Implications of the nuclear EOS with quantified uncertainties for neutron stars

Christian Drischler

FRIB Theory Alliance Annual Meeting – 2022 Low Energy Community Meeting
August 9, 2022

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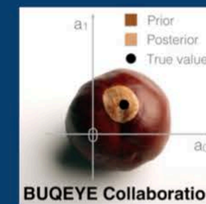

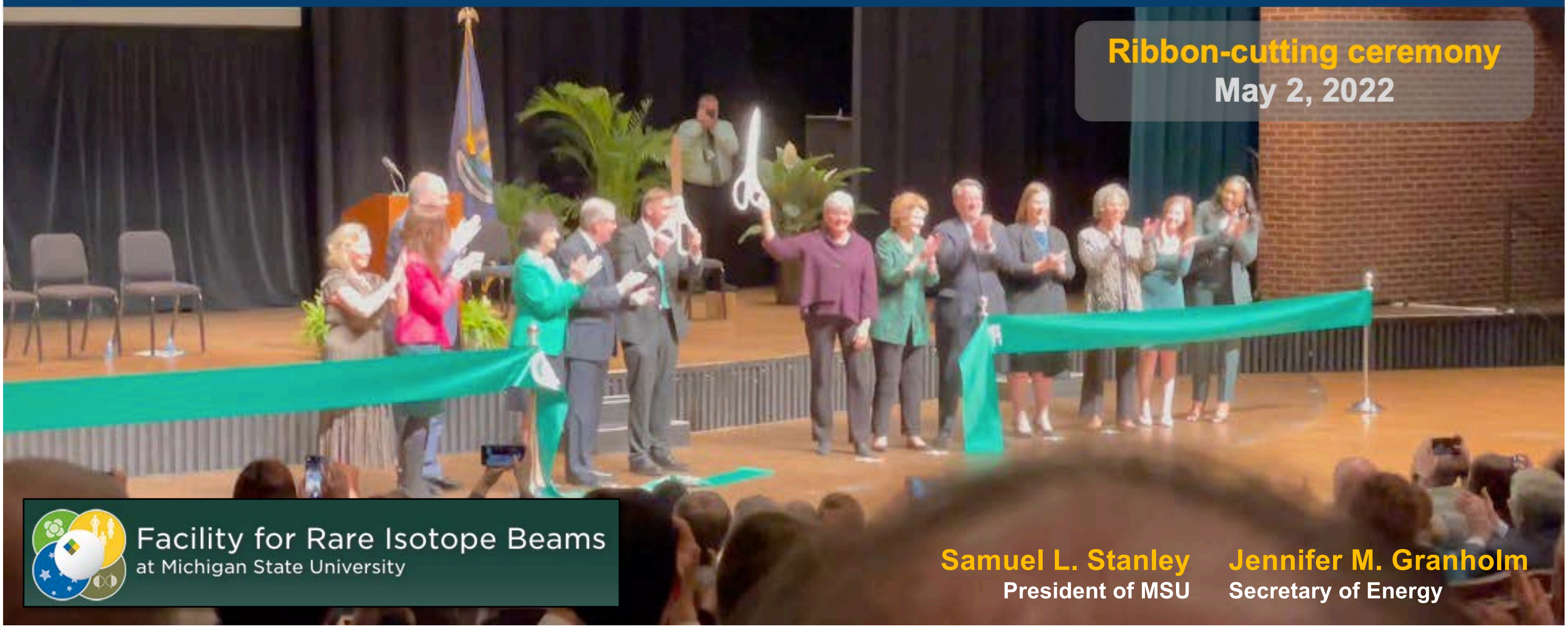

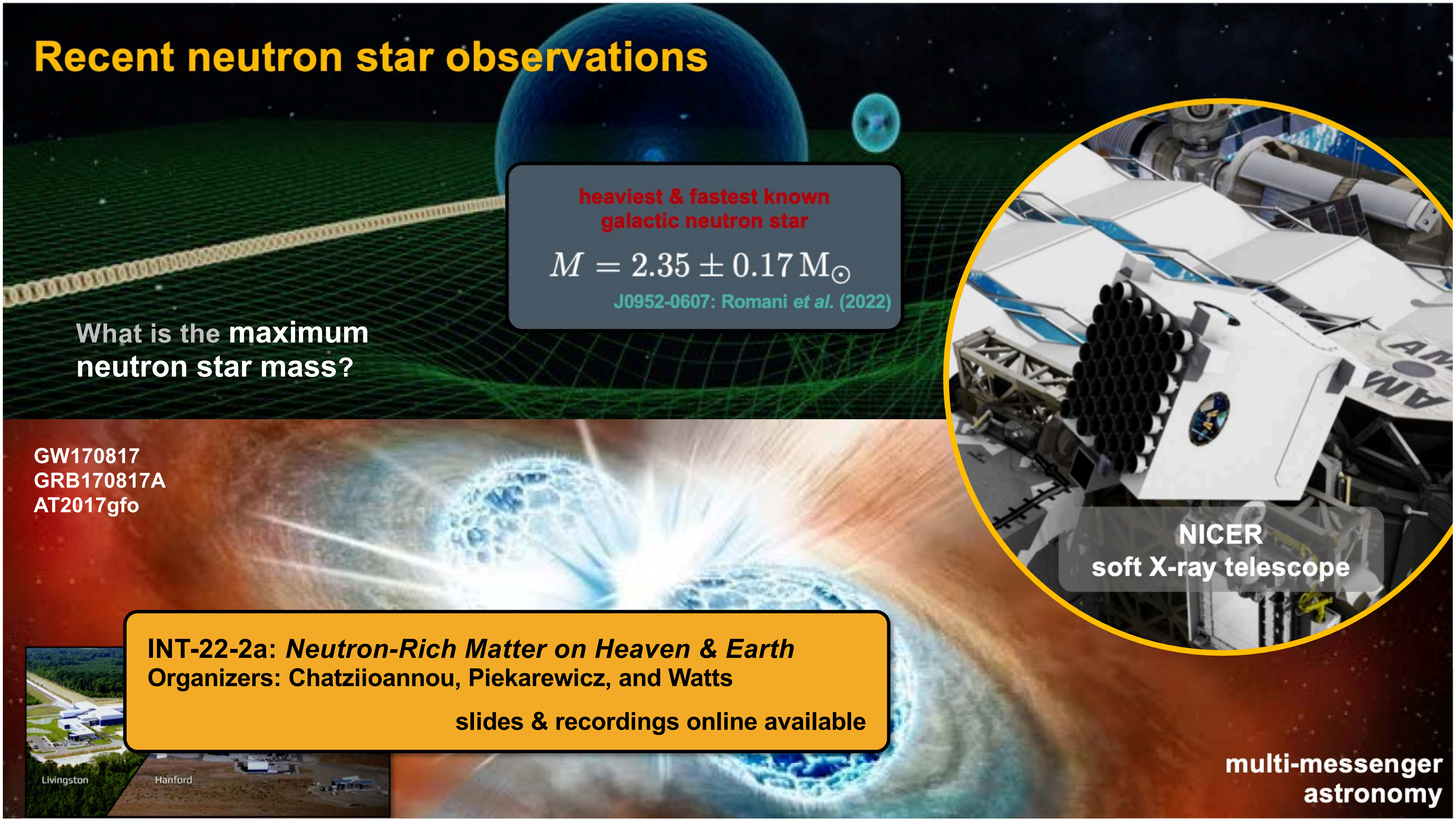
Recent neutron star observations
heaviest & fastest known galactic neutron star
$M = 2.35 \pm 0.17\,\mathrm{M}_\odot$
