Multi-Messenger Astrophysics and the Nuclear Symmetry Energy

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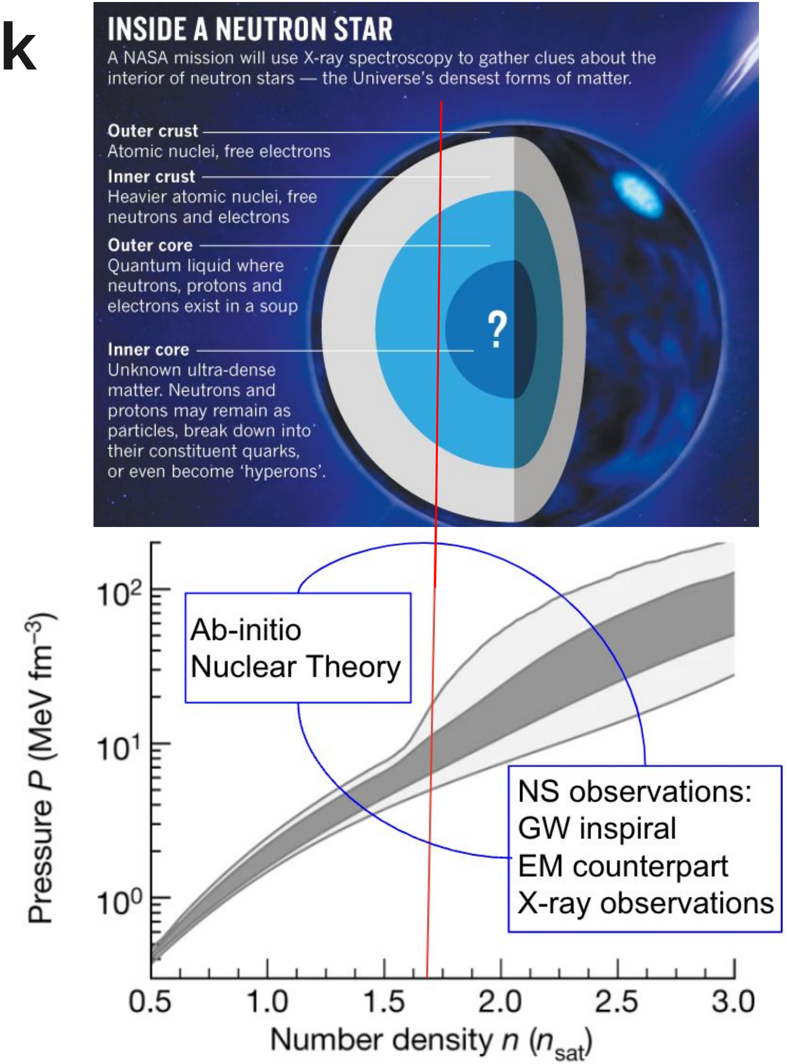
Overview of the talk

What can ab-initio theories like chiral EFT tell us about the EOS at low densities?

Can chiral EFT help constrain density functional methods that can be extended to higher densities?

Are there any direct implications for NS properties, such as the NS crust?



Ab-initio Nuclear Theory

NS observations:
GW inspiral
EM counterpart
X-ray observations

What can we learn about the EOS and the symmetry energy at high densities from multi-messenger data?

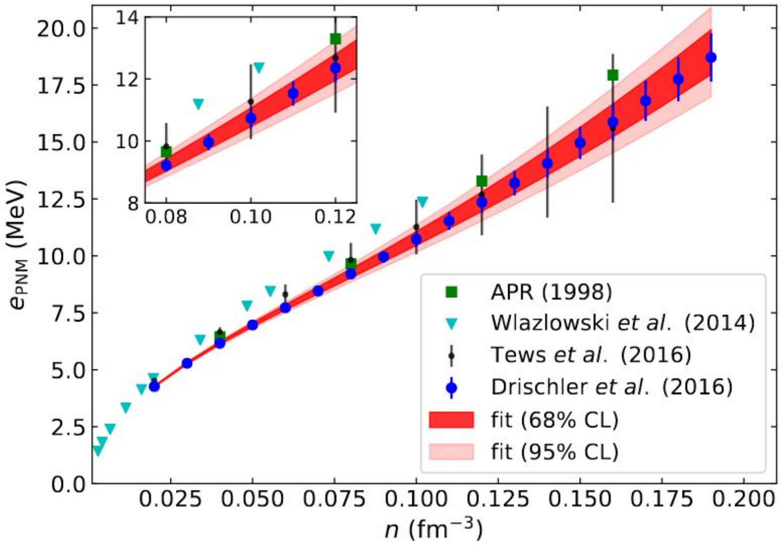
Crucially, how can it be combined with low-density nuclear physics input?

Chiral EFT combined with a Metamodeling approach

- Chiral EFT is the modern approach to describe the nuclear interaction that allows for robust uncertainty quantification.

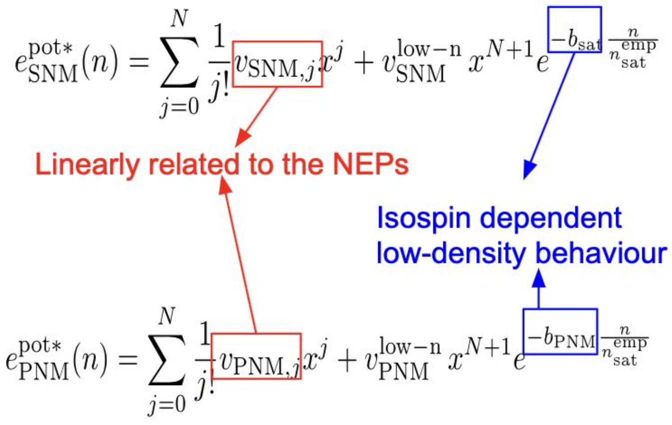
  See talks by R. Machleidt, A. Gezerlis, etc.

- EFT results can be combined with density functionals such as the metamodel. This allows for Bayesian uncertainty quantification and practical applications for NSs.



