Constraining Hamiltonians from Chiral Effective Field Theory with Neutron Star Data

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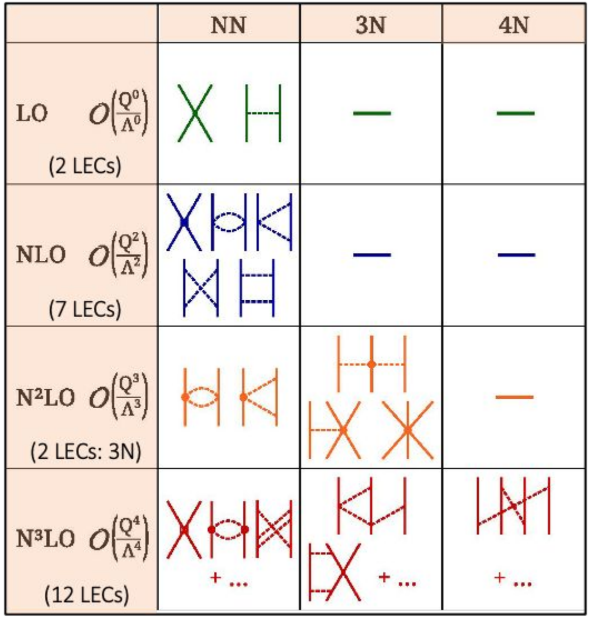
Motivation

- The same nuclear Hamiltonian describes all nuclear systems, from nuclei measured at FRIB to dense matter in neutron stars.

- Some open problems for nuclear Hamiltonians are:
    - How to propagate uncertainties while accounting for correlations between them
    - How to best constrain low-energy couplings (LECs)
    - How to constrain terms for which data is scarce, such as hyperon-nucleon interactions
    - How to best determine interaction terms that are unknown (see talk by Vincenzo on Thursday)

- We present a new way of adjusting LECs to a class of systems that probe the highest densities and highest neutron-to-proton asymmetries: **Neutron Stars**



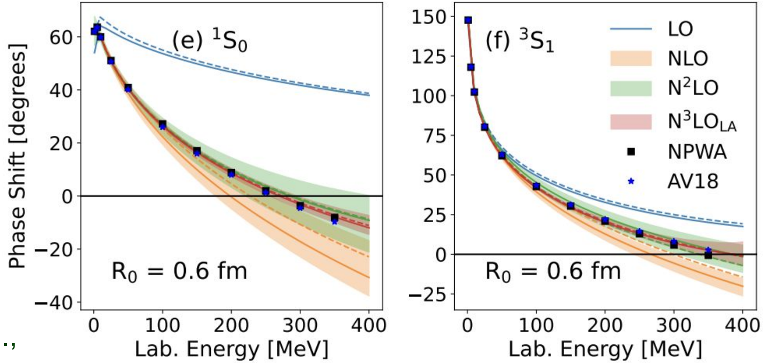
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meißner, Hammer, …

Nuclear Hamiltonians from EFT

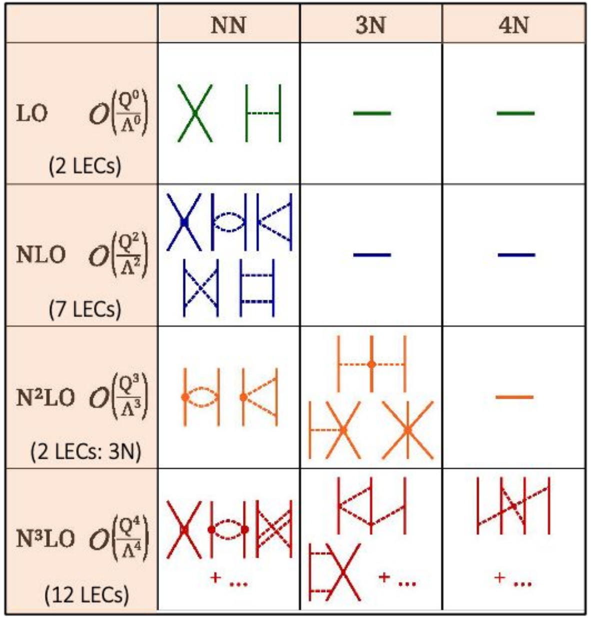
We use Hamiltonians from chiral effective field theory (EFT), a systematic expansion for nuclear forces, to N^2LO

Unknown coefficients (LECs) at N^2LO are fit to scattering data using Bayesian statistics

LEC posteriors reflect truncation uncertainty (see next slide)



Somasundaram et al., PRC (2024)



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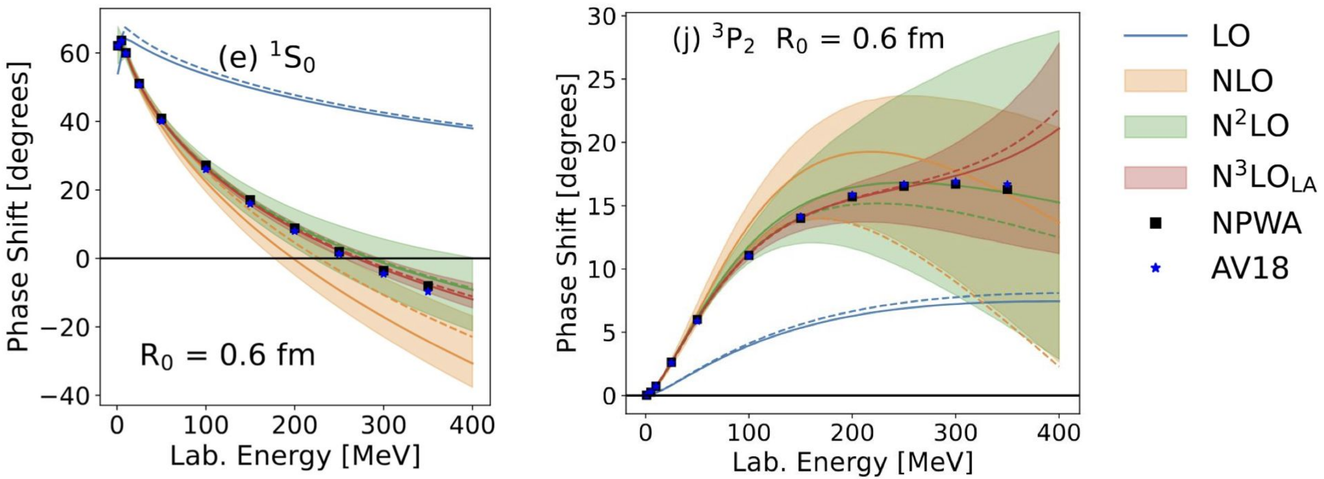
Nuclear Hamiltonians from EFT

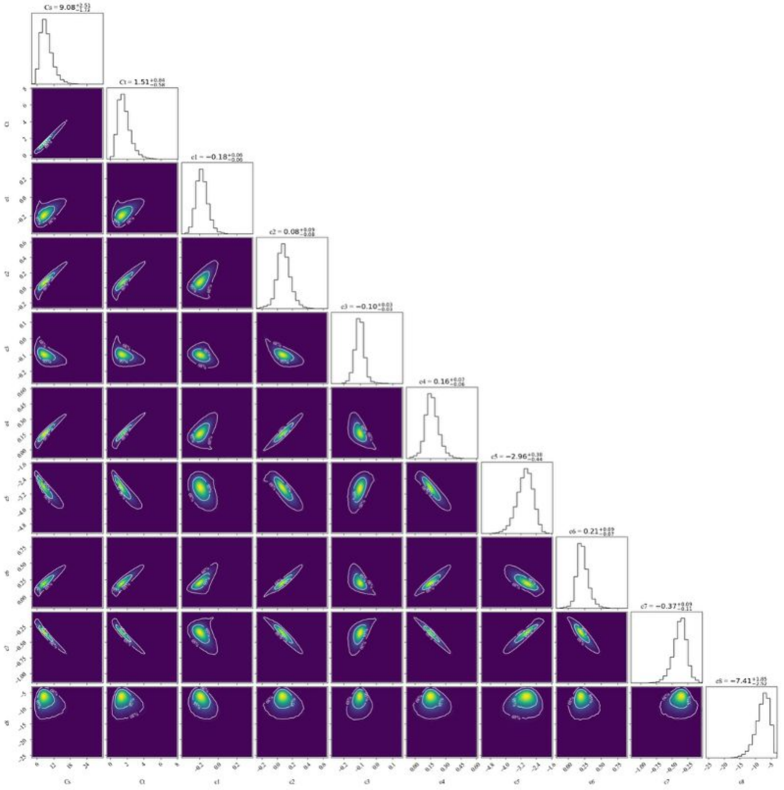
The NN interaction is calibrated to scattering data using Bayesian inference. This allows us to incorporate EFT truncation uncertainties in the fit.