J0952-0607: Romani et al. (2022)
What is the maximum neutron star mass?
GW170817
GRB170817A
AT2017gfo
NICER
soft X-ray telescope
INT-22-2a: Neutron-Rich Matter on Heaven & Earth
Organizers: Chatziioannou, Piekarewicz, and Watts
slides & recordings online available
Livingston
Hanford
multi-messenger astronomy

Golden Window of nuclear (astro)physics

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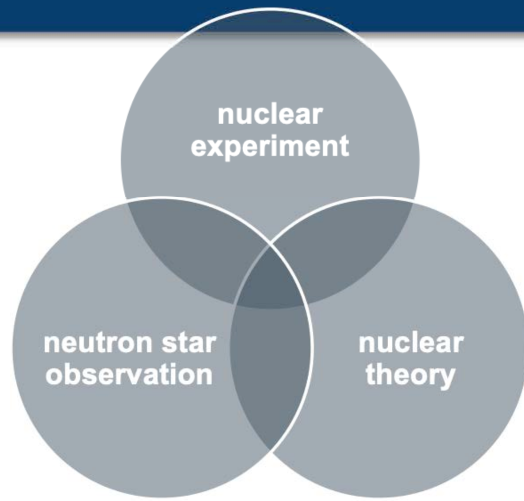
multi-messenger
nuclear precision
FRIB
} era



