Session 3: Nuclear matter theory and challenges at higher density (15 min)

Christian Drischler (drischler@ohio.edu)

The future of neutron-rich matter: from neutron skins to neutron stars

ACFI Workshop | October 14, 2022

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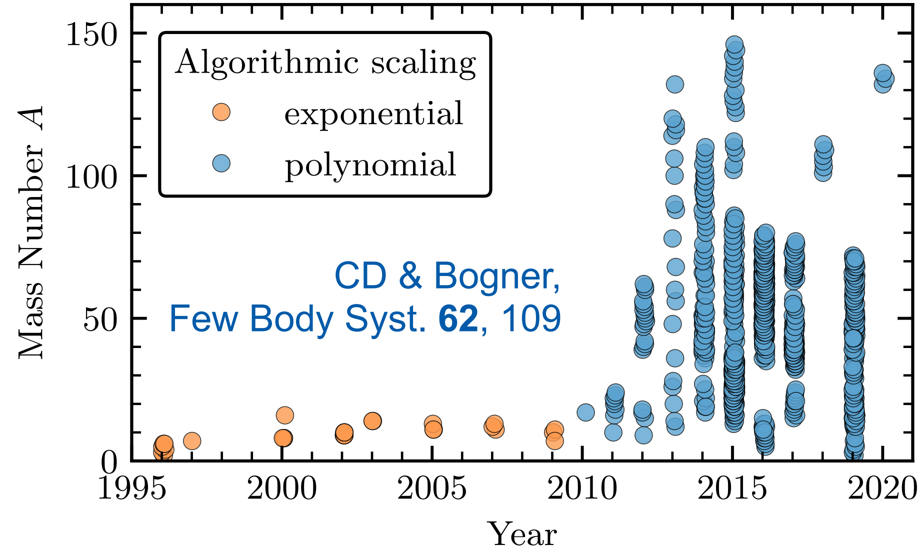
BUQEYE Collaboration

Goals for today:

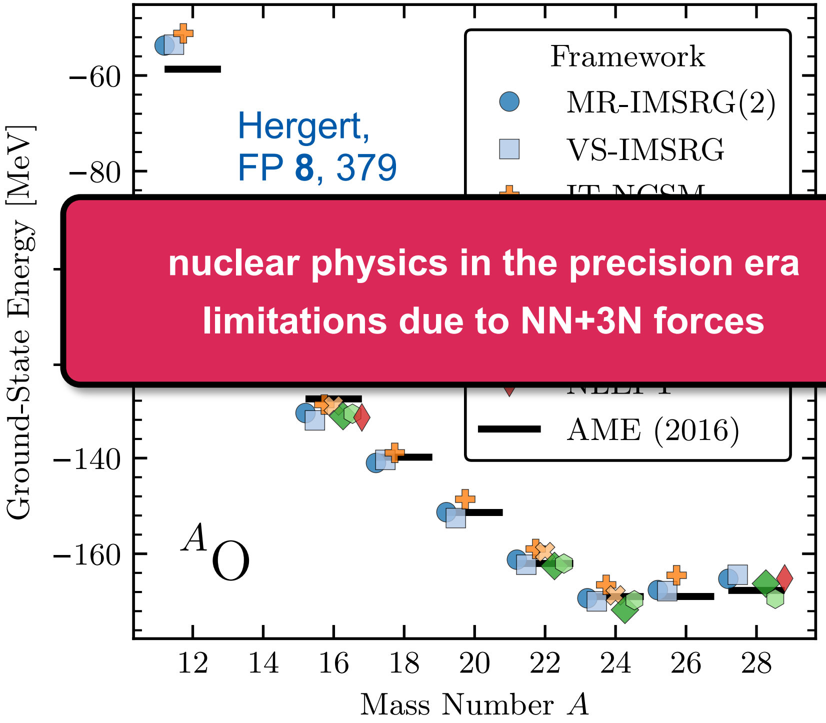
- Introduction of **chiral EFT**
- Current **state of the art of ab initio methods** and their differences
- The art and science of **estimating errors**
- How would **neutron skin measurements** guide, refine, or validate theory?

Facility for Rare Isotope Beams
at Michigan State University

Major process: CEFT, many-body theory, and UQ!