The likelihood accounts for experimental, and theoretical truncation uncertainty:

$$\mathcal{L} \propto \prod_i \exp\left\{-\frac{1}{2}\left(\frac{X_i^{\mathrm{exp}} - X_i^{\mathrm{theo}}}{\sigma_i}\right)^2\right\}, \qquad \sigma^2 = \sigma^2_{\mathrm{exp}} + \sigma^2_{\mathrm{theo}},$$

Nuclear Hamiltonians from EFT



The uncertainty of nuclear interactions and data is mapped into the uncertainty of model parameters (LECs)

Propagate these uncertainties directly to observables, such as matter or **neutron star observables**, and use this to enable the inverse problem

Neutron Stars

Neutron stars are massive (up to 2 M_{sol}) but with radii of only ~12 km

Very **high densities**, of the order of several times the nuclear saturation density

Neutron-rich matter in their outer cores

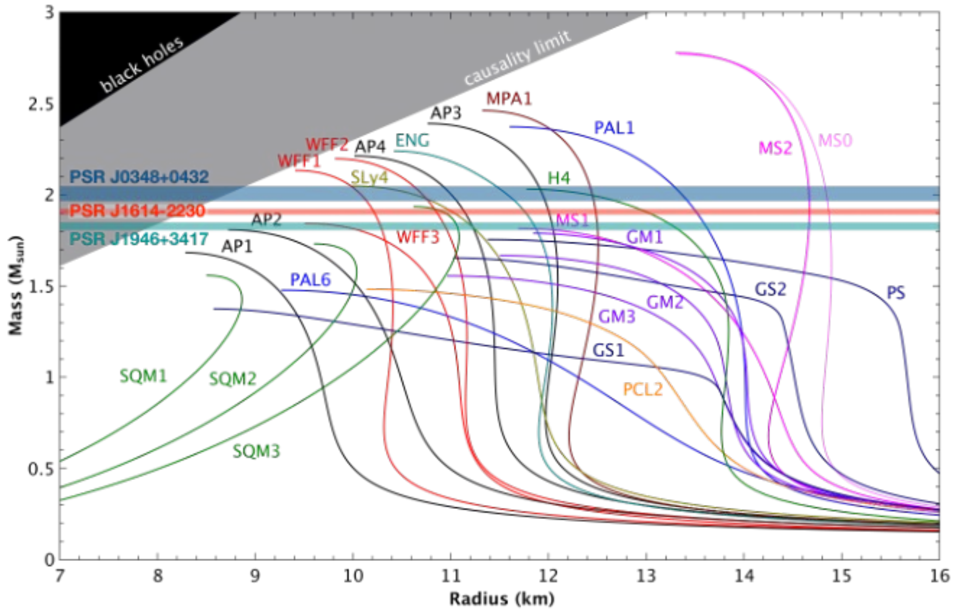
Stabilized by nuclear forces, described by the nuclear Hamiltonian, which allows us to probe these interactions in a **unique regime**

Neutron Stars

The EOS describes how the forces in the nuclear many-body system determine the properties of the stars.

Important constraints on the EOS can be obtained from astrophysical observations and nuclear theory.

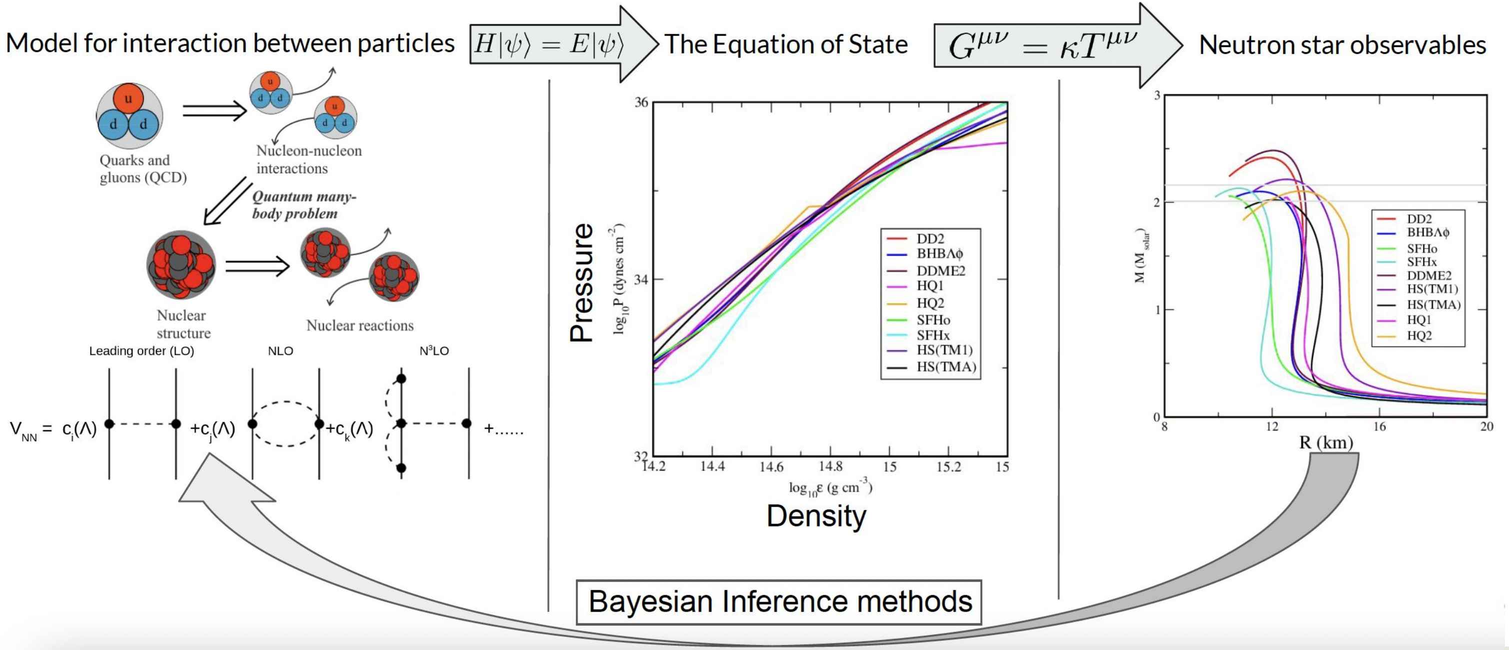
Hence, these observations then also constrain the nuclear forces!