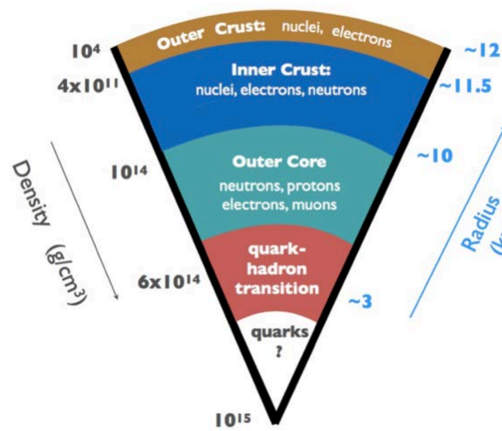
unique opportunity to obtain a **fundamental understanding** of strongly interacting matter, with great **potential for discoveries**

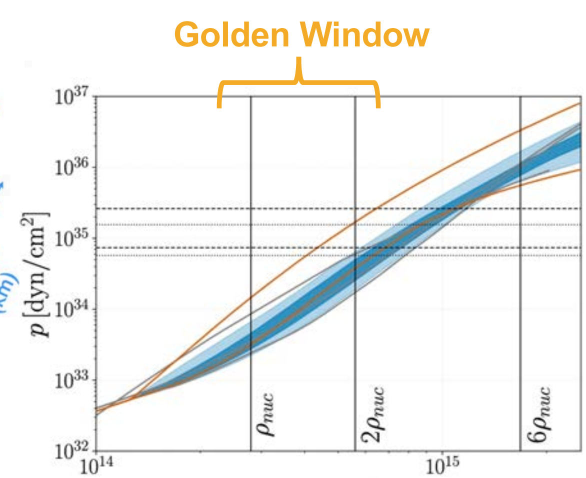
Required: *statistically* meaningful comparisons

What are the **phases of neutron star matter** below two times normal densities ?

At what density scale does nuclear effective field theory **break down** ?

How can experiments & observations help **improve nuclear effective field theories** ?





Abbott *et al.* (2018)

Ab initio workflow (idealized)

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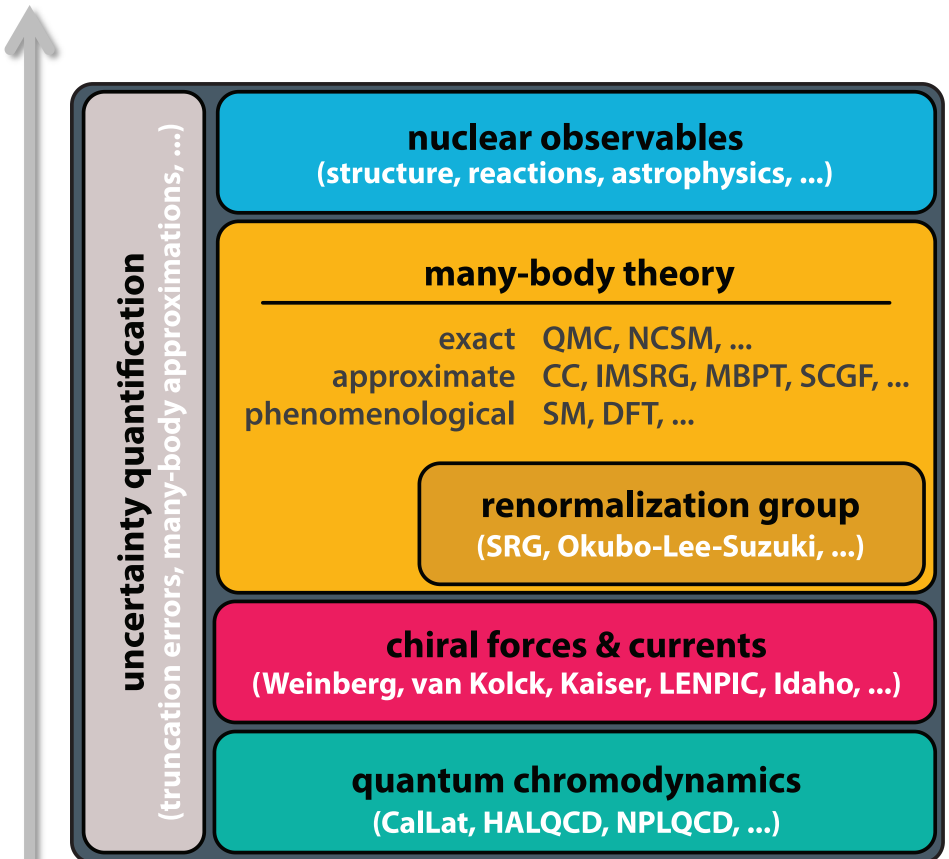