MBPT results from Drischler et al., PRC 93 (2016) 5, 054314

$$e(n,\delta) = t^*(n,\delta) + e^{\mathrm{pot}*}(n,\delta)$$



$$e^{\mathrm{pot}*}_{\mathrm{SNM}}(n) = \sum_{j=0}^{N} \frac{1}{j!} \boxed{v_{\mathrm{SNM},j}} x^j + v^{\mathrm{low-n}}_{\mathrm{SNM}} x^{N+1} e^{\boxed{-b_{\mathrm{sat}}} \frac{n}{n^{\mathrm{emp}}_{\mathrm{sat}}}}$$

Linearly related to the NEPs

Isospin dependent low-density behaviour

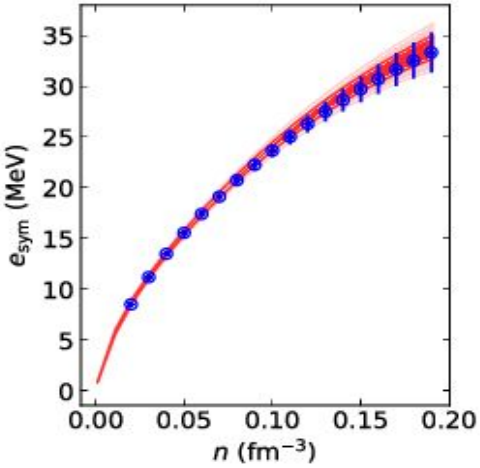
$$e^{\mathrm{pot}*}_{\mathrm{PNM}}(n) = \sum_{j=0}^{N} \frac{1}{j!} \boxed{v_{\mathrm{PNM},j}} x^j + v^{\mathrm{low-n}}_{\mathrm{PNM}} x^{N+1} e^{\boxed{-b_{\mathrm{PNM}}} \frac{n}{n^{\mathrm{emp}}_{\mathrm{sat}}}}$$

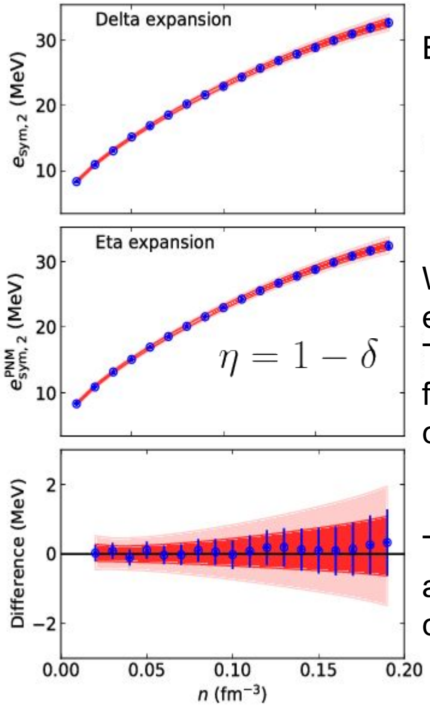
J. Margueron et al. , Phys.Rev.C 97 (2018) 2, 025805

An application to symmetry energy: How good is the ‘Quadratic approximation’?

$$e_{sym} = e_{NM} - e_{SM}$$

$$\boxed{e_{\mathrm{sym}}(n)} = \boxed{e_{\mathrm{sym},2}(n)} + \boxed{e_{\mathrm{sym},4}(n) + \ldots}$$





Expansion around SM:

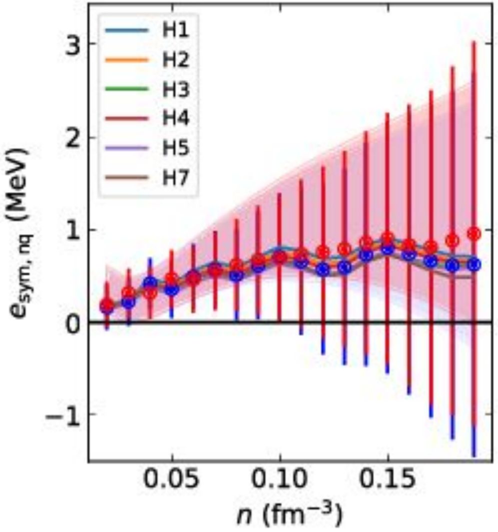
$$e_{sym,2} = \frac{1}{2}\frac{\partial^2 e}{\partial \delta^2}\bigg|_{\delta=0}$$

$$\delta = (n_n - n_p)/n$$

We also used an expansion around NM. This has applications for quantum monte carlo calculations.

The two expansions are remarkably consistent.