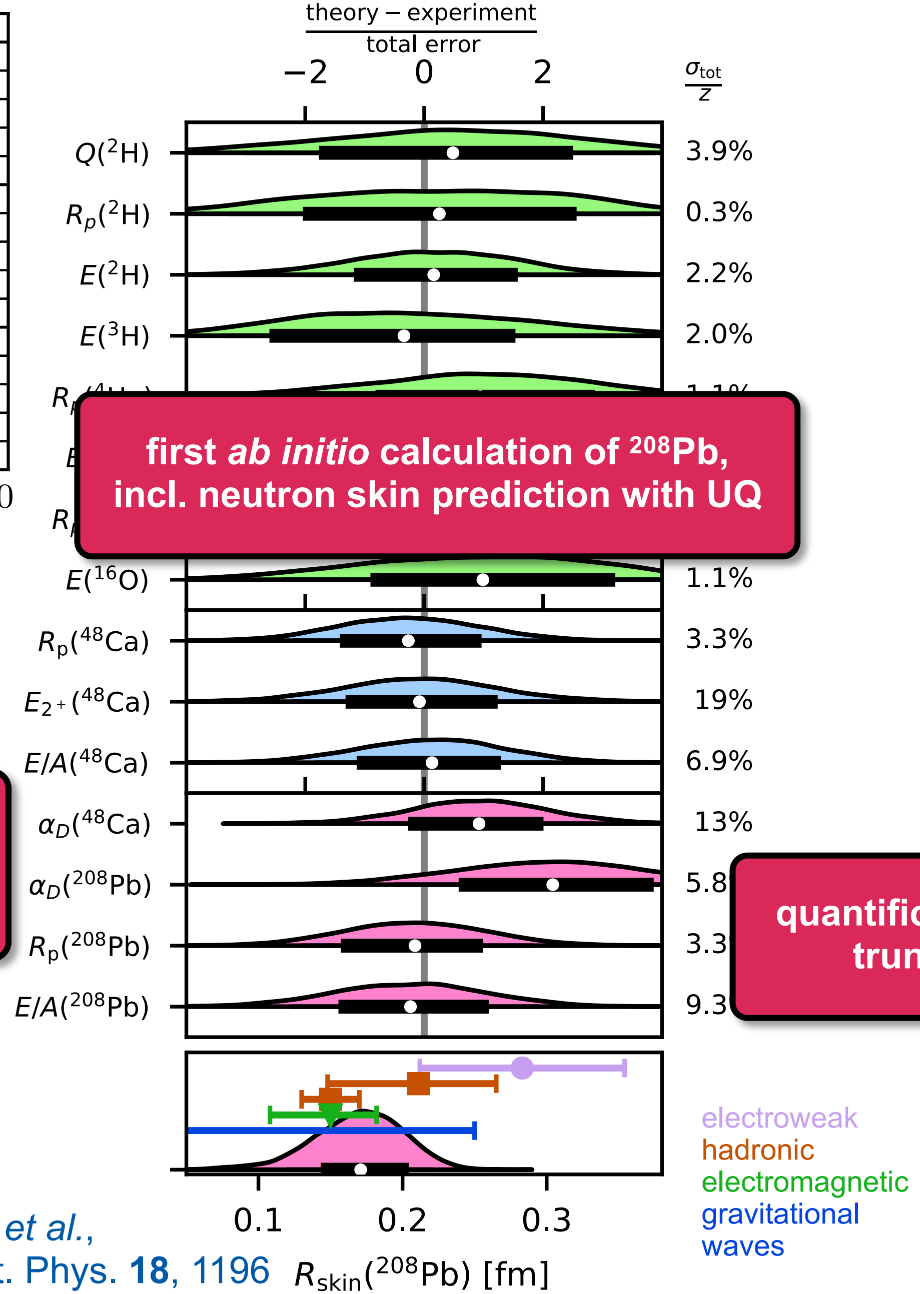
CD & Bogner, Few Body Syst. **62**, 109



Hergert, FP **8**, 379

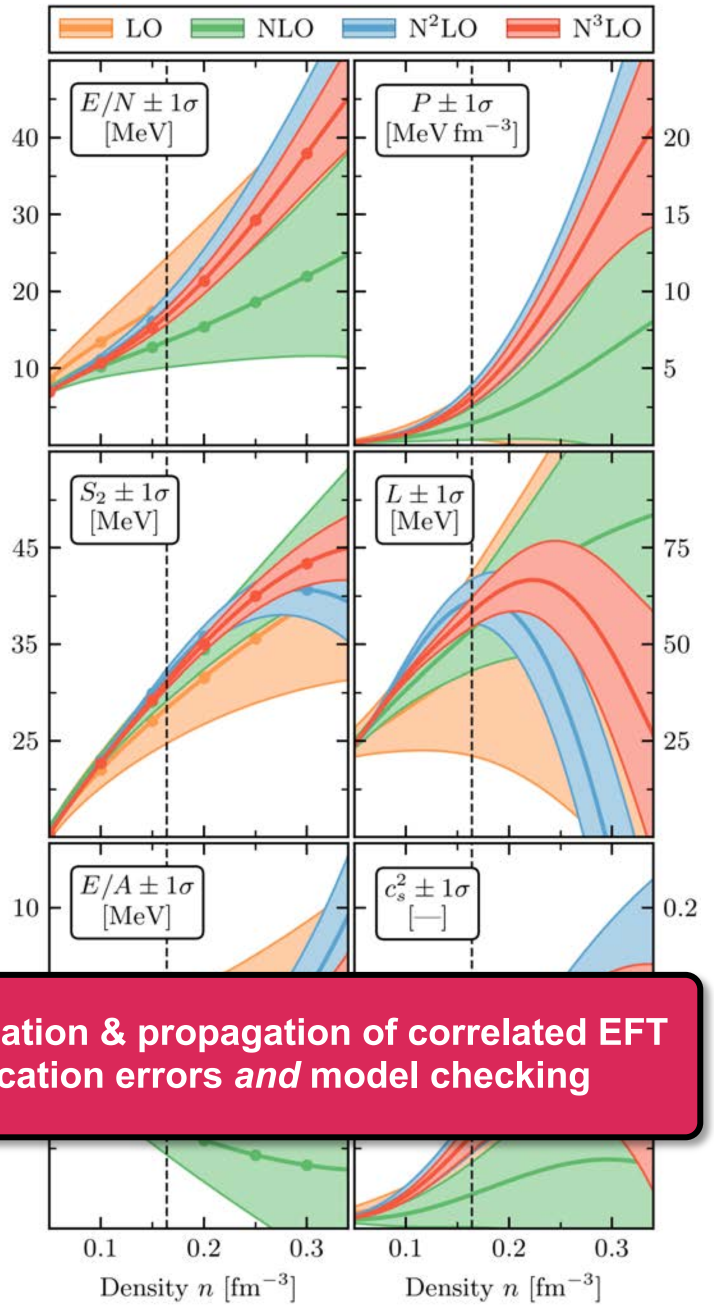
nuclear physics in the precision era

limitations due to NN+3N forces



first *ab initio* calculation of ^{208}Pb, incl. neutron skin prediction with UQ

Hu *et al.*, Nat. Phys. **18**, 1196



quantification & propagation of correlated EFT truncation errors *and* model checking

CD, Furnstahl, Melendez, Phillips, PRL **125**, 202702

Quantifying theoretical uncertainties

next ISNET meeting:
May 22-26, 2023, WashU, St. Louis

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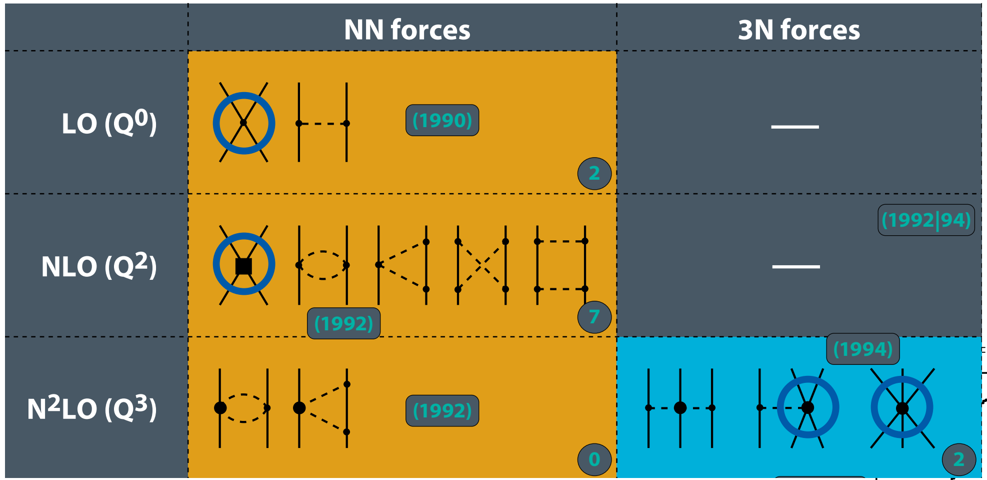
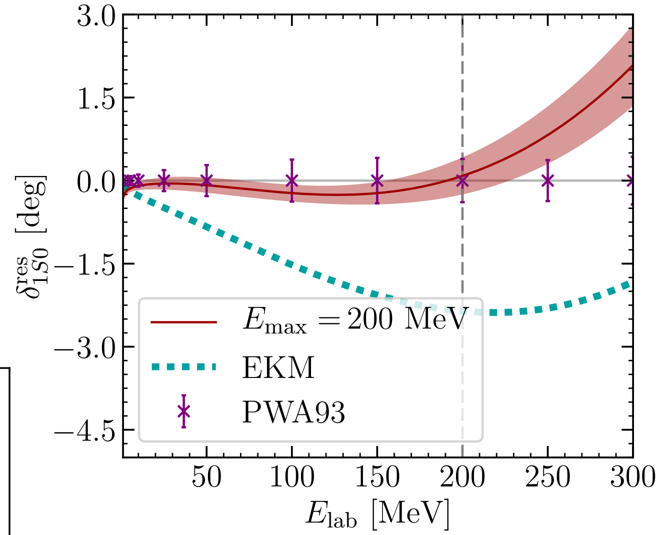
Sources of uncertainty (LEC):

- **experimental data (LEC fits)**
- EFT truncation errors
- computational method





Bayesian statistics is a powerful framework for EFT-based UQ. Everything is a pdf.

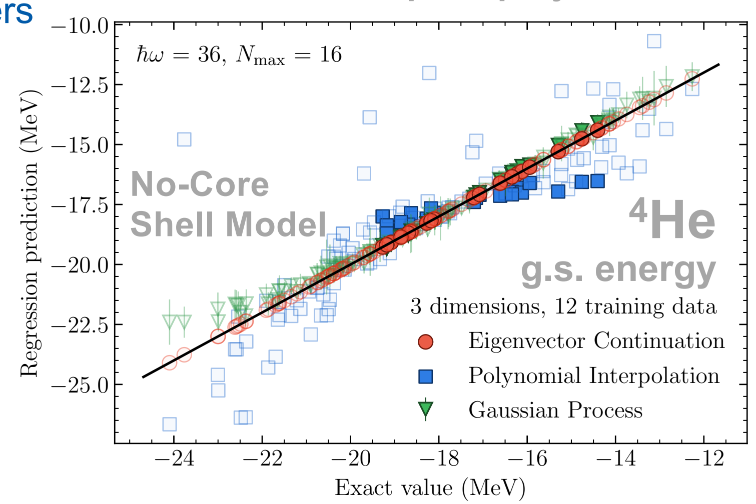
- **parameter estimation**
- model comparison
- sensitivity analysis

BUQEYE
Chalmers
ISNET

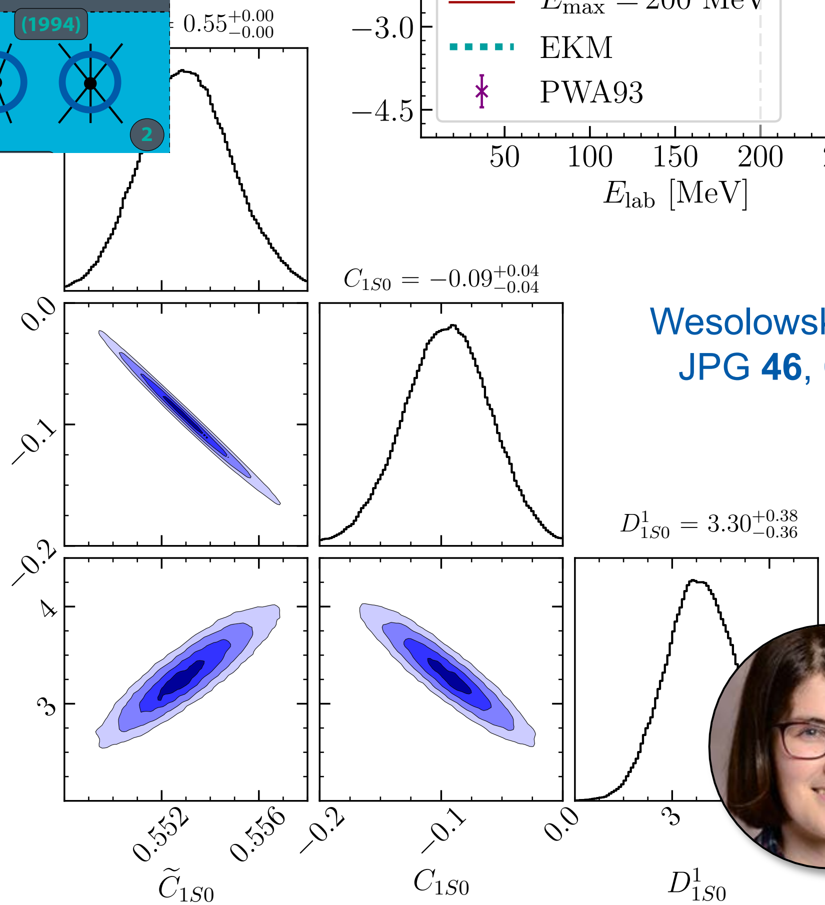
fast & accurate emulators enable applications of Bayesian methods (MC sampling)

Melendez, CD *et al.*, JPG **49**, 102001
CD, Quinonez *et al.*, PLB **823**, 136777
Giuliani *et al.*, arXiv:2209.13039