Recent highlight: *Ab initio* predictions link the neutron skin of ^{208}Pb to nuclear forces by Hu, Jiang *et al.*, arXiv:2112.01125

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 (= 0)

computational framework

solves the (many-body) Schrödinger equation
requires a nuclear potential as input

chiral effective field theory

provides microscopic interactions consistent with the symmetries of *low-energy* QCD

theory of strong interactions

QCD is nonperturbative at the low energies relevant for nuclear physics (cf. pQCD & LQCD)

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

Ab initio workflow (idealized)

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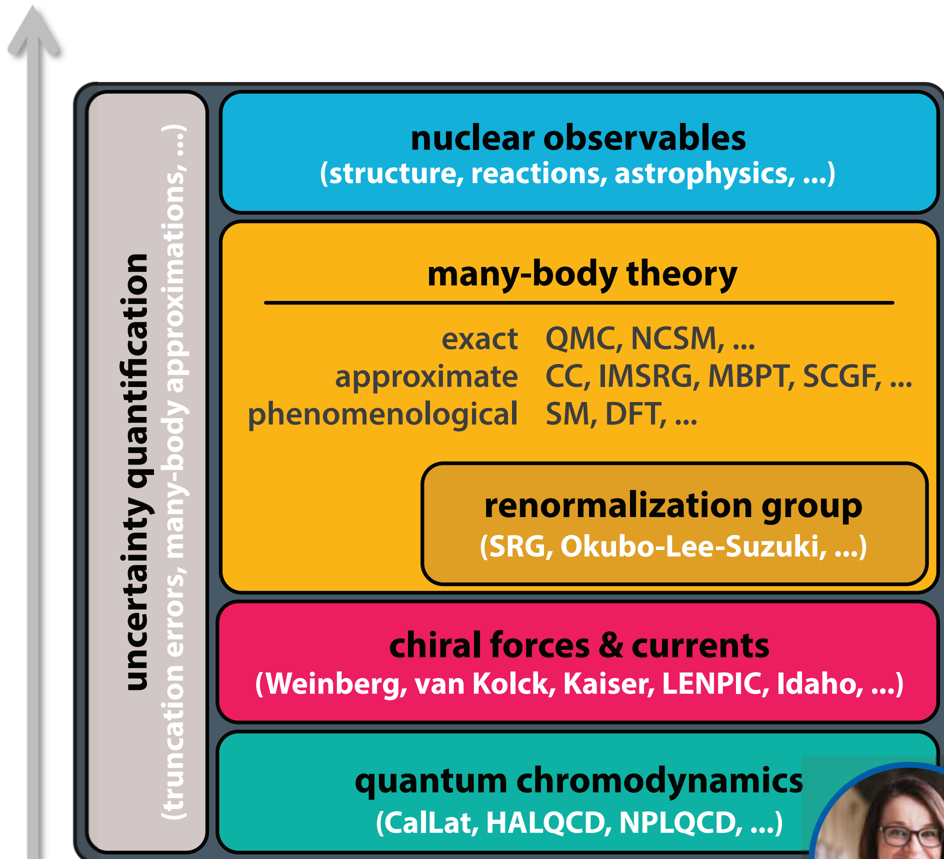

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energy per particle (and derived quantities)

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

baryon density n
neutron excess δ
temperature T (= 0)