$$e_{sym,nq} = e_{sym} - e_{sym,2}$$



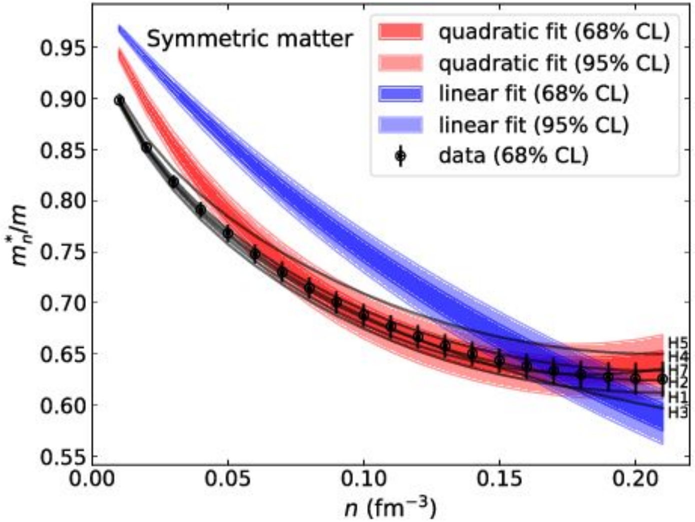
RS et al. ,PRC 103 (2021) 4, 045803

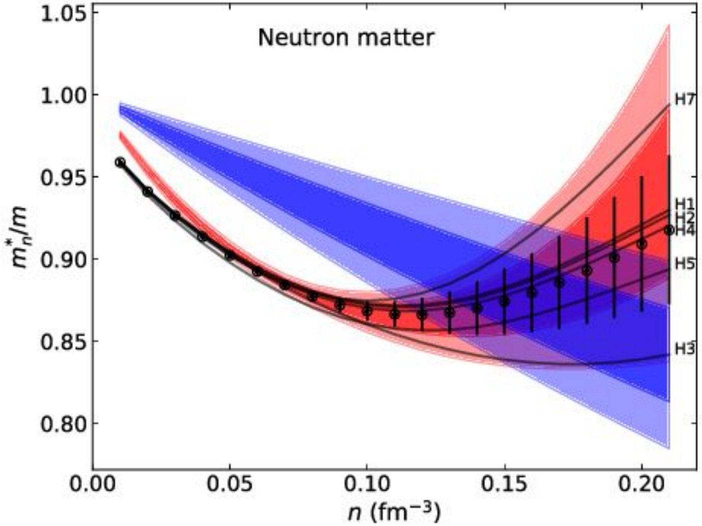
The non-quadratic contribution to the symmetry energy is around 1 MeV.

The Landau Effective Mass: Metamodel fit to Chiral EFT calculations

$$\left(\frac{m^*_{\mathrm{SNM}}}{m}(n)\right)^{-1} = 1 + \frac{\kappa_{\mathrm{sat}}}{n_{\mathrm{sat}}} n + \frac{\kappa_{\mathrm{sat},2}}{n^2_{\mathrm{sat}}} n^2$$

$$\left(\frac{m^*_{\mathrm{PNM}}}{m}(n)\right)^{-1} = 1 + \frac{\kappa_{\mathrm{PNM}}}{n_{\mathrm{sat}}} n + \frac{\kappa_{\mathrm{PNM},2}}{n^2_{\mathrm{sat}}} n^2$$





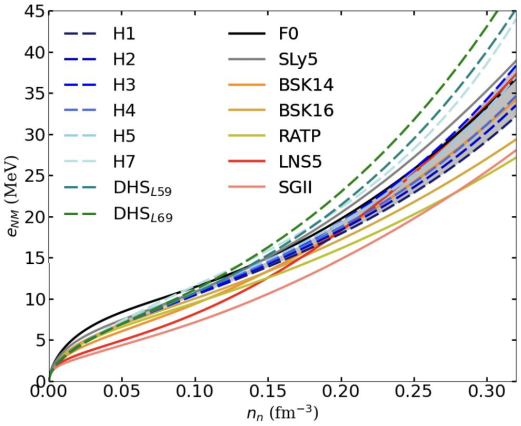
RS et al. ,PRC 103 (2021) 4, 045803

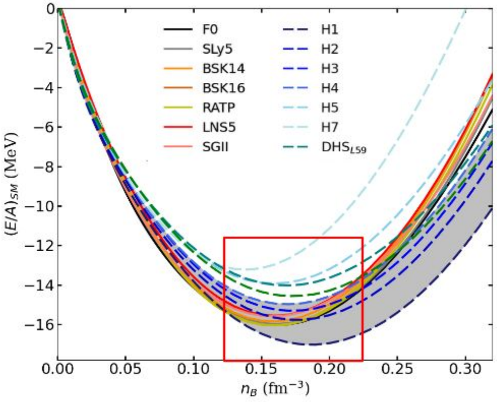
Extension to arbitrary isospin asymmetries:

$$\left(\frac{m^*_{\tau}}{m}(n,\delta)\right)^{-1} = 1 + \left(\frac{\kappa_{\mathrm{sat}}}{n_{\mathrm{sat}}} + \tau_3\delta\frac{\kappa_{\mathrm{sym}}}{n_{\mathrm{sat}}}\right) n + \left(\frac{\kappa_{\mathrm{sat},2}}{n^2_{\mathrm{sat}}} + \tau_3\delta^2\frac{\kappa_{\mathrm{sym},2}}{n^2_{\mathrm{sat}}}\right) n^2$$

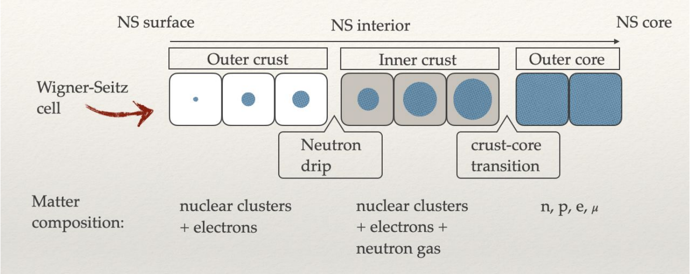
Results for the NS crust

The Equation of State

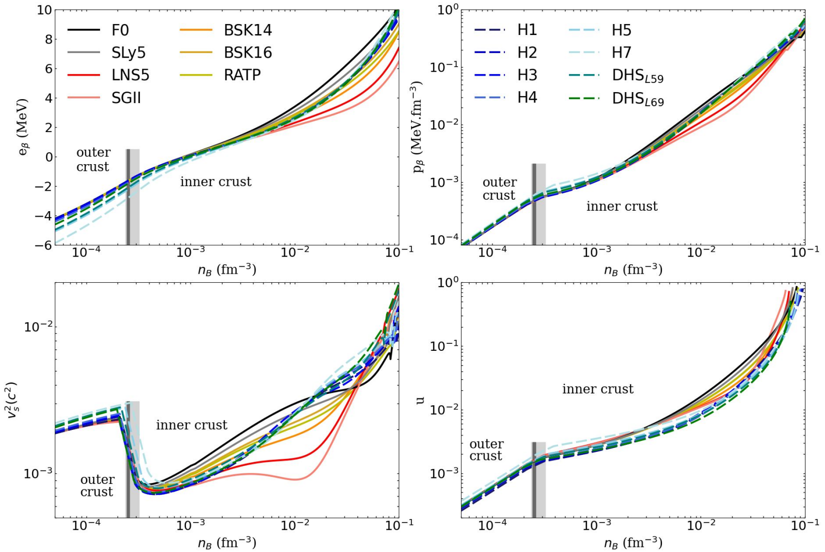




Modeling of the NS crust



G. Grams et al. [incl. RS], EPJA 58 (2022) 3, 56



EFT models perform significantly better than phenomenological interactions in the modeling of the inner crust.