Efficient subspace projection



König, Ekström *et al.*, PLB **810**, 135814



Wesolowski *et al.*, JPG **46**, 045102

First chiral NN+3N potentials (up to N^2LO) with full Bayesian UQ

Wesolowski, Svensson *et al.*, PRC **104**, 064001

First rigorous uncertainty quantification

CD, Furnstahl, Melendez, and Phillips, PRL **125**, 202702

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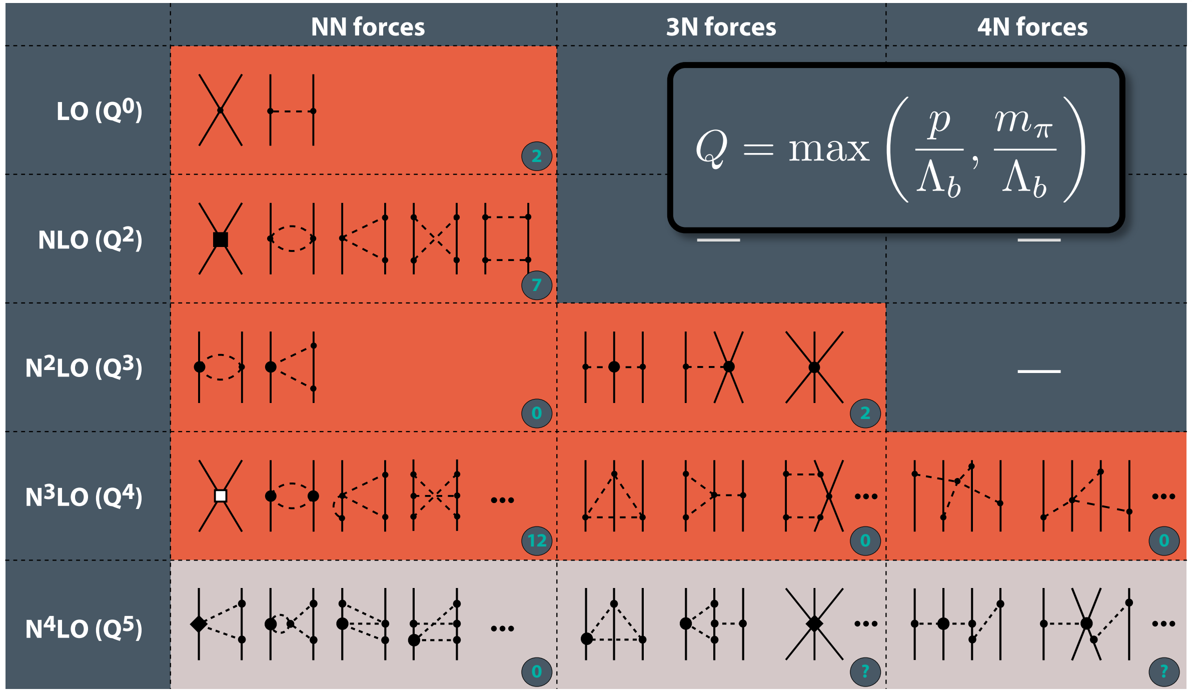
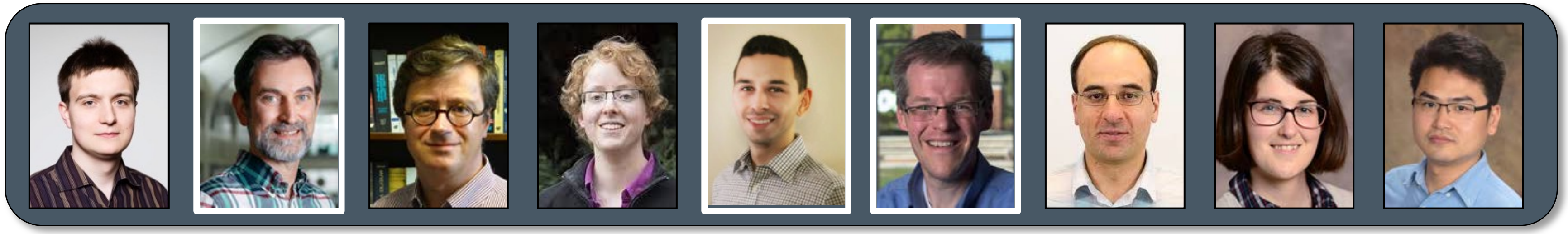


$\{y_0, y_2, y_3, \ldots, y_k\}$ — **predict observable *y* order by order in the chiral expansion**

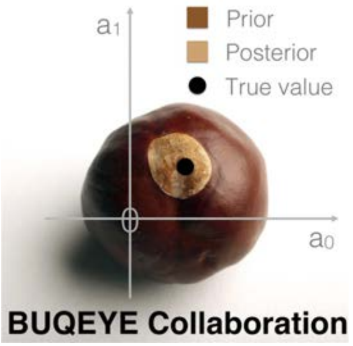
$y_k = y_{\text{ref}} \sum_{n=0}^{k} c_n Q^n$ — **make a *falsifiable* model assumption for the convergence pattern**

$\mathcal{GP}\left[0, \bar{c}^2\, r(x, x'; l)\right]$ — **treat all c_n as independent draws from a single Gaussian Process**

$\delta y_k = y_{\text{ref}} \sum_{n=k+1}^{\infty} c_n Q^n$ — **learn hyperparameters of that GP & compute to-all-orders truncation error**



Open-source software & tutorials (Jupyter): https://buqeye.github.io



Bayesian Uncertainty Quantification: Errors for Your EFT

First rigorous uncertainty quantification

CD, Furnstahl, Melendez, and Phillips, PRL **125**, 202702

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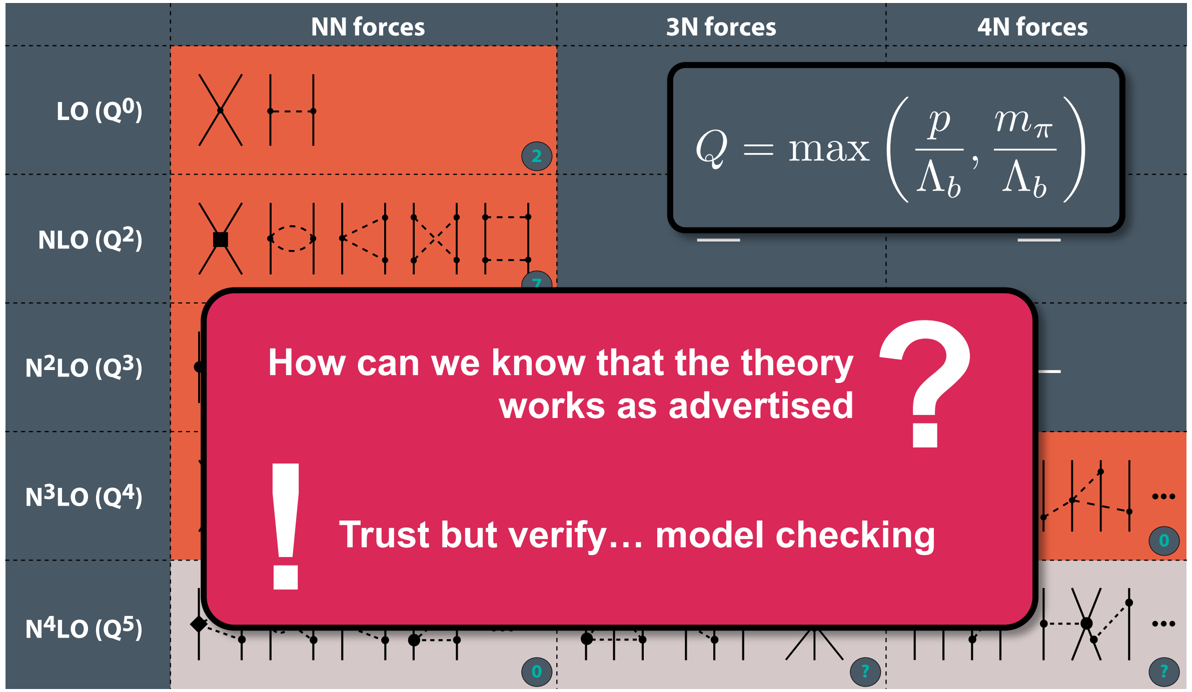