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, …

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

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

Rigorous UQ for nuclear matter

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

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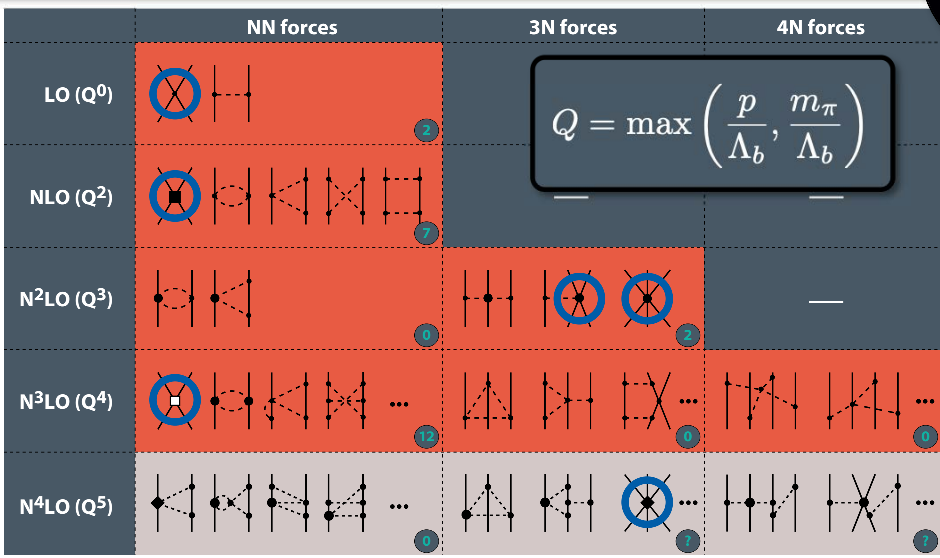
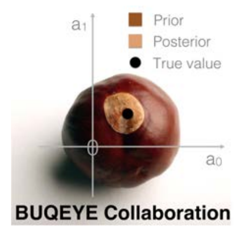


Chiral Effective Field Theory (nucleons & pions)

dominant approach for deriving *microscopic* interactions consistent with the symmetries of *low-energy* QCD

three- and four-neutron forces predicted through N^3LO

enables **uncertainty quantification** (EFT truncation)



Bayesian methods are powerful tools for quantifying & propagating EFT uncertainties based on *falsifiable* model assumptions.

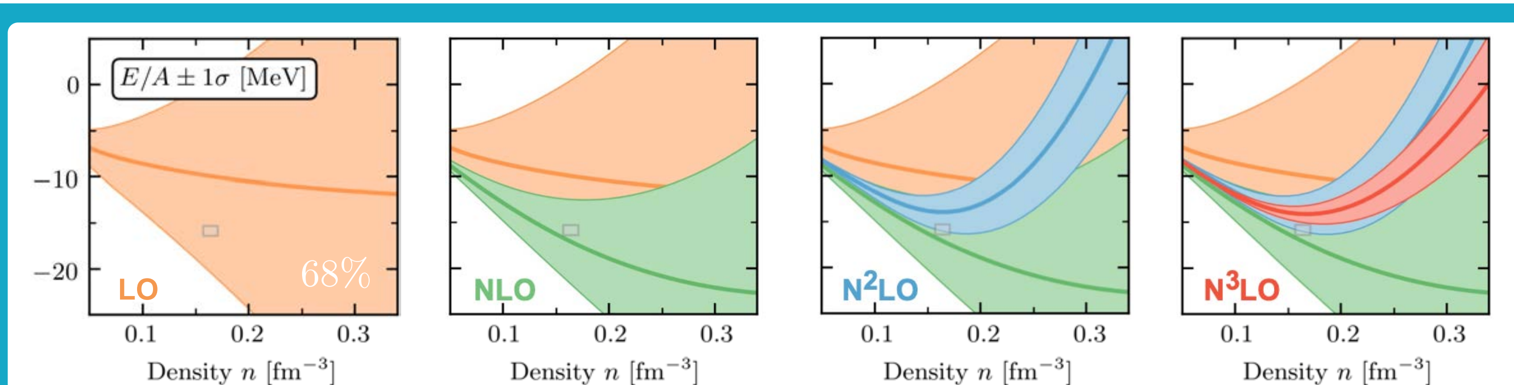
open-source software: https://buqeye.github.io