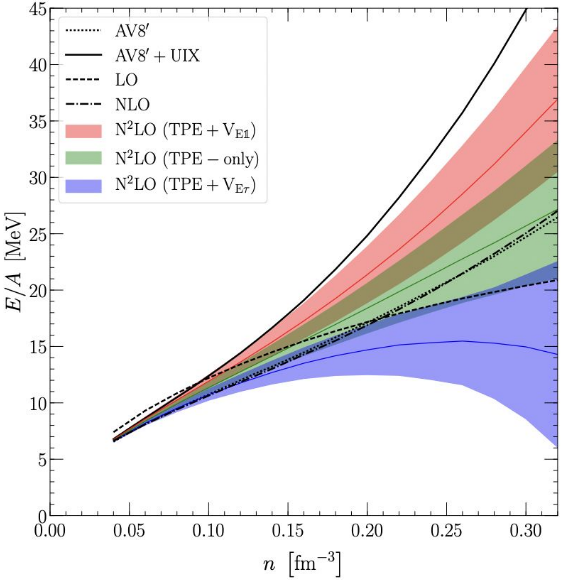
Results for the crust-core transition (n ~ 0.08 fm^{-3}) and the inner-outer crust transition (n ~ 0.002 fm^{-3}) are consistent with other approaches.

Improved chiral interactions for QMC at N^{2}LO

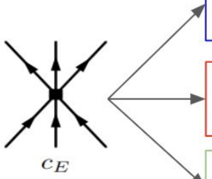
- Quantum Monte Carlo (QMC) methods are among the most accurate many-body methods to solve nuclear systems, but they require local interactions as input.

$$\lim_{\tau \to \infty} e^{-H\tau} |\Psi_T\rangle \to |\Psi_0\rangle$$

where H does not include derivative operators



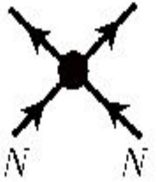
Tews et al., Astrophys.J. 860 (2018) 2, 149



$$V_{E\tau} = \frac{c_E}{\Lambda_\chi F_\pi^4} \sum_{i<j<k} \sum_{\text{cyc}} \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_k \delta_{R_{3N}}(\mathbf{r}_{kj}) \delta_{R_{3N}}(\mathbf{r}_{ij}),$$

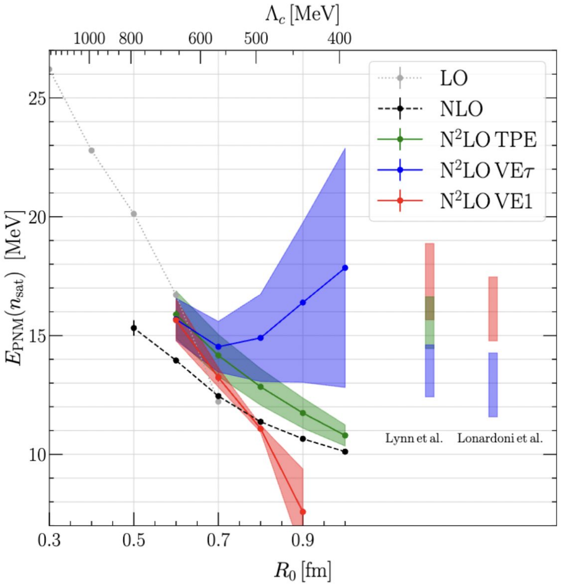
$$V_{E\mathbb{1}} = \frac{c_E}{\Lambda_\chi F_\pi^4} \sum_{i<j<k} \sum_{\text{cyc}} \delta_{R_{3N}}(\mathbf{r}_{kj}) \delta_{R_{3N}}(\mathbf{r}_{ij}),$$

$$V_{E\mathcal{P}} = \frac{c_E}{\Lambda_\chi F_\pi^4} \sum_{i<j<k} \sum_{\text{cyc}} \mathcal{P} \delta_{R_{3N}}(\mathbf{r}_{kj}) \delta_{R_{3N}}(\mathbf{r}_{ij}).$$



$$= \quad \delta(r) \to f_{\text{short}}(r)$$

$$f_{\text{short}}(r) \sim \exp\left(-\left(\frac{r}{R_0}\right)^n\right)$$



Tews et al. [incl. RS], In preparation

Can we do the same at N^3LO?

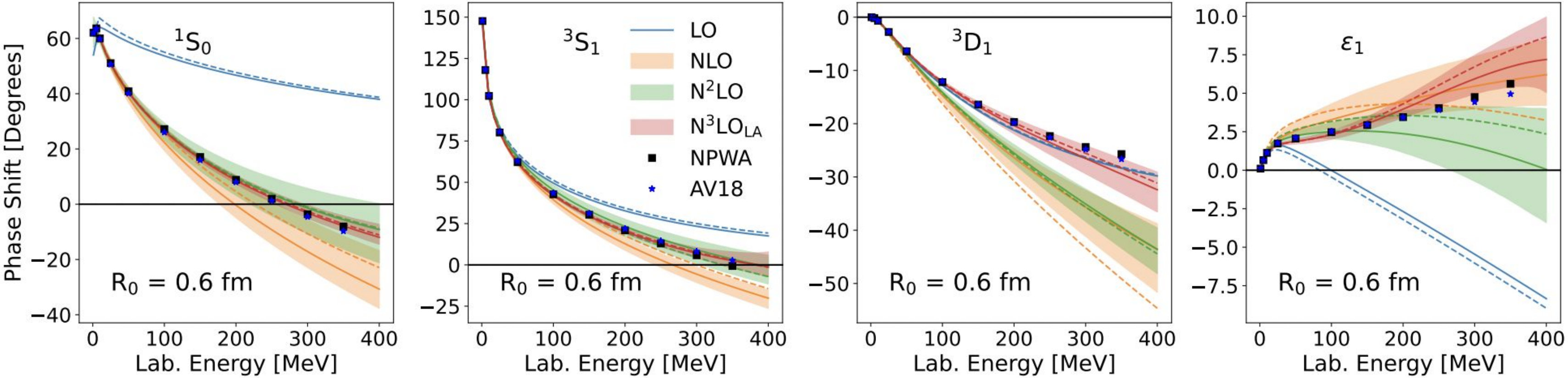
- As the next step, we aim to construct chiral interactions at N^3LO that can be used for QMC calculations. However, the short-range part of the NN interaction contains pieces that are inevitably non-local.