Our goals

(1) Propagate uncertainties directly from interaction to EOS and then to neutron stars

(2) Infer interactions parameters from astrophysical data



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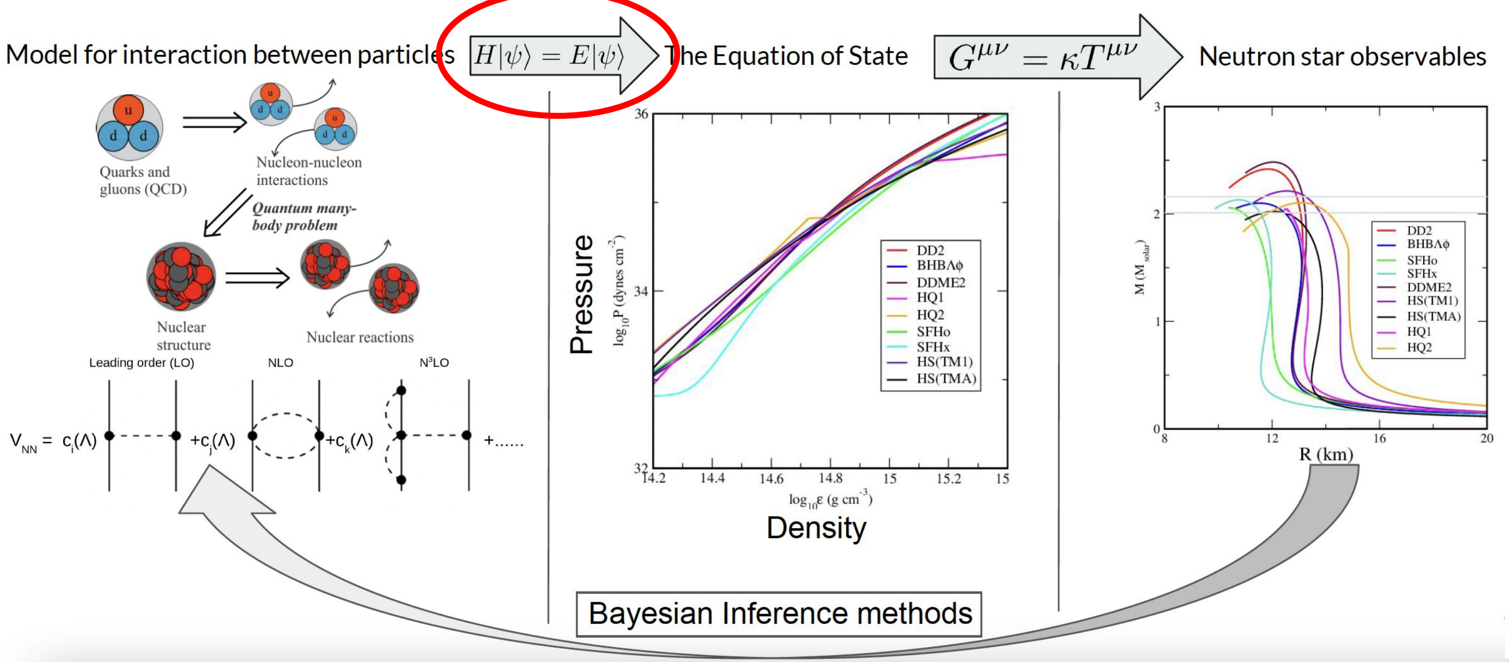
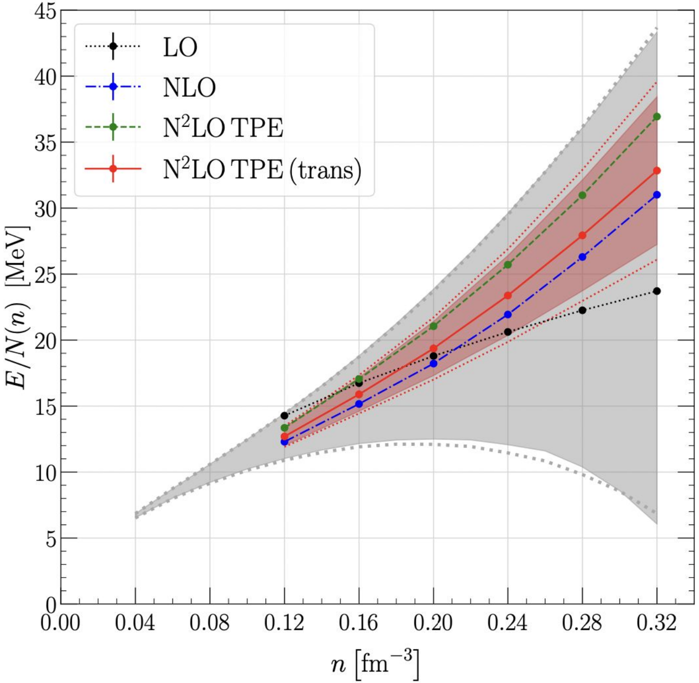


The Equation of State from quantum Monte Carlo



Tews et al., Phys. Rev. Res. **7**,033024 (2025)

Compute EOS using auxiliary-field diffusion Monte Carlo code (AFDMC)

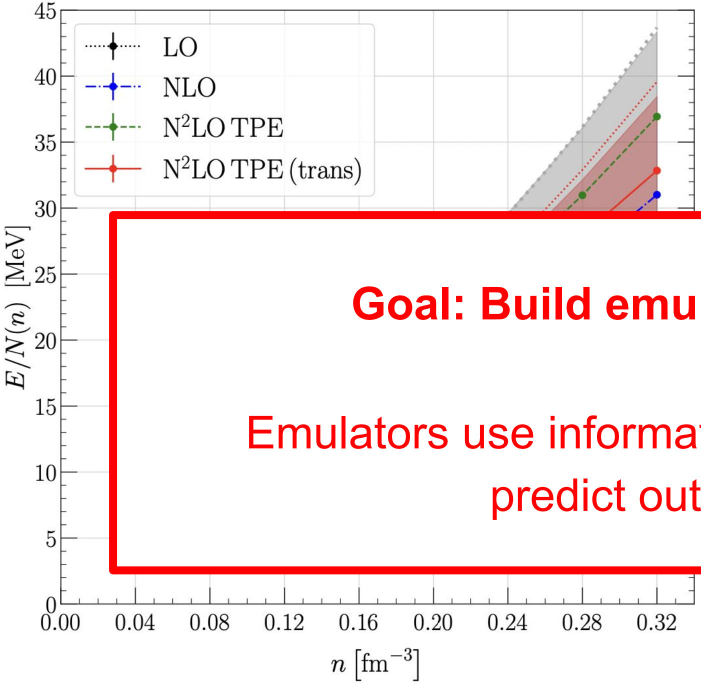
Stochastic propagation of a trial wave function in imaginary time to project out the ground state of a system, very precise (stat. uncertainties 1%)

AFDMC is also very accurate

But AFDMC is very computationally expensive: Calculating the EOS for one Hamiltonian (one set of LECs) costs **O(1 million) CPU-hours**

Prohibits error propagation, Bayesian LEC inference

The Equation of State from quantum Monte Carlo



Tews et al., Phys. Rev. Res. **7**,033024 (2025)

Compute EOS using auxiliary-field diffusion Monte Carlo code (AFDMC)

Stochastic propagation of a trial wave function in … state of a … %)

Goal: Build emulators to accelerate AFDMC!

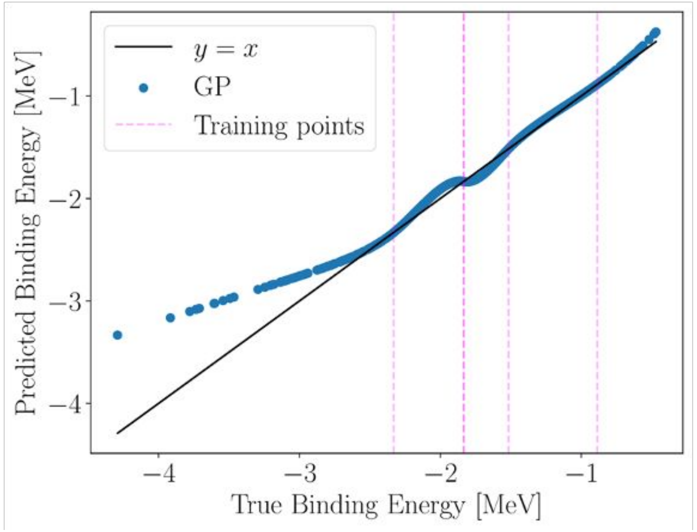
Emulators use information from a set of full calculations to predict outcomes for other inputs.