An example: symmetric matter

$$y = \frac{E}{A}, \quad k = 4 \quad (\mathrm{N^3LO})$$

Uncertainty bands depict 68% credibility regions

$$y = y_k + \delta y_k$$



Exploring the limits of chiral EFT

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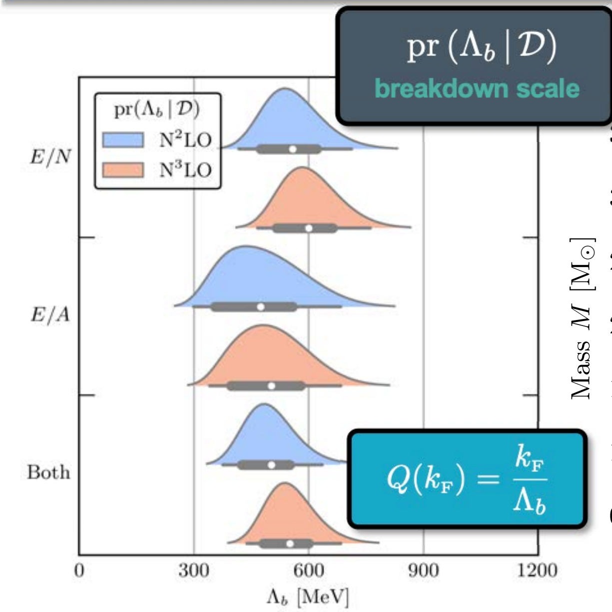
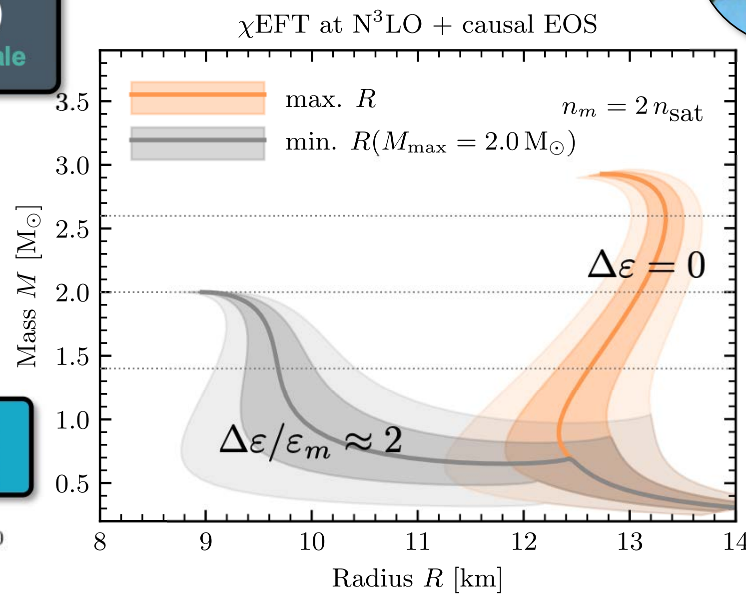


CD, Melendez *et al.*, PRC **102**, 054315

Bayesian inference of the in-medium breakdown scale

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



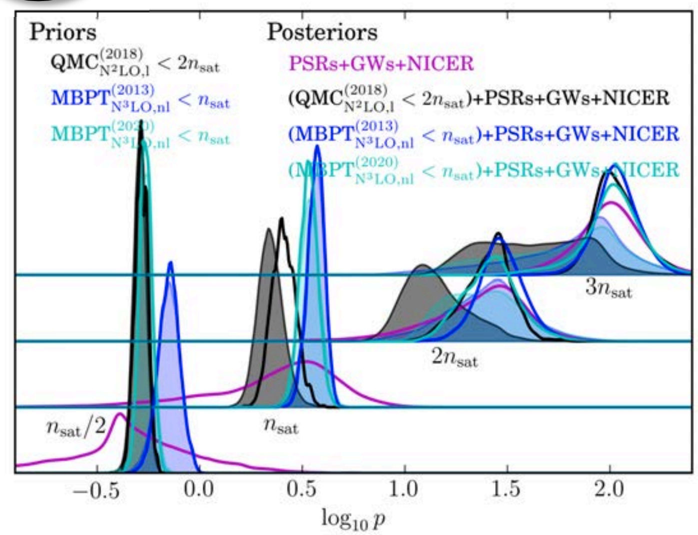
CD, Han, Lattimer *et al.*, PRC **103**, 045808
CD, Han, and Reddy, PRC **105**, 035808