$$H^{\mathrm{N3LO}} = \underbrace{H^{\mathrm{local}}}_{\text{17 operators}} + \underbrace{H^{\text{non-local}}}_{\text{4 operators}}$$

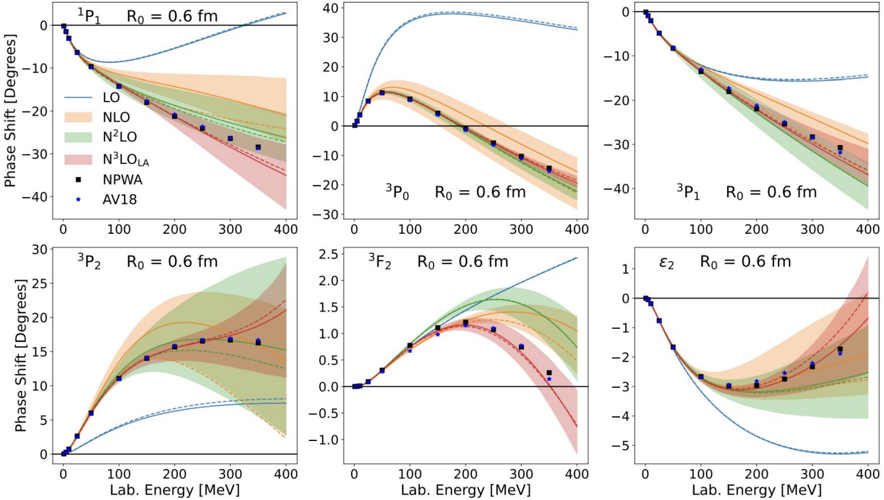
Our idea is to compute H^{local} exactly in QMC and treat $H^{\text{non-local}}$ perturbatively, $\Delta E = \langle\psi_0|H^{\text{non-local}}|\psi_0\rangle$

see talk by A. Gezerlis

RS et al., arXiv:2306.13579



Can we do the same at N^{3}LO?



RS et al., arXiv:2306.13579

The NN interaction is calibrated to scattering data using the method of Bayesian inference. This allows us to incorporate EFT truncation uncertainties using order-by-order calculations.

$$P = \frac{\mathcal{L} \times \Pi}{Z}, \quad \mathcal{L} \propto \prod_i \exp\left\{ -\frac{1}{2}\left(\frac{X_i^{\text{exp}} - X_i^{\text{theo}}}{\sigma_i}\right)^2 \right\},$$

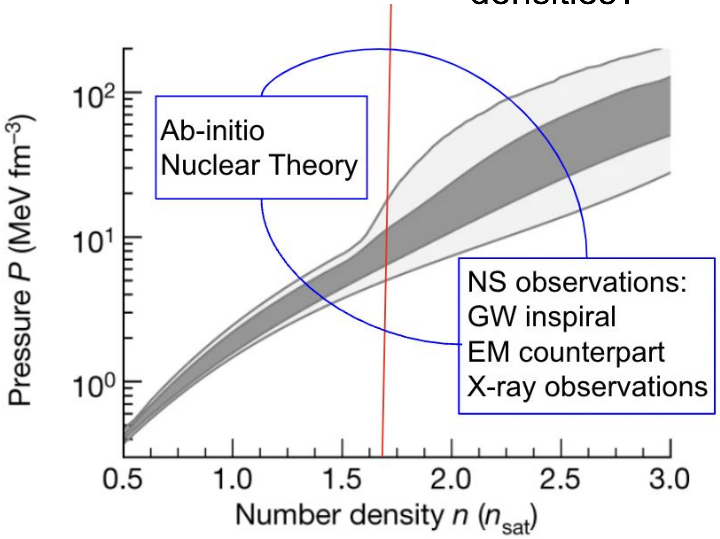
$$\sigma^2 = \sigma^2_{\text{exp}} + \sigma^2_{\text{theo}},$$

$$\Delta X^{\mathrm{N}^j\mathrm{LO}} = Q^{j+2} \max(|c_0|, |c_1|, \ldots, |c_{j+1}|),$$

$$\text{where } Q = \frac{\max(m_\pi, p)}{\min(\Lambda_c, \Lambda_B)} \text{ and } \Lambda_B = 600 \text{ MeV}$$

Uncertainties at $n < 2n_{\text{sat}}$ should decrease by factor 2. So stay tuned!

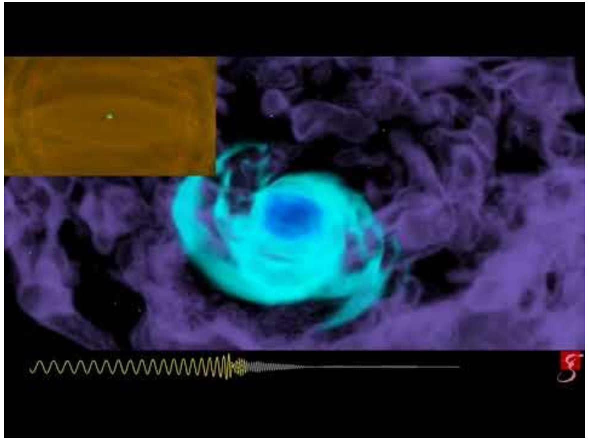
But what the symmetry energy at higher densities?