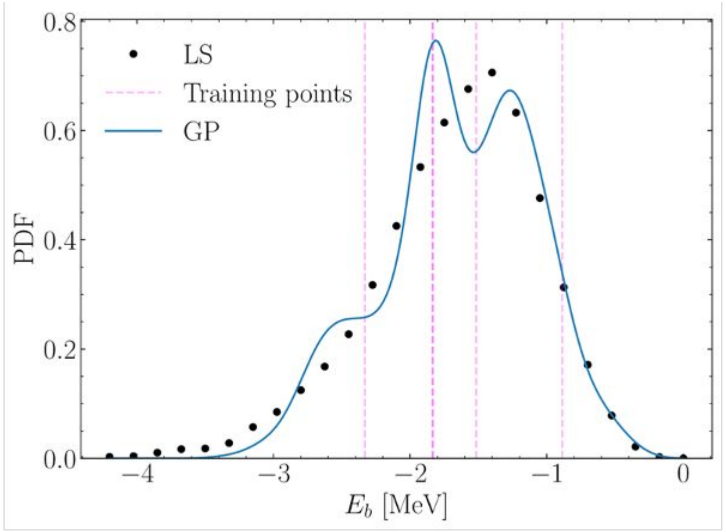
… nsive: … (one set of LECs) costs **O(1 million) CPU-hours**

Prohibits error propagation, Bayesian LEC inference

Emulators - The Case of the Deuteron

We have employed traditional machine learning (Gaussian processes) to AFDMC calculations of the deuteron:





LS: Exact solution with Lippman-Schwinger equations.

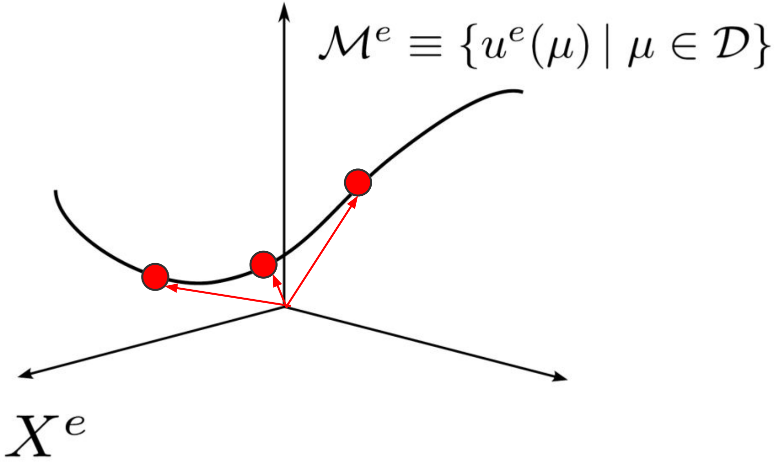
Somasundaram, **CLA**, Giuliani, Godbey, Gandolfi, Tews, Phys. Lett. B **866**, 139558 (2025)

Reduced Basis Method (RBM)

Solution for Hamiltonian $H(\mu)$ lives in lower-dimensional manifold *M* of full Hilbert space

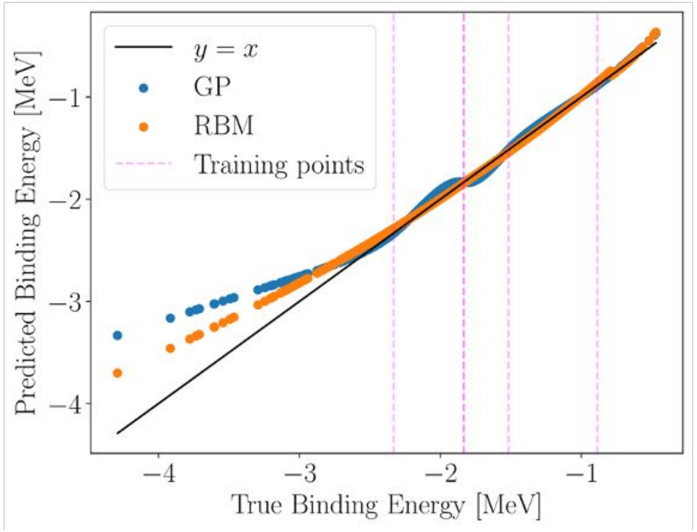
Calculation of *N* high-fidelity solutions for different μ provides basis for *M*

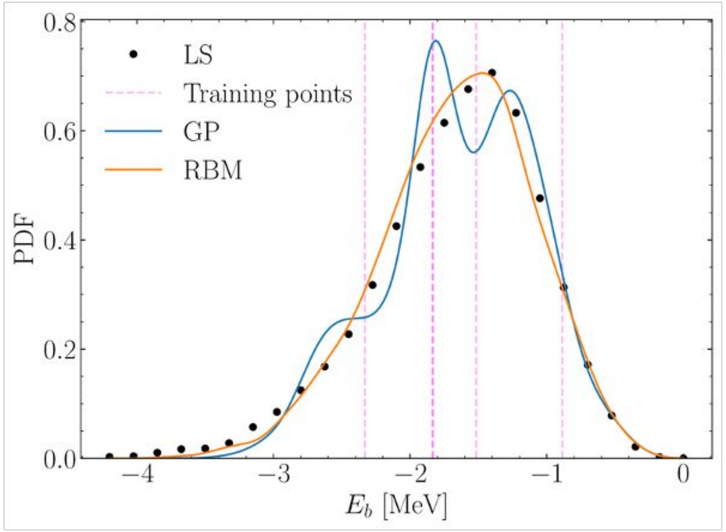
Project $H(\mu)$ into this subspace where diagonalization is simple



Emulators - The Case of the Deuteron

We have employed several emulators to AFDMC calculations of the deuteron: Gaussian Process (GP), Reduced-Basis Method (RBM)





LS: Exact solution with Lippman-Schwinger equations.

Somasundaram, **CLA**, Giuliani, Godbey, Gandolfi, Tews, Phys. Lett. B **866**, 139558 (2025)

Parametric Matrix Model (PMM)

The projected subspace Hamiltonian can generally be written as:

$$H(\mu) = D + c_1 M_1 + c_2 M_2 + \ldots$$

Here, D is a diagonal matrix, M_i are symmetric matrices, and c_i are parameters of the Hamiltonian (LECs from chiral EFT).

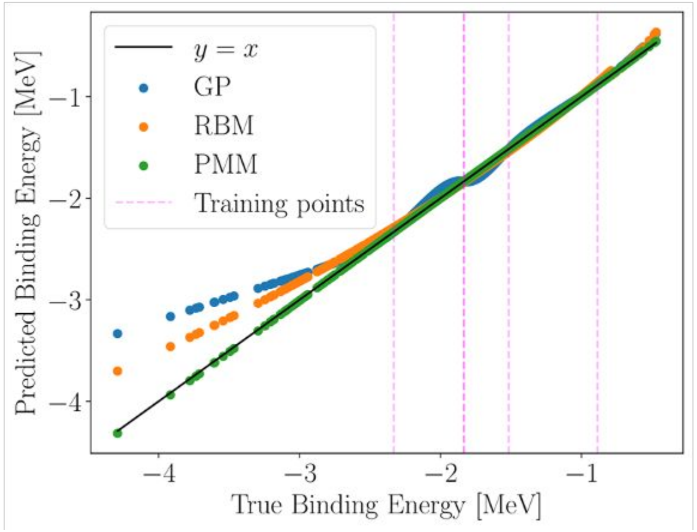
The **PMM** fits the matrix elements to high-fidelity solutions: lowest eigenvalue of $H(\mu)$ is fit to AFDMC energies for different LECs.