$$Q = \max\left(\frac{p}{\Lambda_b}, \frac{m_\pi}{\Lambda_b}\right)$$

How can we know that the theory works as advertised **?**

! Trust but verify… model checking

$$\{y_0, y_2, y_3, \dots, y_k\}$$

predict observable *y* order by order in the chiral expansion

$$y_k = y_{\mathrm{ref}} \sum_{n=0}^{k} c_n Q^n$$

make a *falsifiable* model assumption for the convergence pattern

$$\mathcal{GP}\left[0, \bar{c}^2\, r(x, x'; l)\right]$$

treat all c_n as independent draws from a single Gaussian Process

$$\delta y_k = y_{\mathrm{ref}} \sum_{n=k+1}^{\infty} c_n Q^n$$

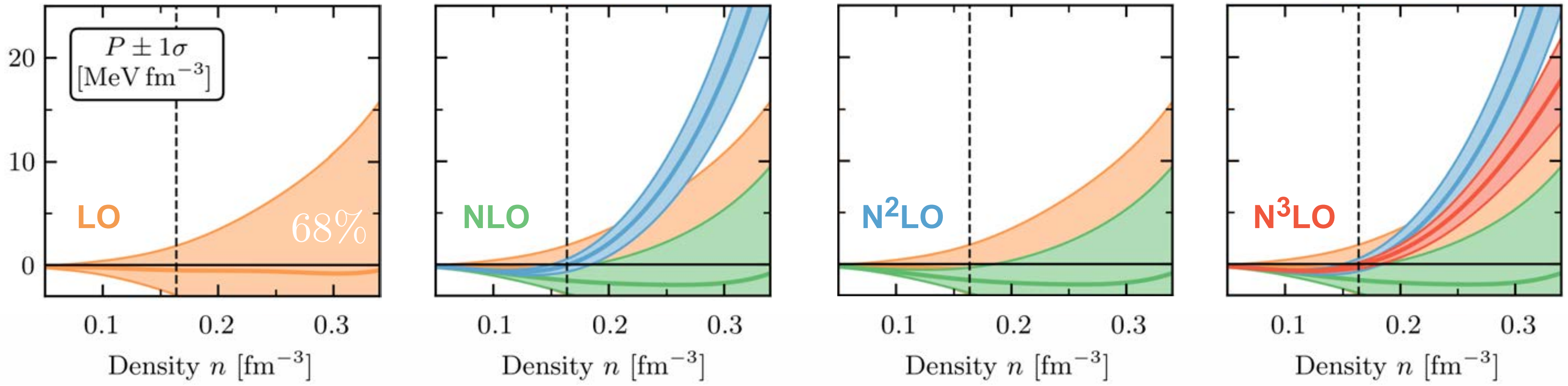
learn hyperparameters of that GP & compute to-all-orders truncation error

An example: symmetric matter

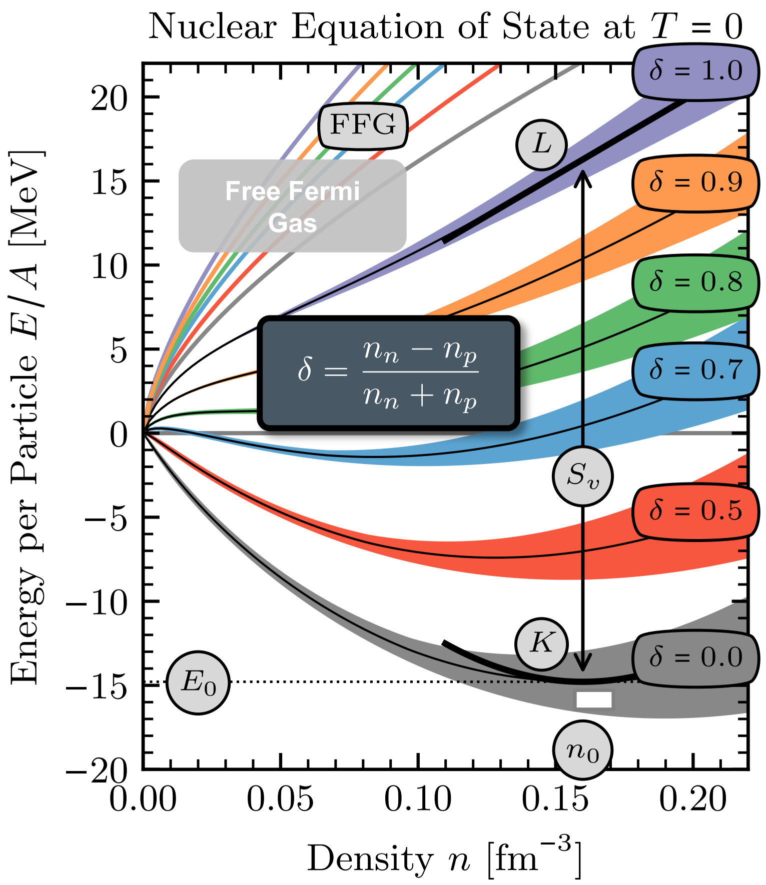
$$y = P \equiv n^2 \frac{\mathrm{d}}{\mathrm{d}n}\frac{E}{A}, \quad k = 4$$

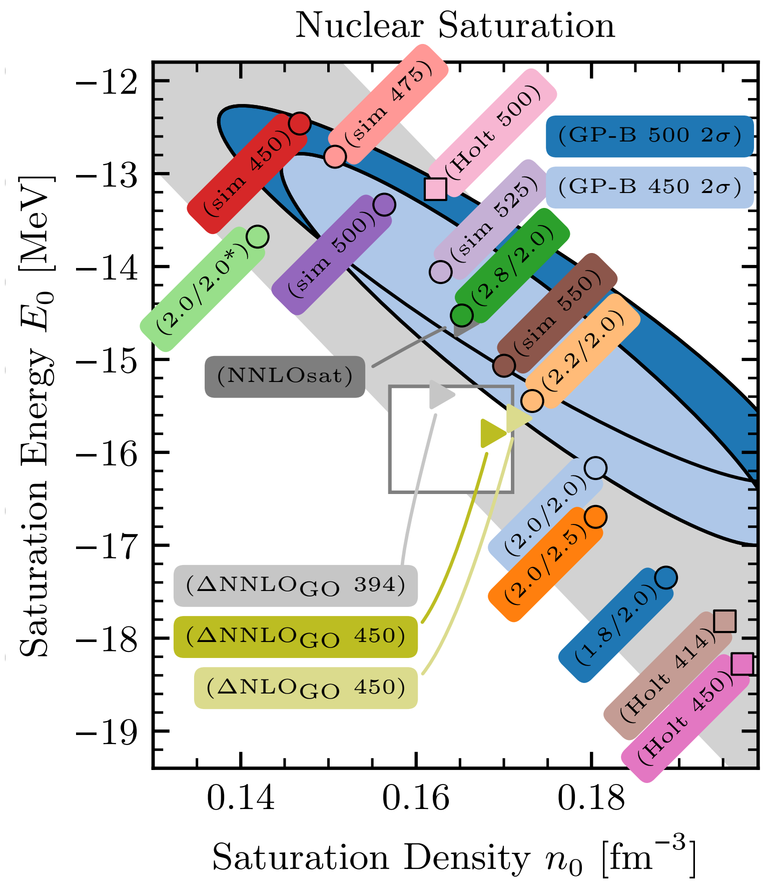
Uncertainty bands depict 68% credibility regions

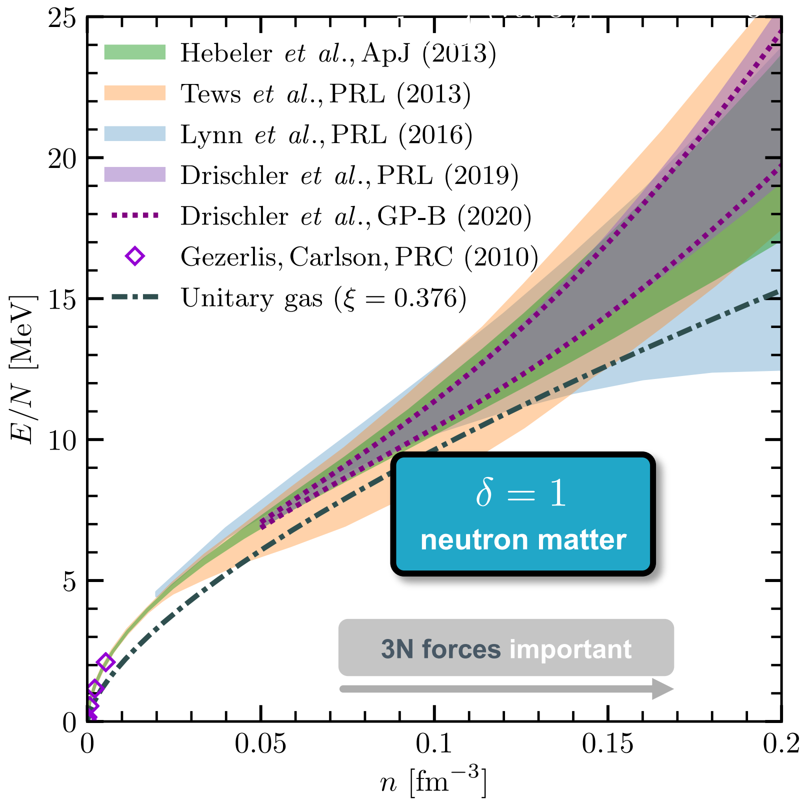
$$y = y_k + \delta y_k$$



Neutron matter | nuclear saturation







CD, Holt, and Wellenhofer, Annu. Rev. Nucl. Part. Sci. **71**, 403

Huth *et al.*, PRC **103**, 025803

saturation point: **fine-tuned cancellation** between the kinetic and interaction contributions (ideal testbed for chiral EFT)

Coester band overlaps with the empirical box (but limited meaning without errors)

Annotations: (λ / Λ_{3N}) in fm^{-1} or (Λ) in MeV

neutron matter below saturation density is **well-constrained** by NN scattering phase shifts