Ab-initio Nuclear Theory

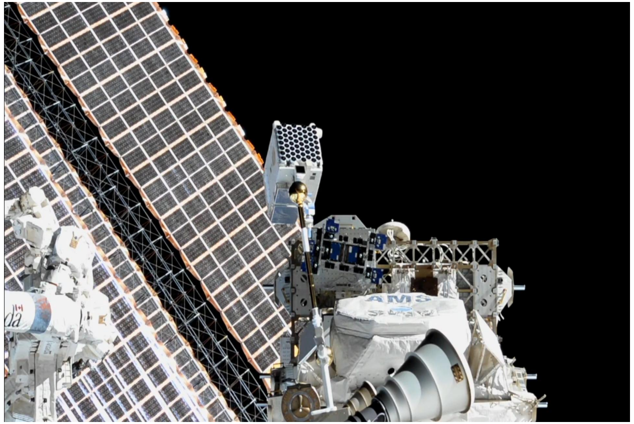
NS observations:
GW inspiral
EM counterpart
X-ray observations

Multi-Messenger NS observations



The first binary NS merger

Virgo GW detector



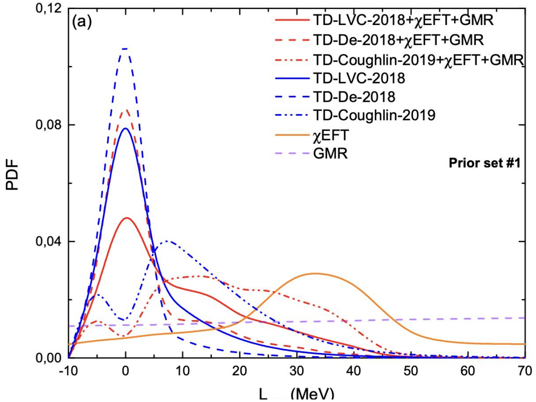
The NICER experiment

Neutron Stars emit Gravitational waves, neutrinos and photons (thermal x-rays, radio waves, etc).

This leads to various observables: Mass, Radius, Tidal Deformability, Angular Momentum, Glitches, Temperature cooling curves, etc

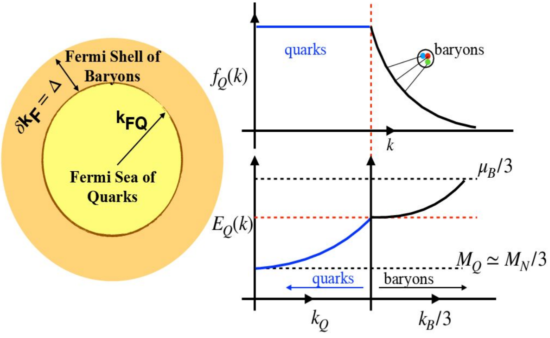
We are living in a new era of NS observations

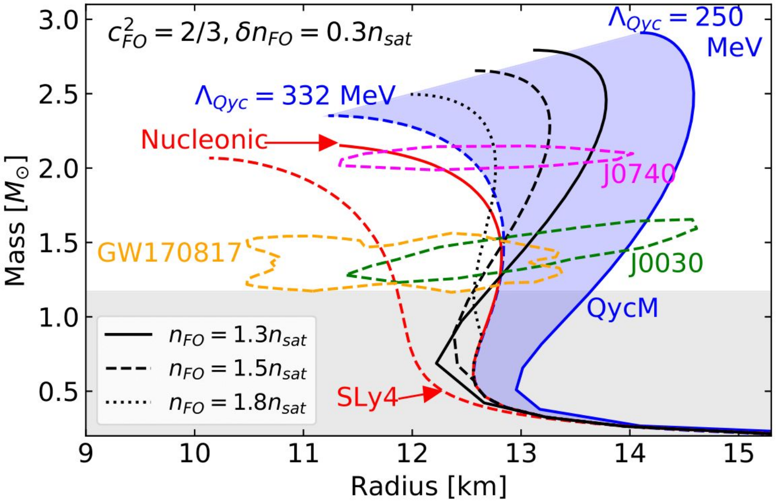
Posterior on Lsym from GW170817 from the metamodel approach

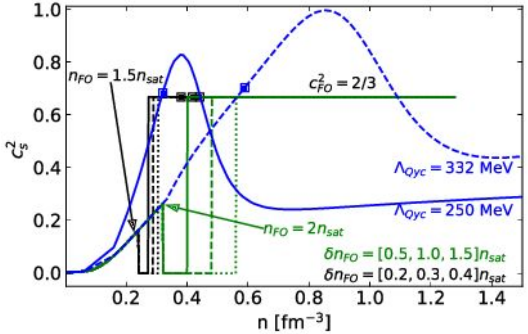


But NS matter does not have to be nucleonic!