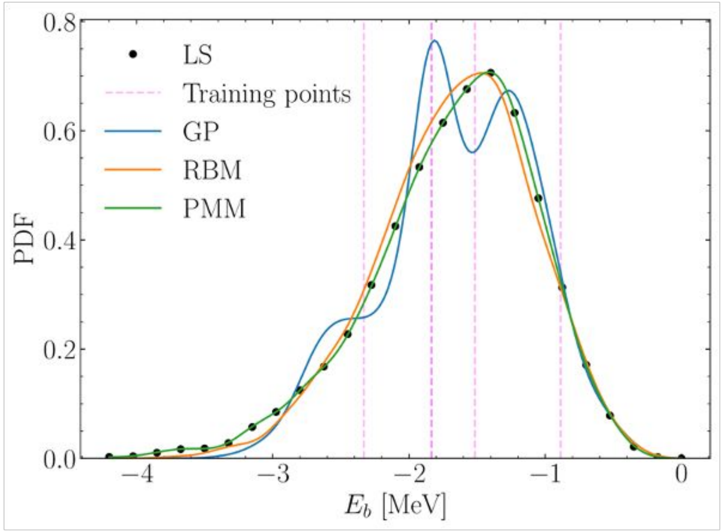
The dimension of $H(\mu)$ is a choice, we will explore different choices.

Cook et al., Nat. Comm. **16**, 5929 (2025)

Emulators - The Case of the Deuteron

We have employed several emulators to AFDMC calculations of the deuteron:
Gaussian Process (GP), Reduced-Basis Method (RBM), **Parametric Matrix Model (PMM)**

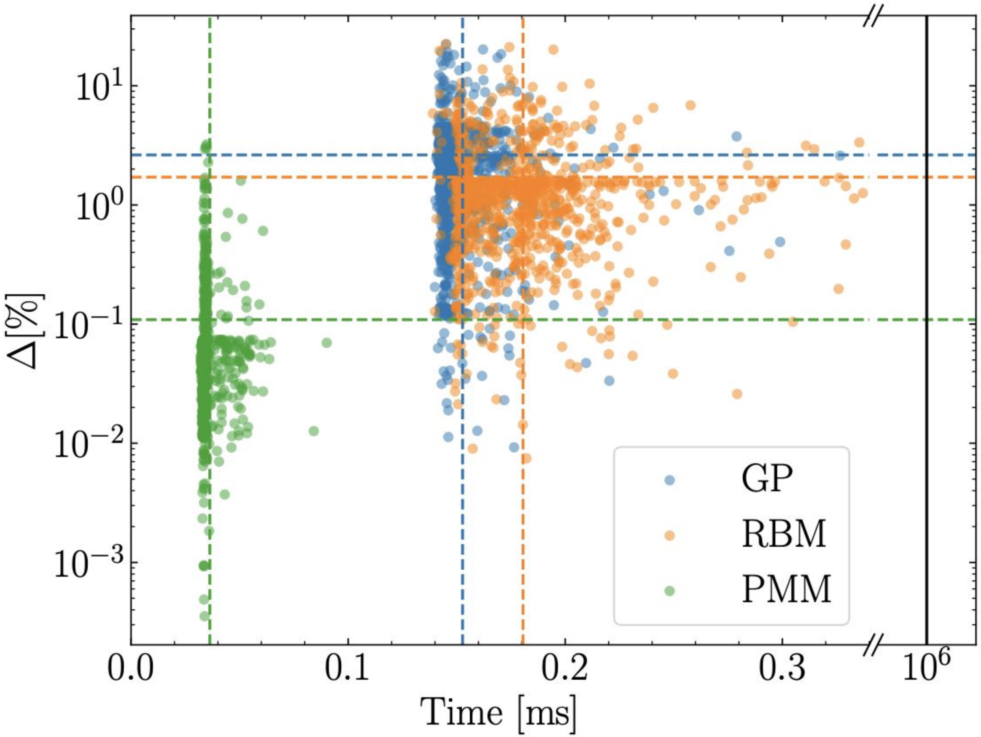




PMM best for interpolation and extrapolation!

Somasundaram, **CLA**, Giuliani, Godbey, Gandolfi, Tews, Phys. Lett. B **866**, 139558 (2025)

Emulators - Time versus Accuracy



PMM is fastest emulator, gaining speed ups of 10^8!

Error in the case of the deuteron is smallest for PMM: 0.1 %

Somasundaram, **CLA**, Giuliani, Godbey, Gandolfi, Tews, Phys. Lett. B 866, 139558 (2025)

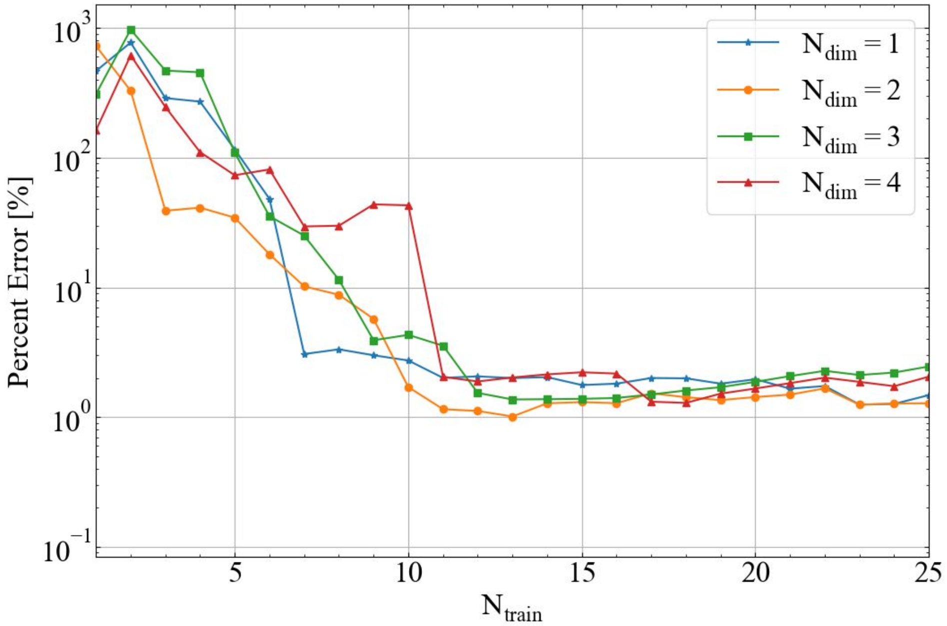
PMM for Pure Neutron Matter (PNM) - N^2LO

Compute exact AFDMC energies for 30 different LEC sets at N^2LO at various densities ~O(10 mio CPU-h)

Split into training set (N=20) and validation set (N=10)

