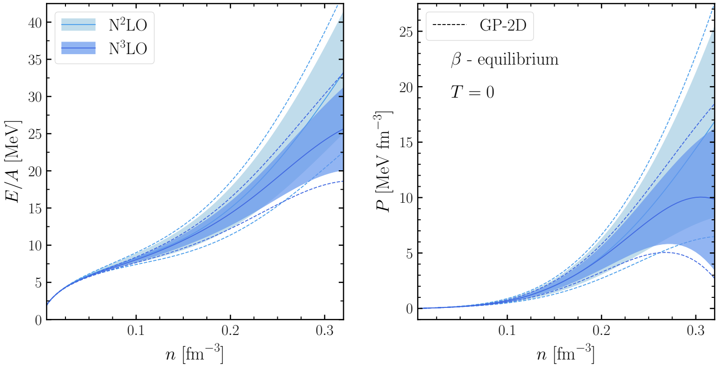
- expansion coefficients for all n and x justify a stationary kernel



Finite temperature
comparison of zero temperature results

preliminary

- compare GP-3D bands with GP-2D bands at zero temperature



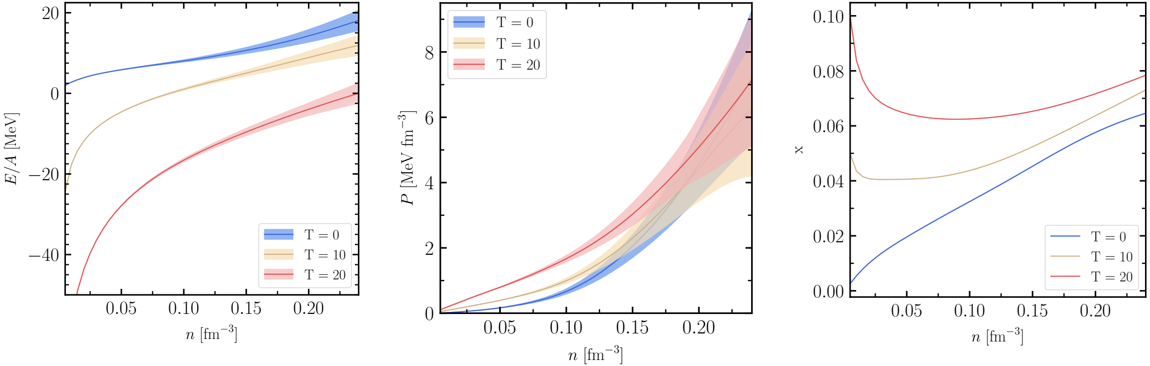
GP-3D

- smaller $\bar{c}^2$
- reduced $T = 0$ bands
- similar behavior

Neutron star matter at finite temperatures

preliminary

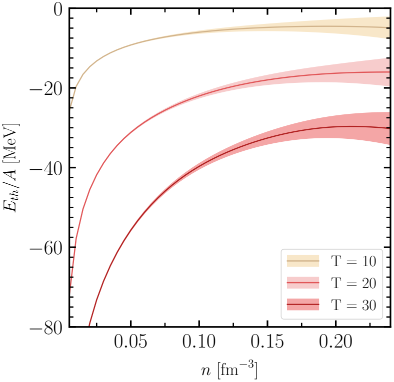
- thermodynamic quantities calculated in β-equilibrium

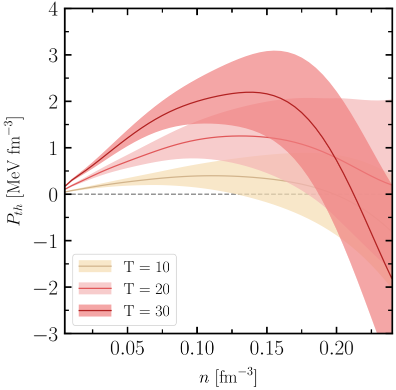


Neutron star matter at finite temperatures
thermal contribution

preliminary

- consider only the thermal contribution to thermodynamic quantities





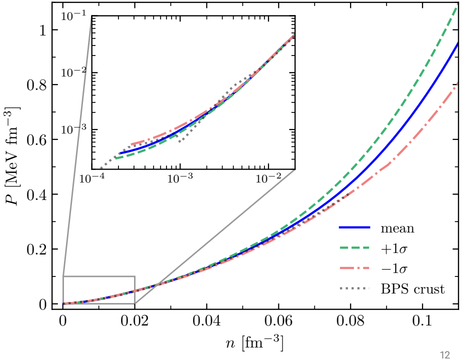
EOS application
neutron star crust - Göttling et al., PRC (2026)

- extending the EOS distribution to a lower density regime

challenge:
- not only homogeneous matter anymore
- combining matter results with further conditions

method:
- providing P and μ by GP-2D
- taking the limits of the 68% bands
- create continuous low density extension

- phase coexistence allowing proton drip in all scenarios



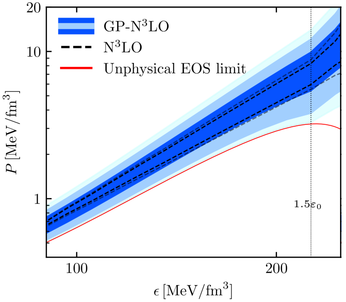
EOS application

observation inference - Mendes et al., arXiv:2605.18560

see Melissa's talk

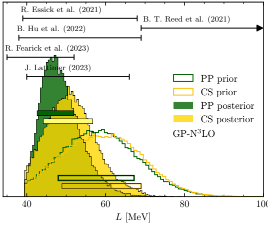
- integration of the EOS bands in an inference framework to compare with observations

EOS model: combined chiral EFT constraints with crust and high density extensions (PP, CS)
observations: pulsar mass measurements, NICER, and LIGO/Virgo



- create EOS samples from EFT band
- ensure the pressure to never decrease

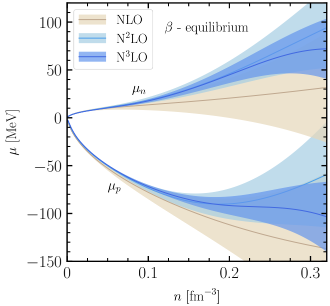
→ use correlations to infer PNM properties from the posterior

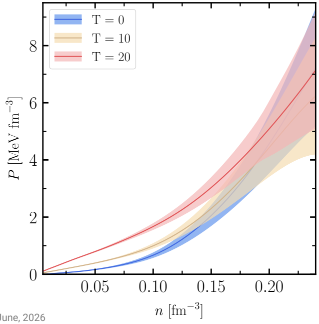


Summary and outlook

- extension of the GP uncertainty quantification
  $\rightarrow$ Bayesian chiral EFT uncertainties with GP for n, x, T

- accessing β-equilibrium and propagating uncertainties to other thermodynamic quantities





application:

- crust extension
  $\rightarrow$ consistent crust EOS
- incorporation in astrophysical inference framework

goal: incorporate finite temperature EOS