Nuclear symmetry energy

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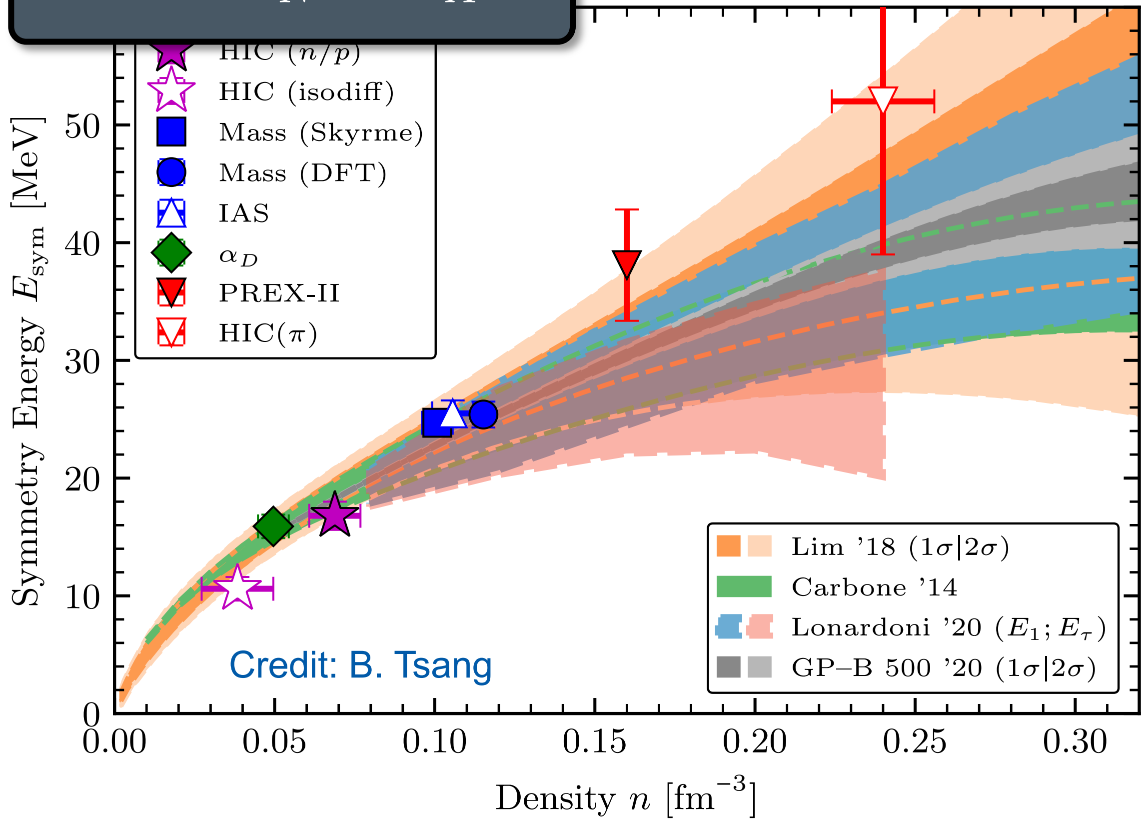
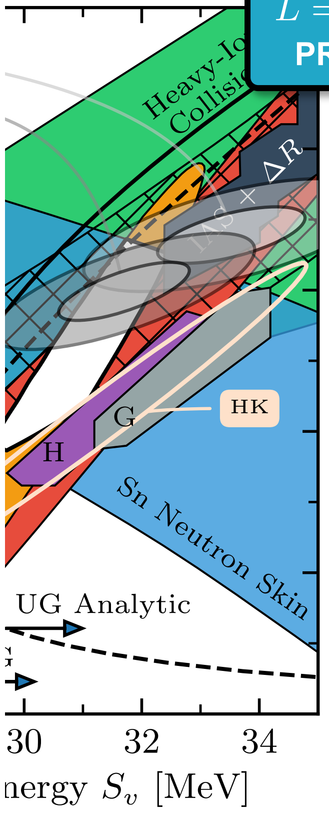
$$E_{\rm sym}(n) \approx \frac{E}{N}(n) - \frac{E}{A}(n)$$

(not all at the same density)

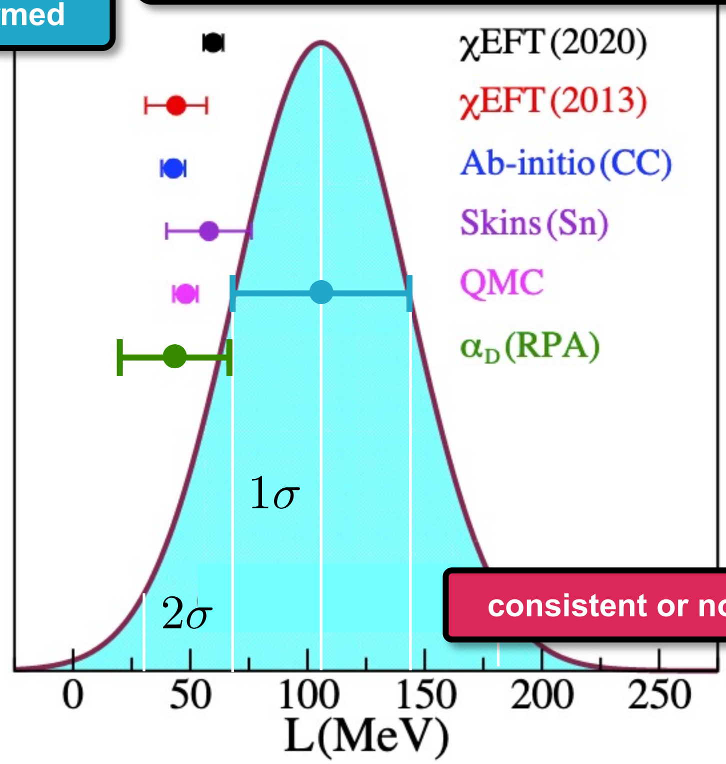
$$S_2(n) \equiv S_v + \frac{L}{3}\left(\frac{n-n_0}{n_0}\right) + \ldots$$

$L = 106 \pm 37\,\text{MeV}$
PREX–II informed





CD, Holt *et al.*, ARNPS **71**, 403
Lattimer & Lim, APJ **771**, 51



consistent or not?

Reinhard *et al.*, PRL **127**, 232501
Reed, Fattoyev *et al.*, PRL **126**, 172503
Piekarewicz, PRC **104**, 024329

$$\text{pr}(S_v, L\,|\,\mathcal{D}) = \int \text{pr}(S_v, L\,|\,\mathcal{D}, n_0)\, \text{pr}(n_0\,|\,\mathcal{D})\, dn_0$$

$$\text{pr}(n_0\,|\,\mathcal{D}) \approx 0.17 \pm 0.01\,\text{fm}^{-3}$$

Correlations are important: uncertainties can be smaller than one *might* naively think

"Tension" between PREX-II and different theoretical approaches at the ~68-95% level

Neutron skins in ^{48}Ca & ^{208}Pb (*ab initio*)