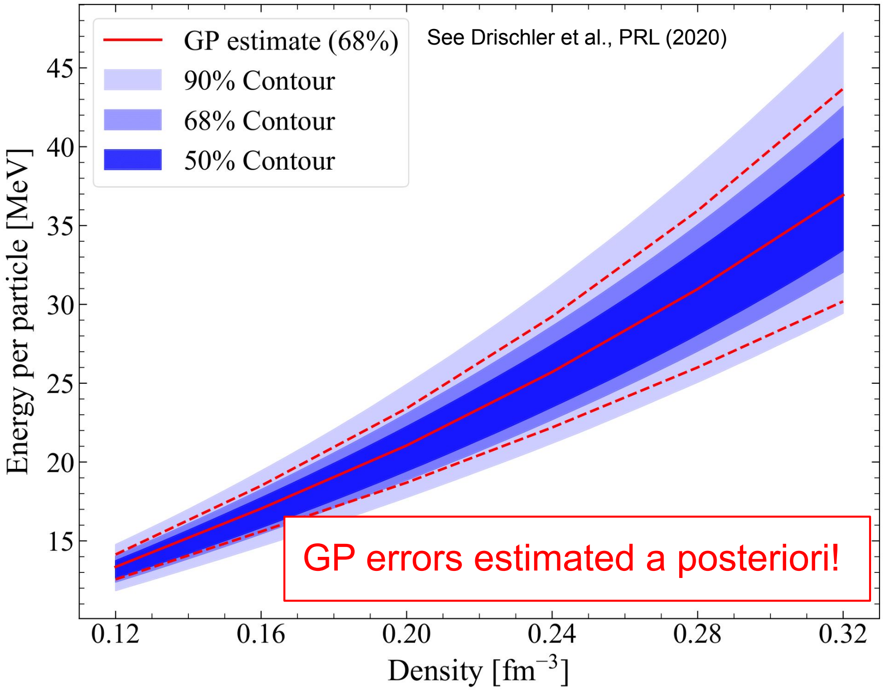
Fit PMM to training data and calculate percent error for validation data

Propagation of 272,000 LEC sets takes only around 1.5 seconds



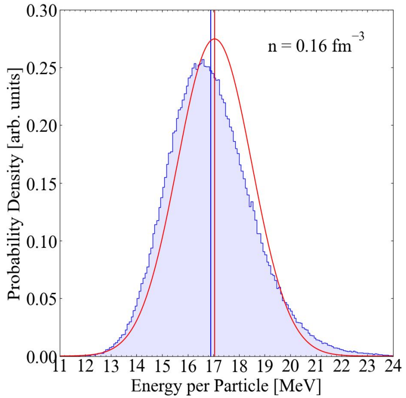
CLA et al., Phys. Rev. Lett. **135**, 142501 (2025)

PMM for Neutron Matter: Energy vs Density

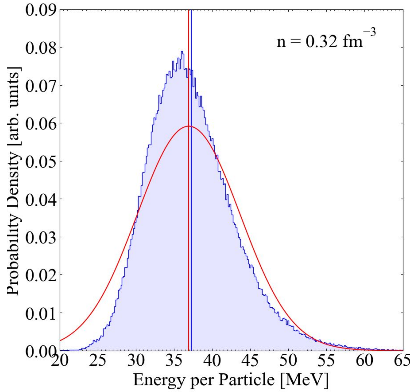


Now full distributions:

PDF at nsat:

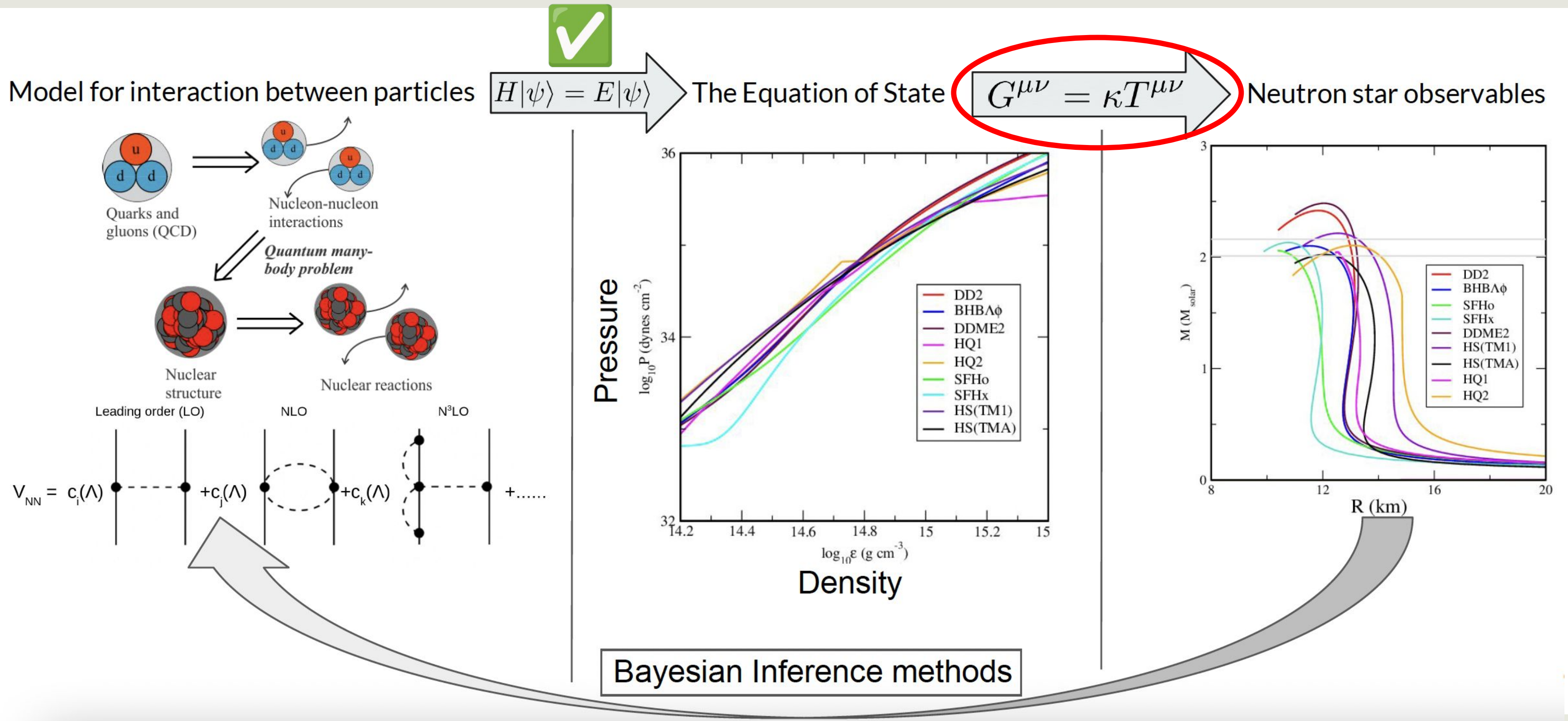


PDF at 2nsat:

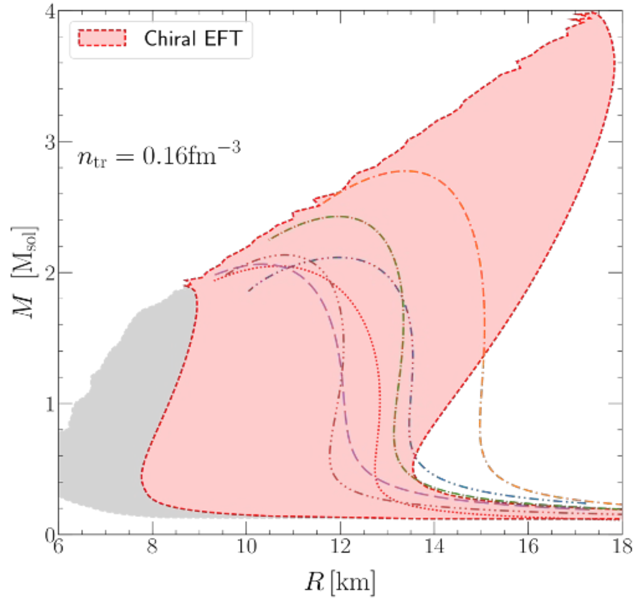


CLA et al., Phys. Rev. Lett. **135**, 142501 (2025)

Next: Neutron-Star Structure



Tolman-Oppenheimer-Volkoff (TOV) Equations



Tews, Gandolfi, Carlson, Reddy, ApJ 2018

Now, compute neutron-star properties using TOV equations

$$\frac{dP}{dr} = -\frac{Gm\varepsilon}{c^2r^2}\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{c^2 r}\right)^{-1}$$

$$\frac{dm}{dr} = 4\pi\frac{\varepsilon}{c^2}r^2 .$$

To infer underlying Hamiltonian, TOV equations must be solved many times for many EOS (1-2s per solution).