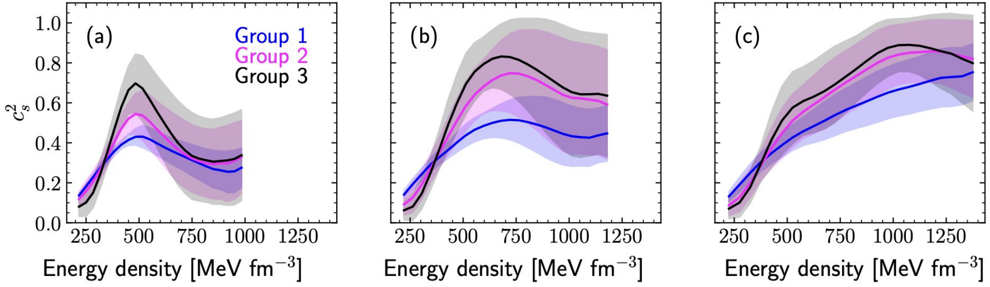
See also the talk by J. Margueron







R. Somasundaram and J. Margueron, EPL 138 (2022) 1, 14002



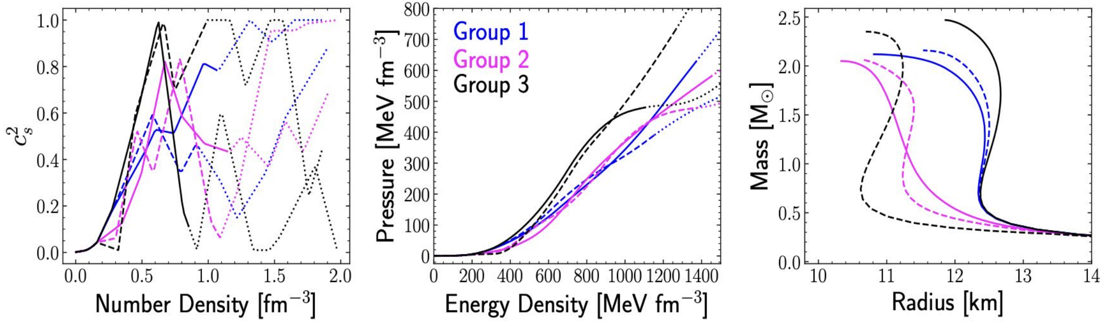
Present astrophysical data are consistent with the nucleonic hypothesis as well as the existence of phase transitions.

Inferences of the symmetry energy from NS observations need to take this into account.

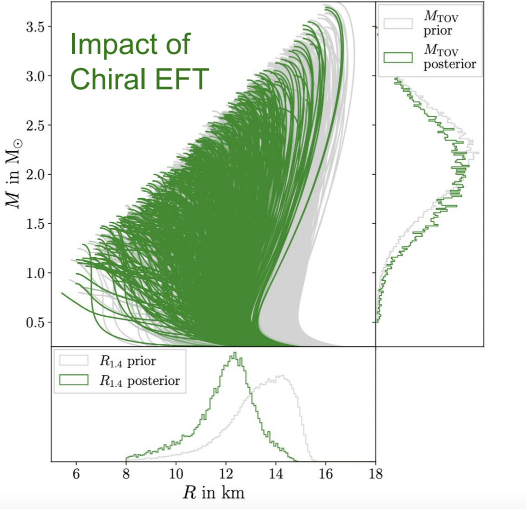
A more conservative approach:

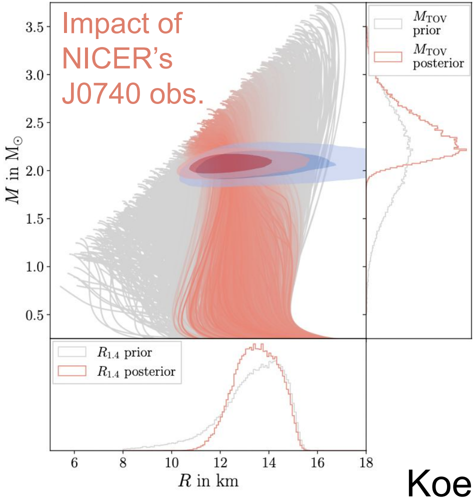
1. Use models with nucleonic degrees of freedom, such as the metamodel, up to a certain ‘breakdown density’.

2. Use composition agnostic models at higher densities such as Gaussian Process or the speed of sound model.



Preliminary





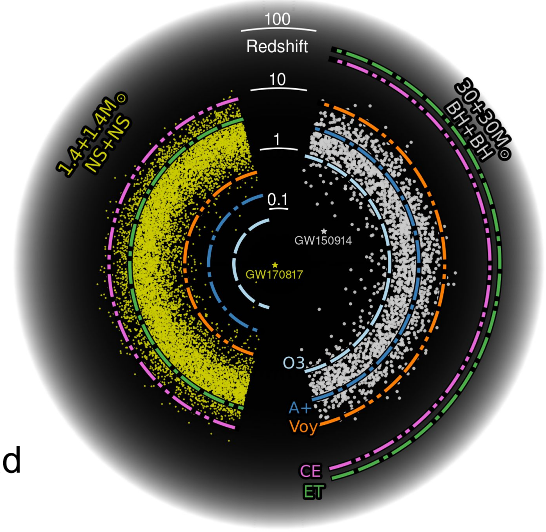
This EOS prior can be used in the Bayesian analysis of multi-messenger astrophysical observations of NSs.

Work is in progress towards extracting the symmetry energy from this analysis.

Koehn et al., In preparation

The future of GW astronomy: Precision measurement of the EOS

- Third generation GW detectors (10x more sensitive) are expected to come online by mid 2030s.
- This will lead to ~300 detections of neutron star mergers with signal-to-noise ratio greater than 100, leading to unprecedented, high-precision measurement of the EOS.

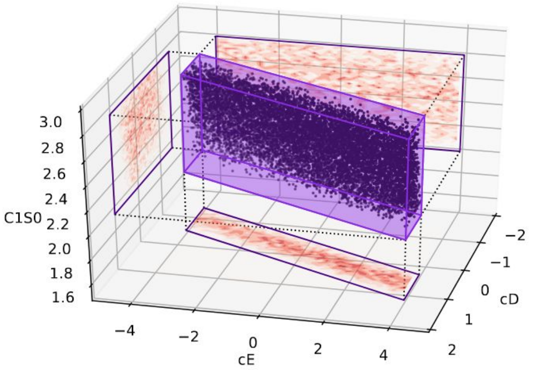


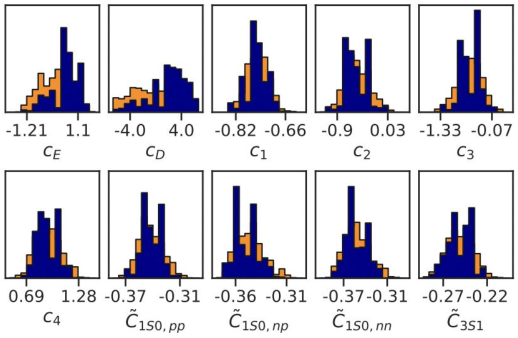
Credits: https://cosmicexplorer.org/

See also the talk by J. Read

<u>What do we need from the nuclear physics community?</u>

Efficient emulators for the fast determination of many body observables (the EOS). This is required for a full propagation of nuclear uncertainties via Bayesian methods.