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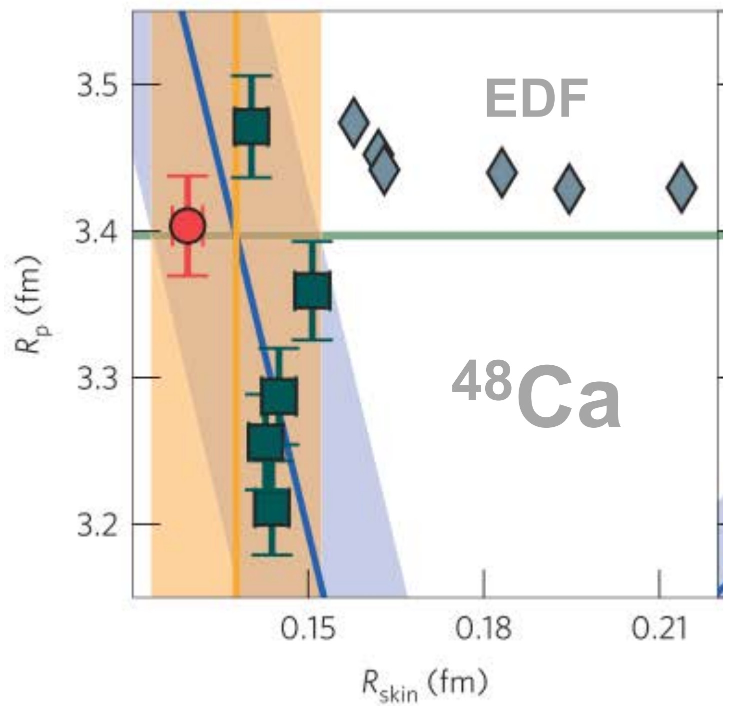
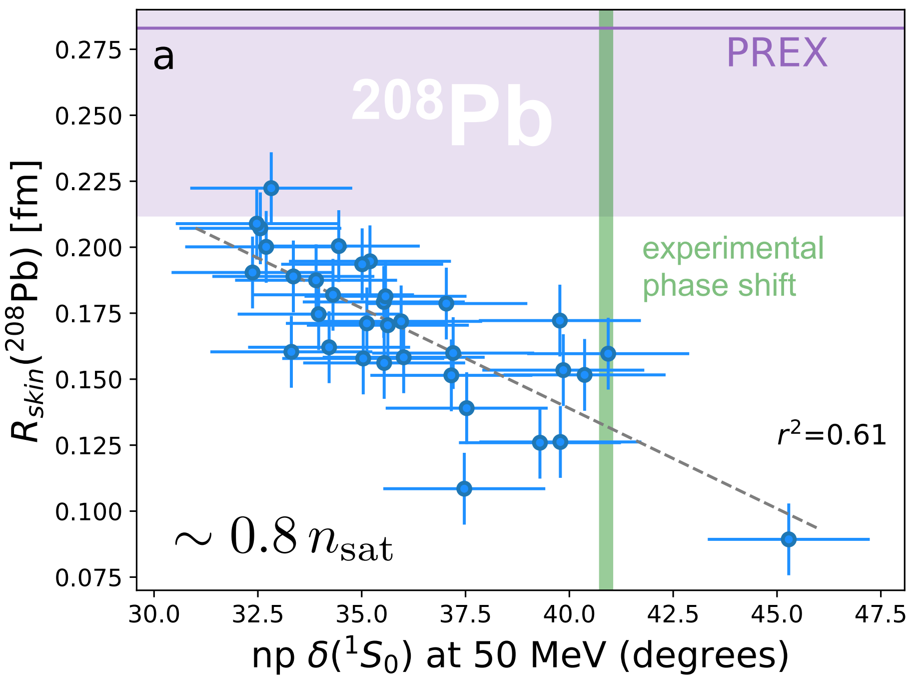
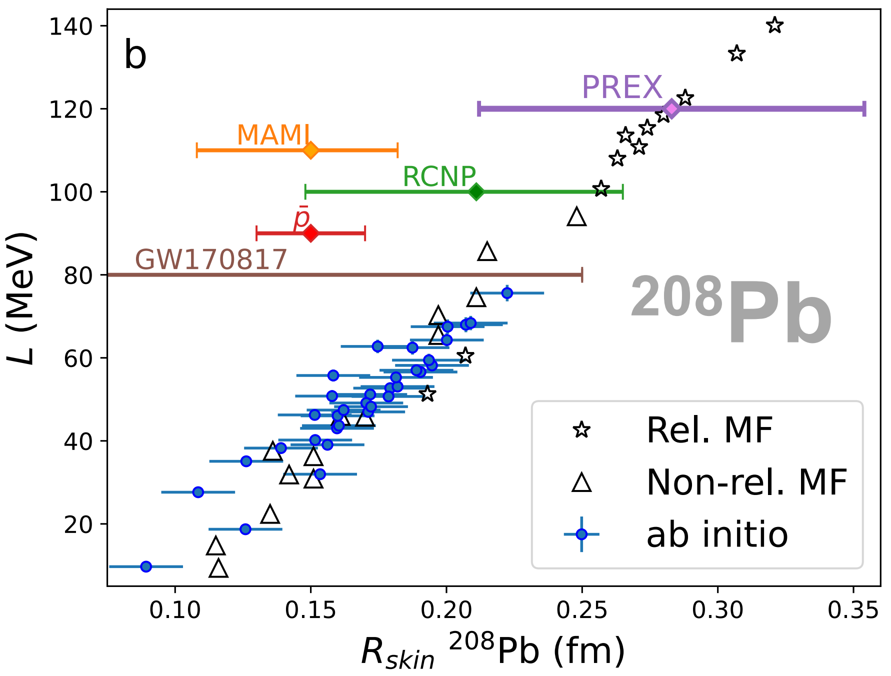
$0.12 \lesssim R_{\rm skin}^{48} \lesssim 0.15\,{\rm fm}$

$0.14 \lesssim R_{\rm skin}^{208} \lesssim 0.20\,{\rm fm}$







Hagen *et al.*, Nat. Phys. **12**, 186

Hu, Jiang, Miyagi *et al.*, Nat. Phys. **18**, 1196

***ab initio* calculations predict small neutron skins in ^{48}Ca,** in agreement with CREX

Adhikari *et al.* (CREX), PRL **129**, 042501

predicted dipole polarizability agrees with experiment

Birkhan *et al.*, PRL **118**, 252501

uncertainty quantification via history matching: 34 non-implausible NN+3N interactions found

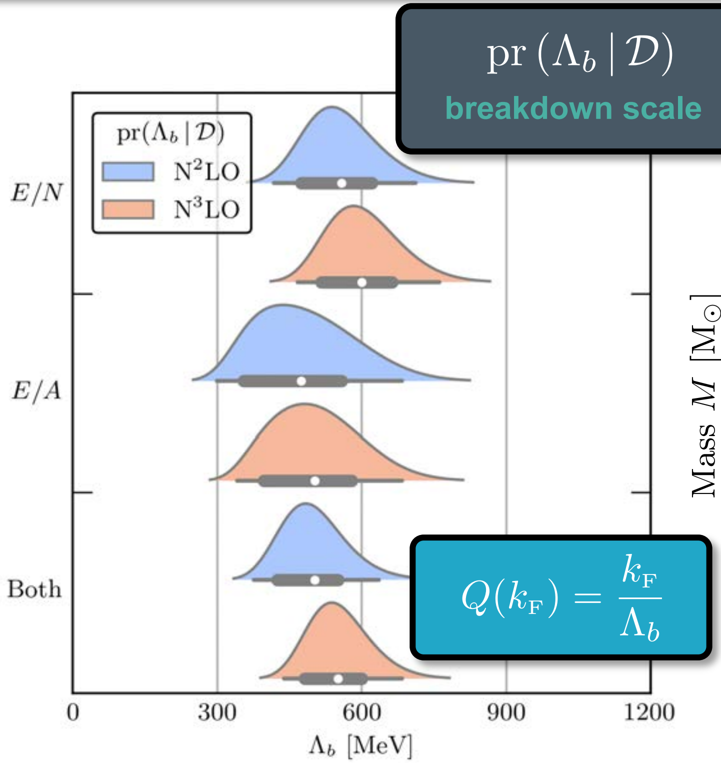
incl. EFT and method uncertainties

correlations found with $^1S_0$ (np) scattering phase shifts at $E_{\rm lab}$ = 50 MeV

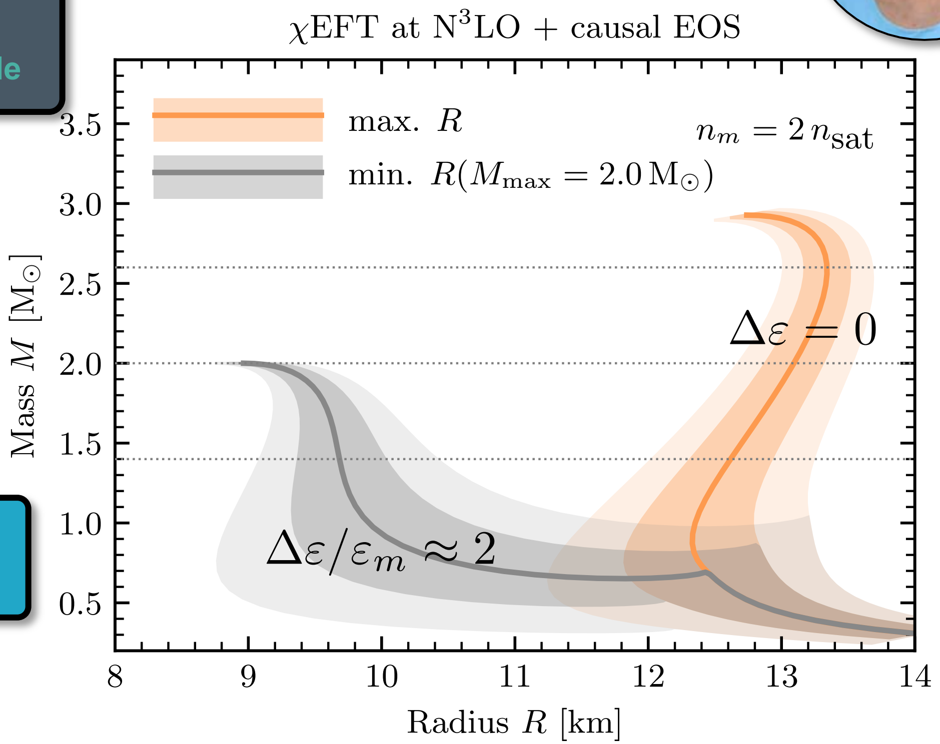
constraints on neutron skins with **uncertainties of ±0.03 fm (or better)** are very important

future: MREX @ MESA

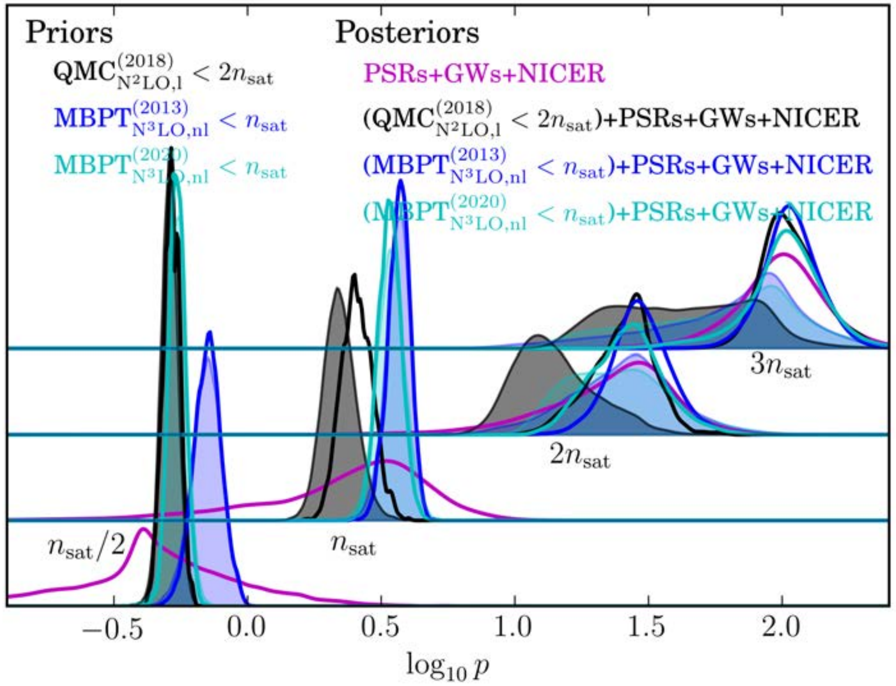
Exploring the limits of chiral EFT



CD, Melendez *et al.*, PRC **102**, 054315



CD, Han, Lattimer *et al.*, PRC **103**, 045808
CD, Han, and Reddy, PRC **105**, 035808