Too slow for Bayesian inference!

Goal: Accelerating TOV calculations

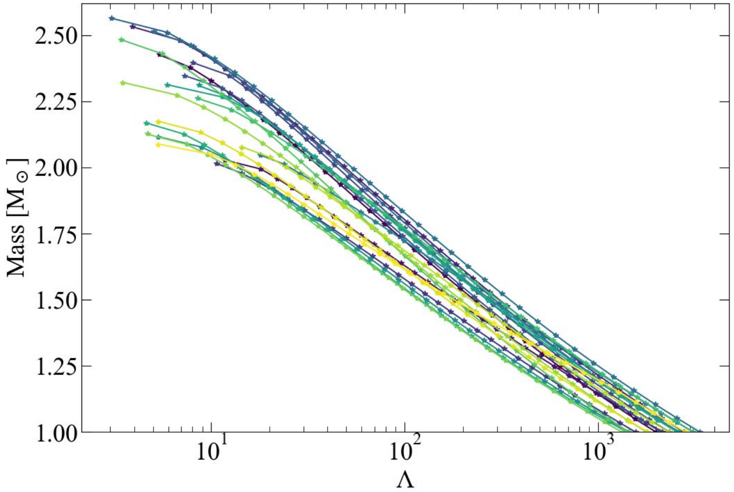
Machine Learning for TOV Equations

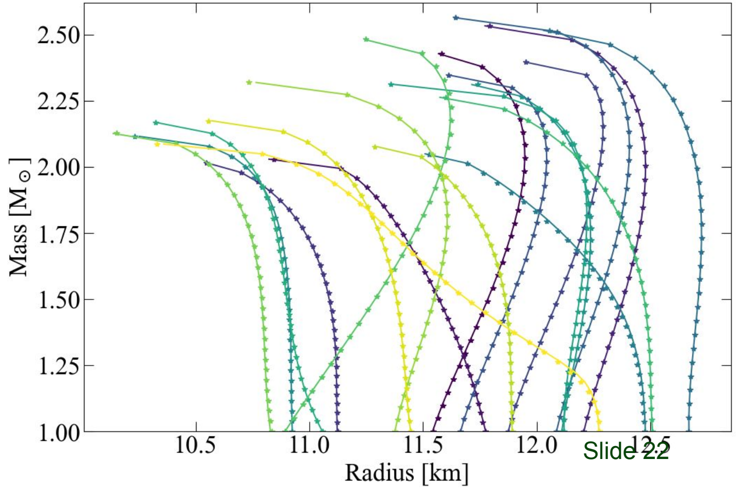
Using results from the PMM for pure neutron matter up to $2n_{sat}$ and a general EOS model above, we compute exact M_{TOV}, radii, and tidal deformabilities for 272k LEC sets (lines).

Split into training (N=200k) and validation (N=72k) sets

Fit neural-network regressor to training data and calculate EOS in validation set (points) with uncertainties <0.01%

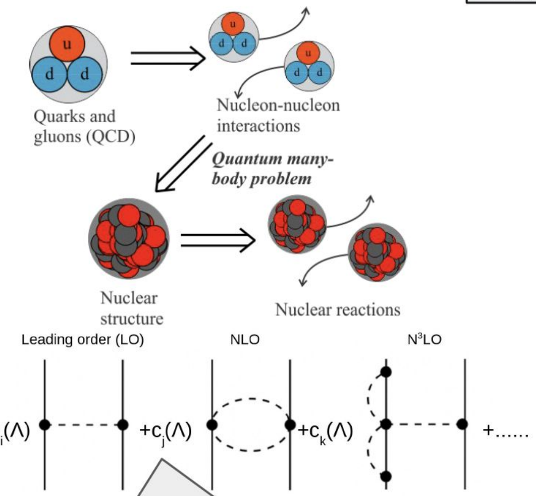
CLA et al., arXiv:2601.05999.



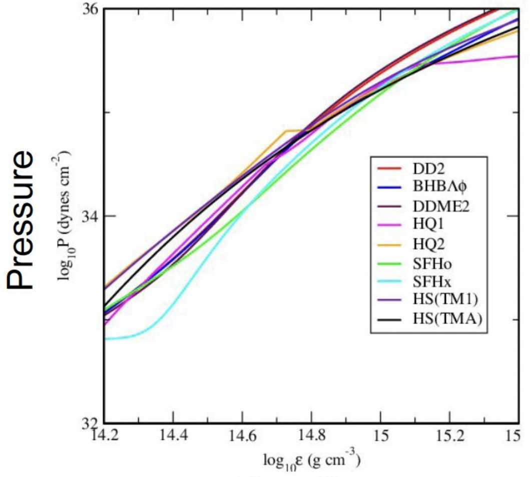


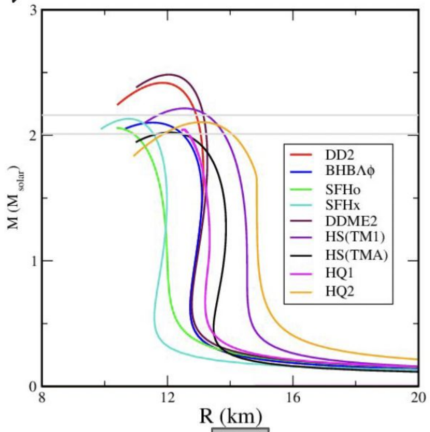
Next: Inferring LECs in the Hamiltonian

Model for interaction between particles $H|\psi\rangle = E|\psi\rangle$ The Equation of State $G^{\mu\nu} = \kappa T^{\mu\nu}$ Neutron star observables



$V_{NN} = c_i(\Lambda) \cdots + c_j(\Lambda) \cdots + c_k(\Lambda) \cdots + \ldots$





Bayesian Inference methods

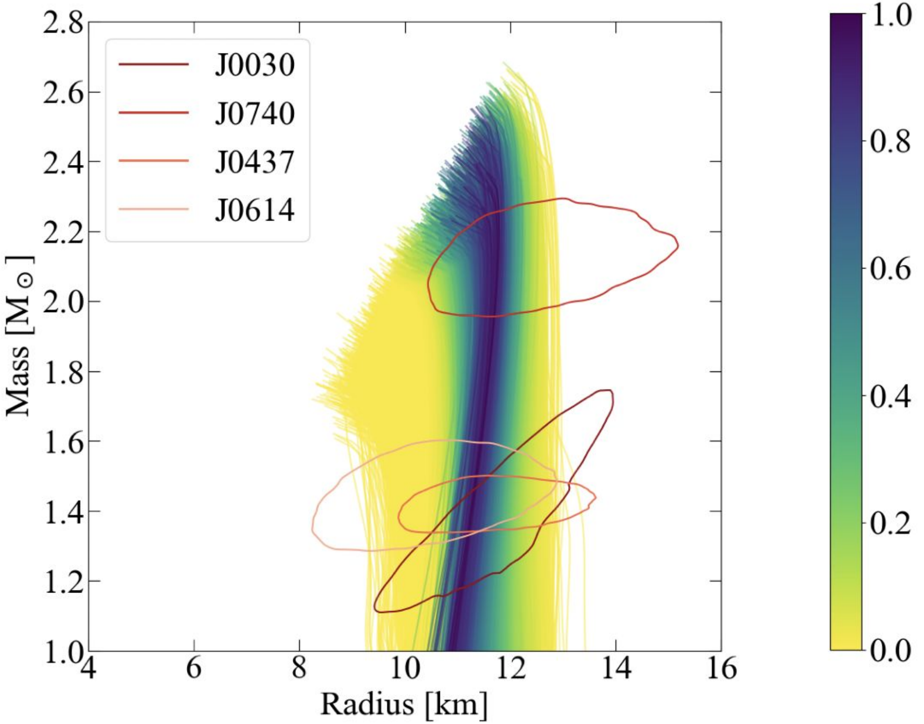
Direct EOS Inference

Use emulators to directly sample LECs in gravitational-wave data analysis: Emulators implemented in PyCBC inference software.