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

$$R_{2.0} = (11.4 - 16.1)\ \mathrm{km}$$

Riley *et al.*, AJL **918**, L27
Miller *et al.*, AJL **918**, L28



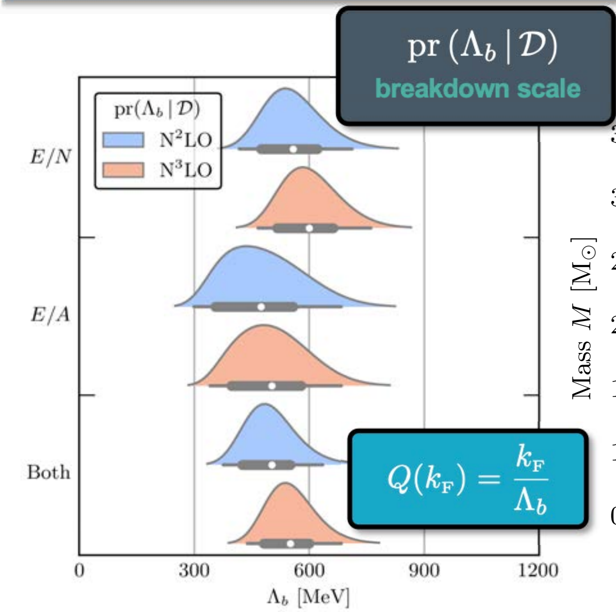
LIGO/Caltech/MIT/R. Hurt (IPAC)
Abbott *et al.*, ApJL **896** L44

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

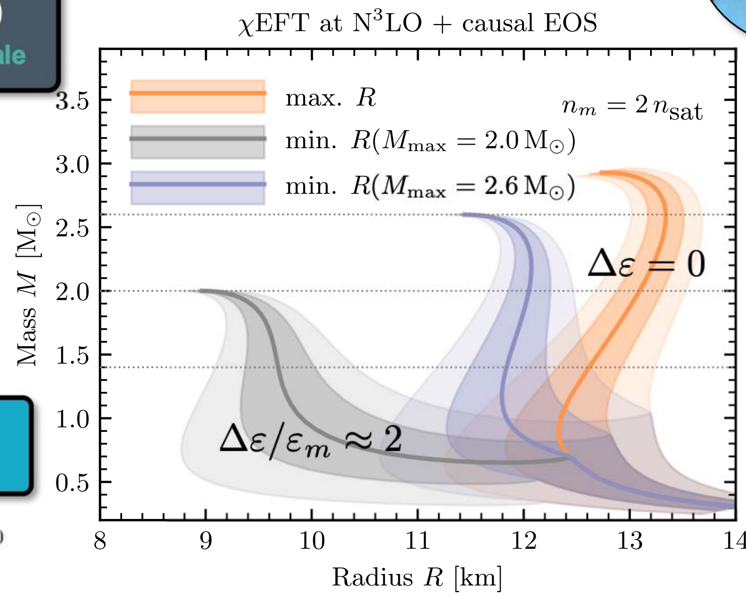
current astrophysical constraints are *not* tight enough to be conclusive (will change soon)

see also: Essick, Tews *et al.*, PRC **102**, 055803

Exploring the limits of chiral EFT



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



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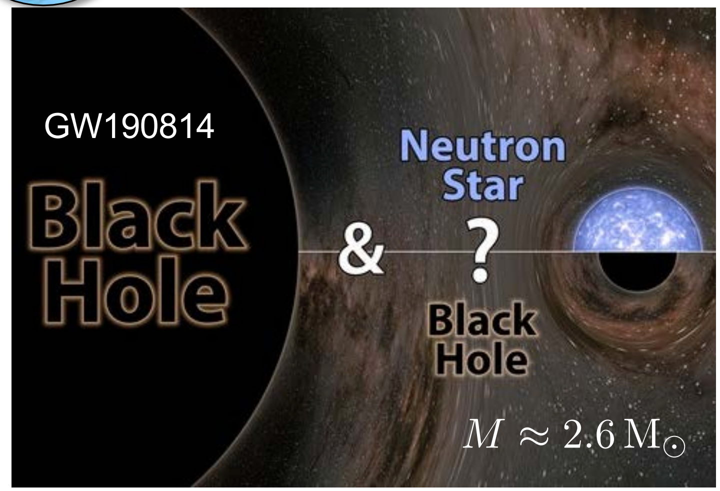

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Microscopic EOS calculations