Essick, Tews *et al.*, PRC **102**, 055803

Bayesian inference of the in-medium **breakdown scale** (and **correlations lengths**)

But: at what *density* does chiral EFT break down?

derived **bounds on the neutron star radius** (and sound speed) assuming chiral EFT is valid up to a given critical density (here: $2n_0$)

could already be challenged by NICER

$R_{2.0} = (11.4 - 16.1)$ km — Riley *et al.*, AJL **918**, L27; Miller *et al.*, AJL **918**, L28

comparison to ***theory-agnostic* EOS constraints** provides further insights

observations could be used for:

model checking & selection of chiral EFT

constraining LECs in nuclear forces

Ab initio predictions for SNM at intermediate densities

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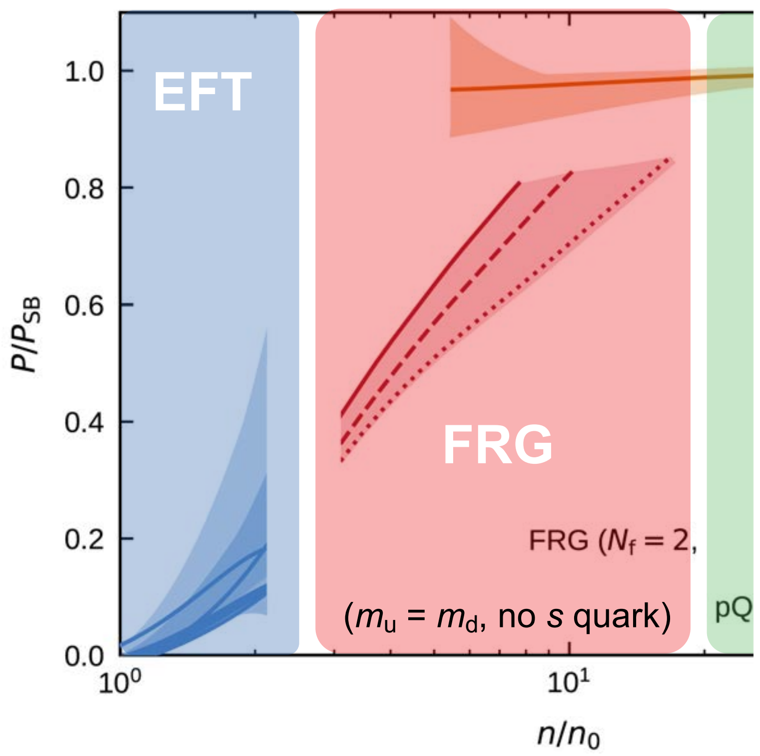

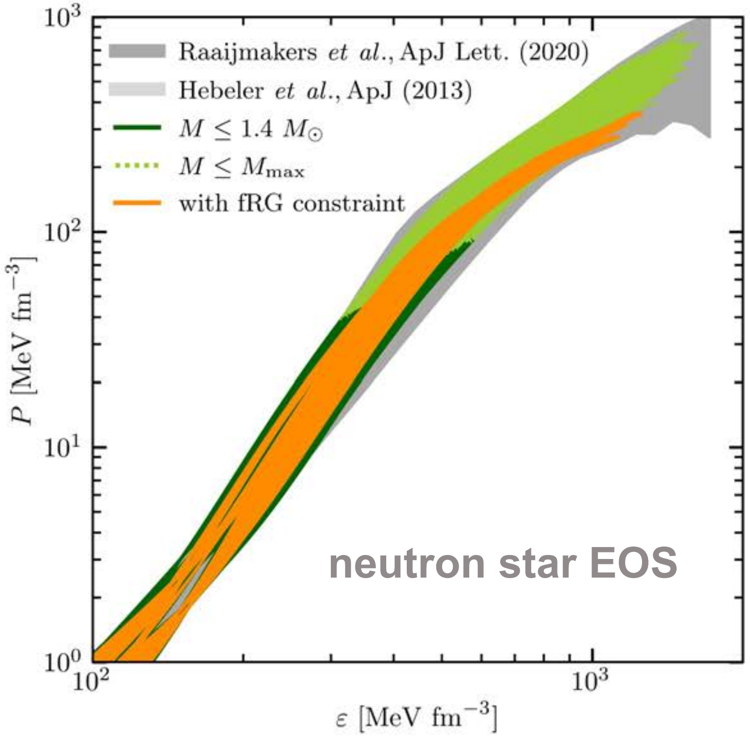

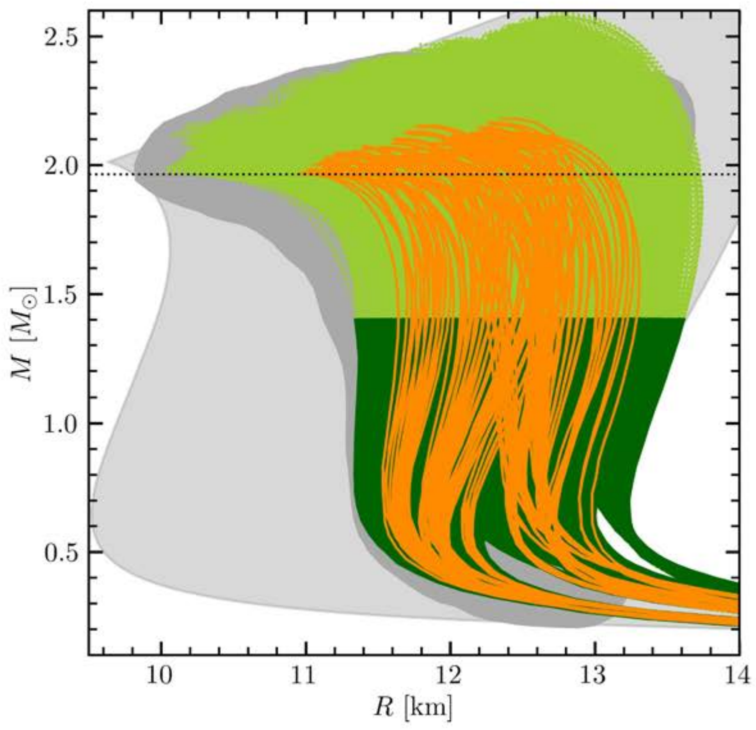

Leonhardt, Pospiech, Schallmo, Braun, CD, Hebeler, and Schwenk, PRL **125**, 142502

Huth, Wellenhofer, and Schwenk, PRC **103**, 025803

Functional Renormalization Group (based on QCD action):
ab initio constraints at intermediate densities (~3—10n_0)

suggests that the different density regions can be straightforwardly combined

remarkable consistency between theory predictions, experiment, and astrophysics

for neutron star matter, see: Braun & Schallmo, arXiv:2204.00358

Ab initio workflow (idealized)