B. Reed, **CLA,** et al., Class. Quant. Grav. **43**, 055015 (2026)

Allows for direct sampling of LECs, which is beneficial for large parameter spaces of nuclear Hamiltonians.

We also add information from observations of two-solar-mass neutron stars and from Neutron Star Interior Composition Explorer (NICER)



CLA et al., arXiv:2601.05999.

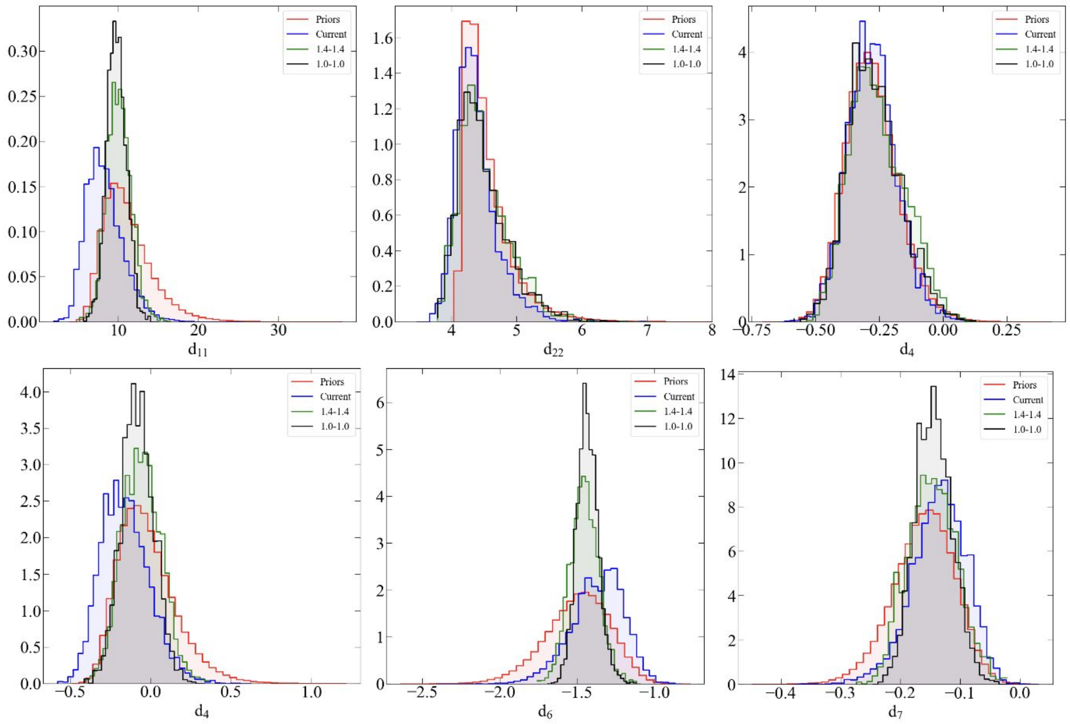
Direct LEC Inference

Sample two-nucleon LECs of EFT Hamiltonian at N^{2}LO (pion-nucleon LECs well constrained from pion-nucleon scattering)

Mild constraints on two-nucleon LECs that contribute to P waves from current neutron-star data

Strong constraints possible with future detectors, e.g., Cosmic Explorer

Such constraints are impossible without using emulators



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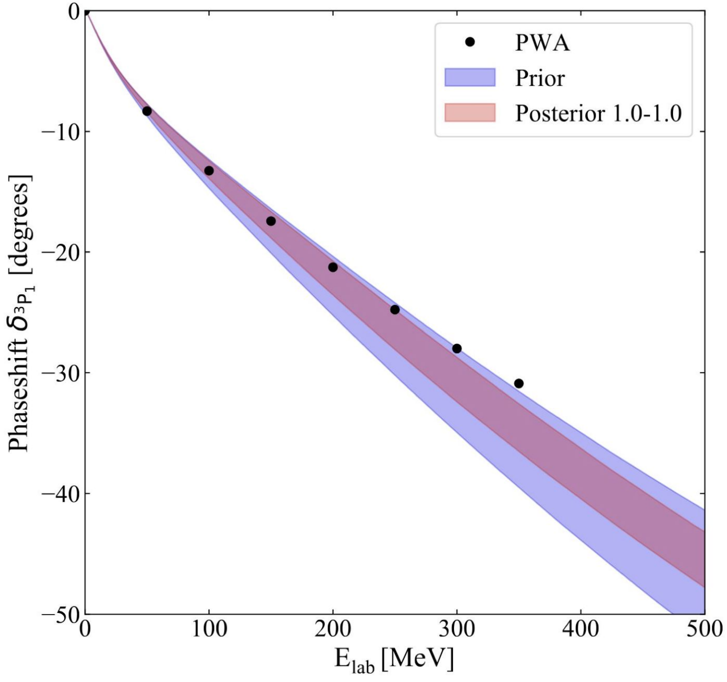


CLA et al., arXiv:2601.05999.

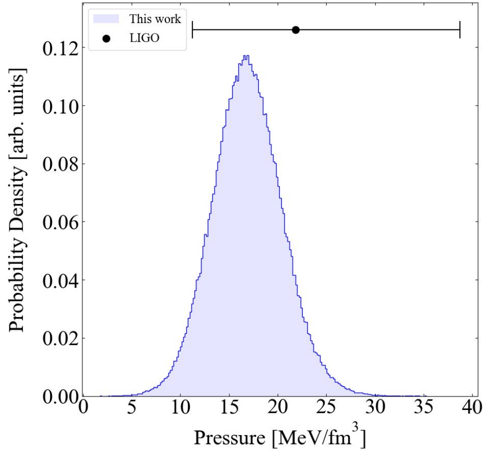
Summary

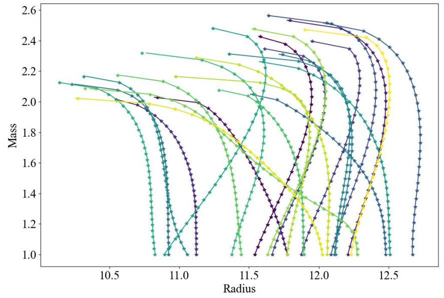
We applied the PMM to AFDMC calculations of pure neutron matter, and obtain emulator uncertainties of ~1% at N^2LO.

The PMM allows us to propagate uncertainties directly from LECs to the EOS: straightforward way of uncertainty estimation without the need of a posteriori assumptions.

We have also applied emulators to the TOV equations and implemented them in PyCBC to directly infer LECs from observations.

Injection studies show potential of future GW observatories for LEC inference.





Open questions

How can observations of neutron star properties provide a complementary/better understanding of the importance and strength of individual terms in the nuclear Hamiltonian?

- Sensitivity to interactions between neutrons
- Possibility to probe new three-nucleon force terms that are important at high densities probed in neutron stars
- Constrain hyperon-nucleon interactions with neutron stars?

How can current and next-generation astrophysical observatories improve and complement data from terrestrial experiments to constrain Hamiltonians?

Thank you for your attention!

Thanks!!!

Los Alamos National Laboratory: S. De, H. Johnson, T. Plohr, B. Reed, R. Somasundaram, I. Tews

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University of Potsdam: H. Koehn, H. Rose

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