W.G. Jiang et al., 2212.13216

An Injection study of a year's worth of 3G GW detections

- We inject GW signals into a network of 3 next gen. GW detectors using 3 different EOSs.

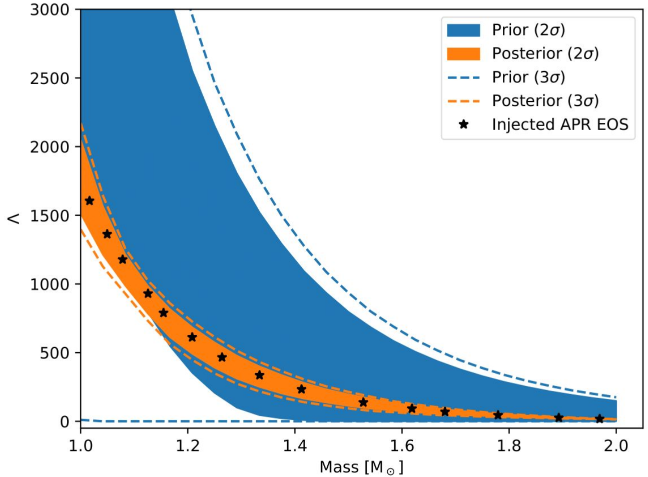
- The GW signals are analysed using ~ 10^4 samples calibrated to A=2-4 observables. This constitutes our prior. Each sample is given a GW likelihood using Bayesian statistics. This results in posteriors on all EOS parameters

EOS input

$$P(\boldsymbol{d}|\boldsymbol{\theta}) \propto \prod_i \int P(d_i|\mathcal{M}, q, \tilde{\Lambda})\, \pi(\mathcal{M}, q, \tilde{\Lambda}|\boldsymbol{\theta})\, d\mathcal{M}\, dq\, d\tilde{\Lambda}.$$

GW likelihood of EOS sample $\boldsymbol{\theta}$

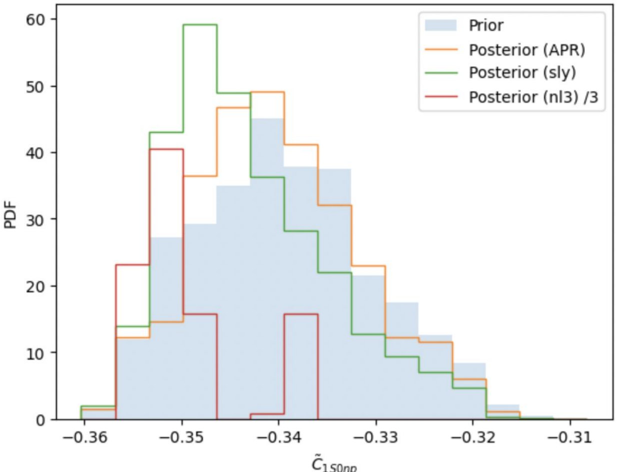
GW data

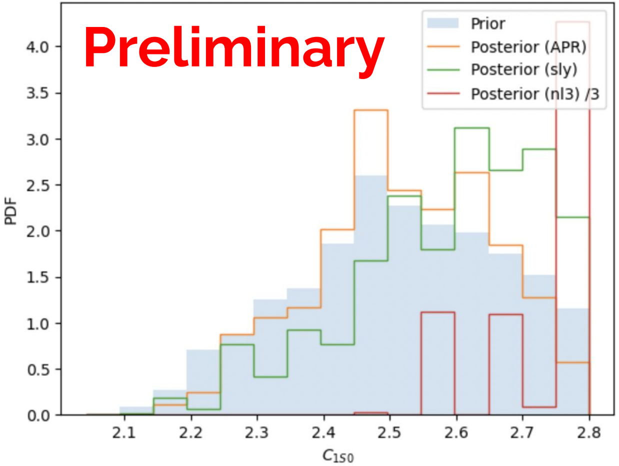


RS et al., In preparation

- Marginalizing over the high-density EOS, leads to posterior over the LECs.

- In the future, we will be able to calibrate subleading 3N, 4N and possibly YN couplings to NSs.

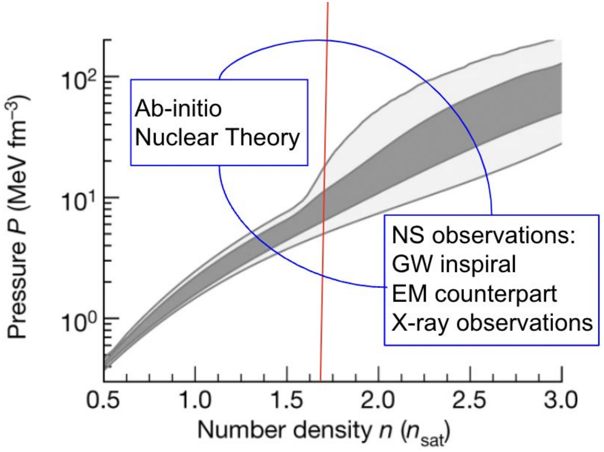




Conclusions and outlook

Nuclear theory:

- We have developed methods to combine powerful DFT approaches such as the metamodel with ab-initio chiral EFT methods. Work is in progress towards calibrating relativistic DFTs that have implications for PREX and CREX.
- We have developed novel (maximally) local chiral interactions at N^2LO (NN+3N) and N^3LO (NN) for quantum monte carlo calculations. We can expect a factor 2 reduction in uncertainties in the near future.



Applications to astrophysics:

- Combining DFT and chiral EFT approaches is important to extract the symmetry energy from multi-messenger NS observations.
- We have also shown how efficient emulators can help in the analysis of astrophysical observations of NSs. The ‘golden age’ of GW astronomy will allow us to measure the nuclear interaction and calibrate subleading 3N, 4N and possibly YN LECs to astrophysical data.

Thank You!