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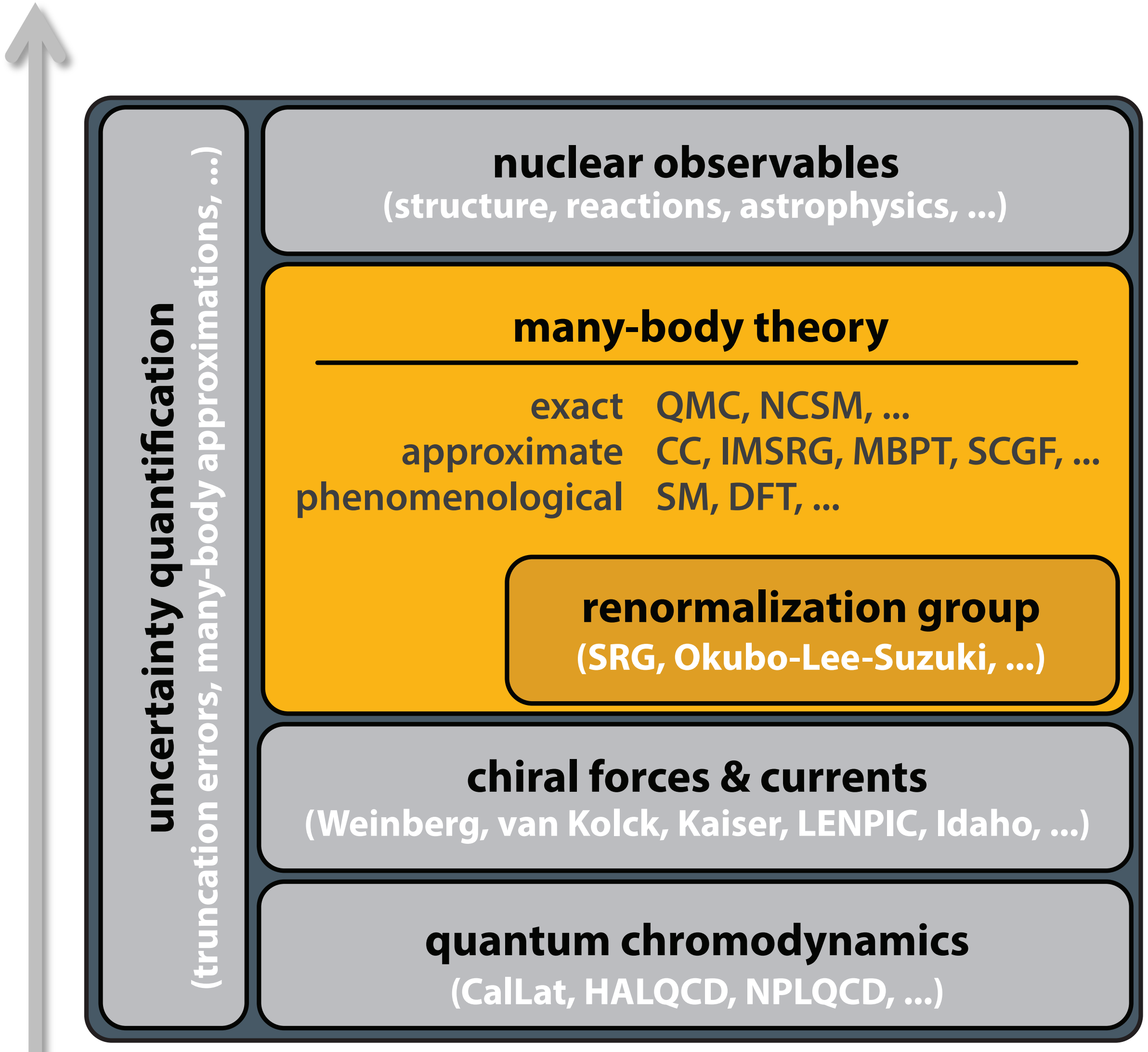

CD & Bogner, Few Body Syst. **62**, 109

Here: nuclear equation of state (EOS)

energy per particle (and derived quantities)

$$\frac{E}{A}(n, \delta, T)$$

baryon density n
neutron excess δ
temperature T

Here: many-body perturbation theory (MBPT)

computationally efficient method (HPC-friendly)
allows to estimate many-body uncertainties

Widely applicable:

- ✓ arbitrary proton fractions
- ✓ finite temperature
- ✓ optical potentials, linear response, nuclei, …

RG methods for softening nuclear interactions

Other frameworks include **quantum Monte Carlo**, coupled cluster, and self-consistent Green's functions

Renaissance of MBPT

CD, Hebeler, Schwenk, PRL **122**, 042501
CD, McElvain *et al.*, in prep.

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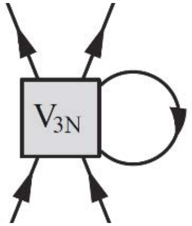
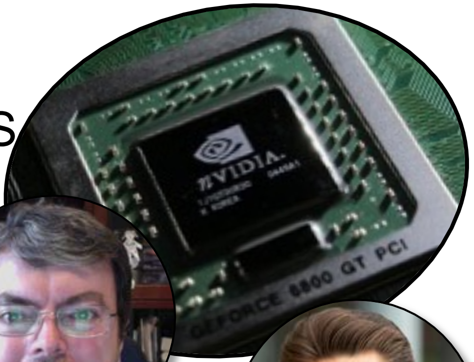
Efficient evaluation of MBPT diagrams

with **NN**, **3N**, and **4N forces**



- **implementation of arbitrary diagrams** has become **straightforward** (numerically exact)
- ...ved VEGAS
- ...eractions
- propagation of importance sampling distributions
- **controlled evaluation of 1000s of MBPT diagrams**

novel many-body methods in nuclear physics: diagrammatic Monte Carlo ?




Application to dilute Fermi gas:
Wellenhofer, CD, Schwenk, PRC **104**, 014003 & PLB **802**, 135247

Arthuis *et al.*,
Comput. Phys. **240**, 202

high-order MBPT calculations of the EOS

automated code generation

analytic expressions interaction & MBPT diagrams

automated diagram generation

More details? Recent review article

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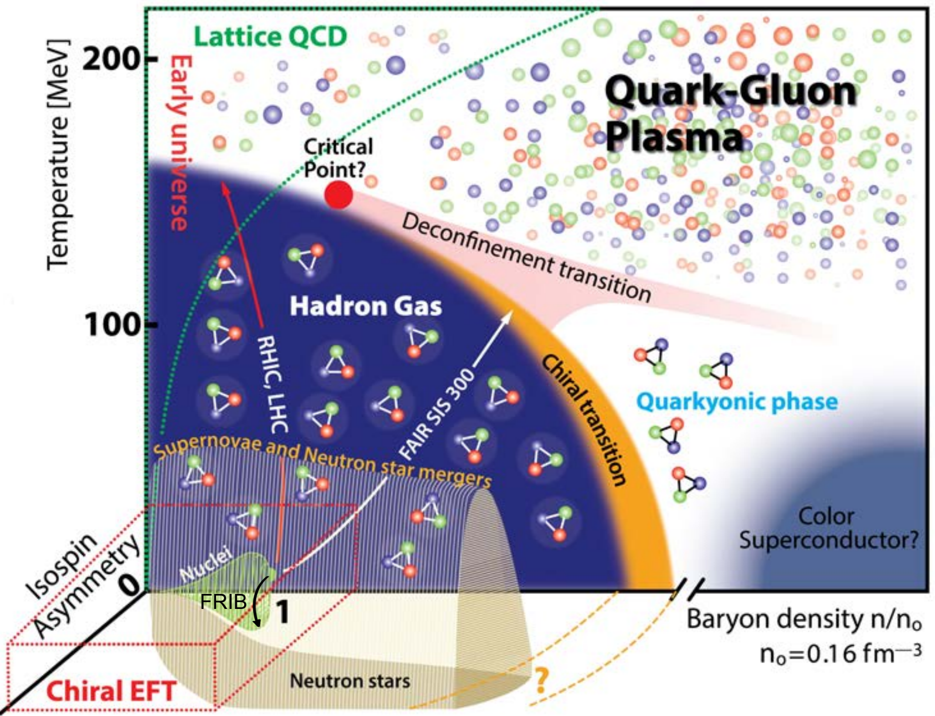

Chiral Effective Field Theory and the High-Density Nuclear Equation of State

Annual Review of Nuclear and Particle Science

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Keywords:

Chiral EFT | neutron stars | MBPT
nuclear matter at zero and finite temperature
Bayesian uncertainty quantification
recent neutron star observations

see also in the same journal:
James Lattimer, Annu. Rev. Nucl. Part. Sci. **71**, 433

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Take-away points

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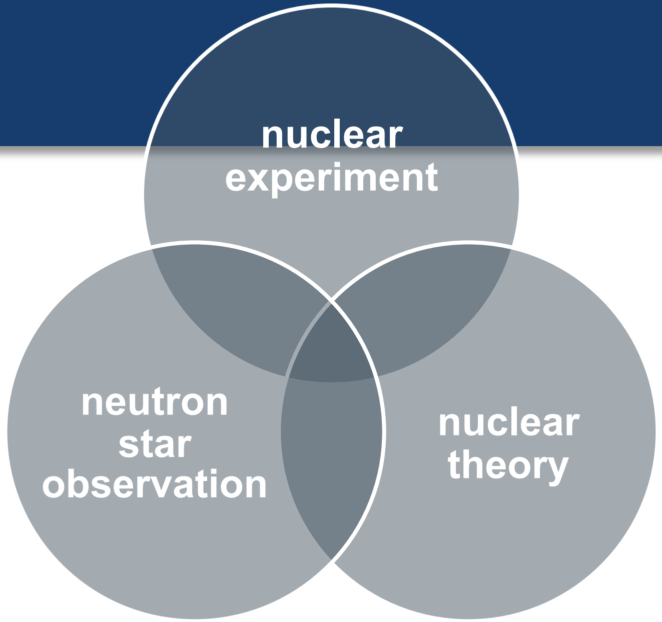
multi-messenger
nuclear precision
FRIB
} **era**



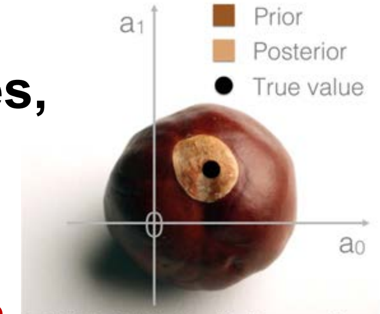
great **potential for discoveries**

unique opportunity to obtain a **fundamental understanding** of strongly interacting matter

1. **Chiral EFT enables microscopic calculations with quantified uncertainties up to about $2n_{sat}$. PNM is well constrained at sub-saturation densities.**

2. **Bayesian methods: powerful tools for quantifying & propagating correlated uncertainties in EFT-based calculations (*model checking* is important).**

3. **Automated MBPT: efficient EOS calculations across a wide range of densities, isospin asymmetries, and temperatures, as well as nuclear interactions.**



BUQEYE Collaboration

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