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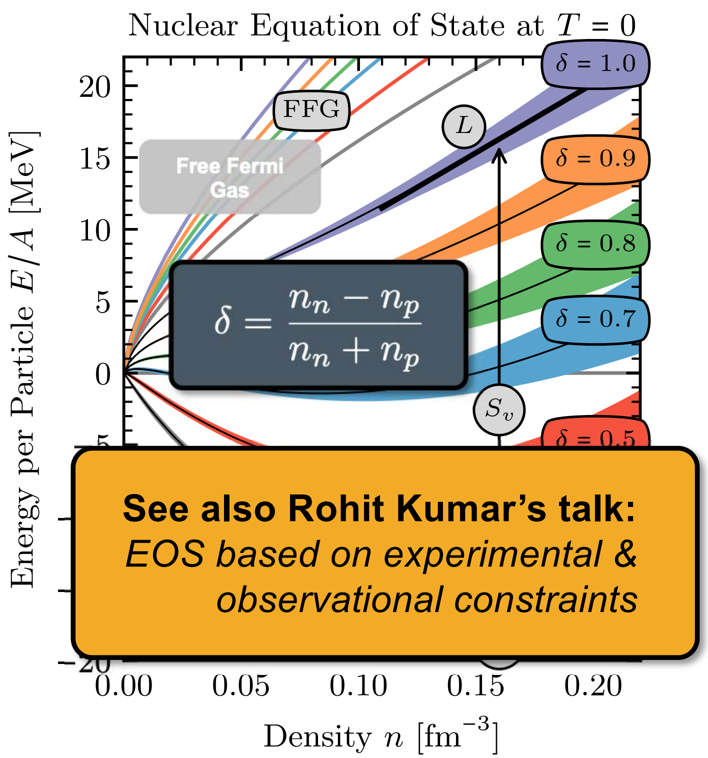


See also Rohit Kumar's talk:
EOS based on experimental & observational constraints

low-density EOS parameters

- symmetry energy S_v
- slope parameter L
- saturation point (n_0, E_0)
- incompressibility K

connection to experiment

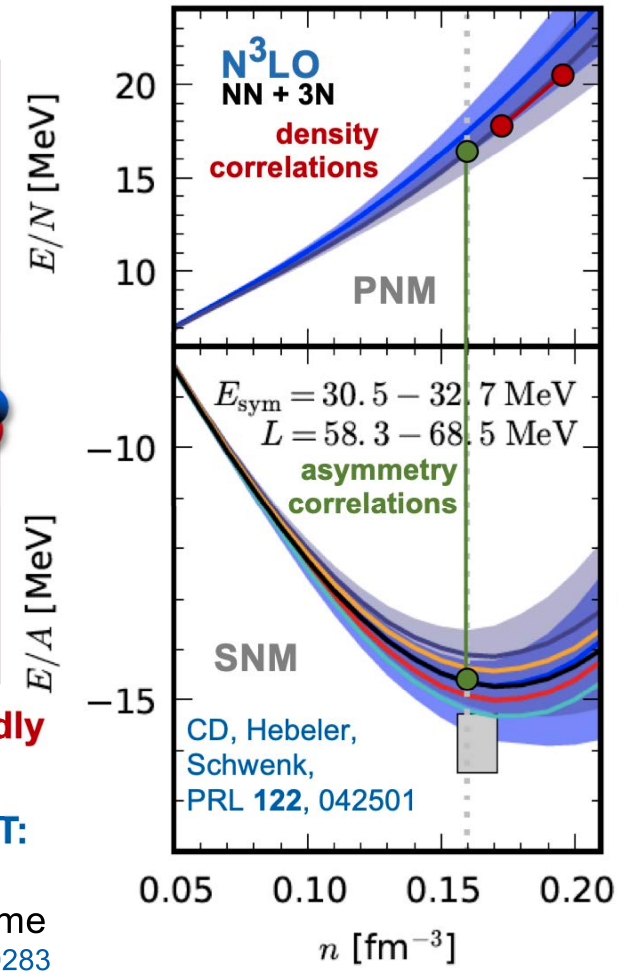
- binding energies
- neutron skin thicknesses
- giant resonances
- heavy-ion collisions

EFT truncation errors increase rapidly with increasing density

Synergy between nuclear DFT & EFT:

- benchmark EFT near SNM
- guide EDFs in the neutron-rich regime

e.g., see Alford *et al.*, arXiv:2205.10283



Great progress in **microscopic EOS calculations** at densities $\lesssim 2n_0$ and predictions for the neutron star structure

Nuclear symmetry energy

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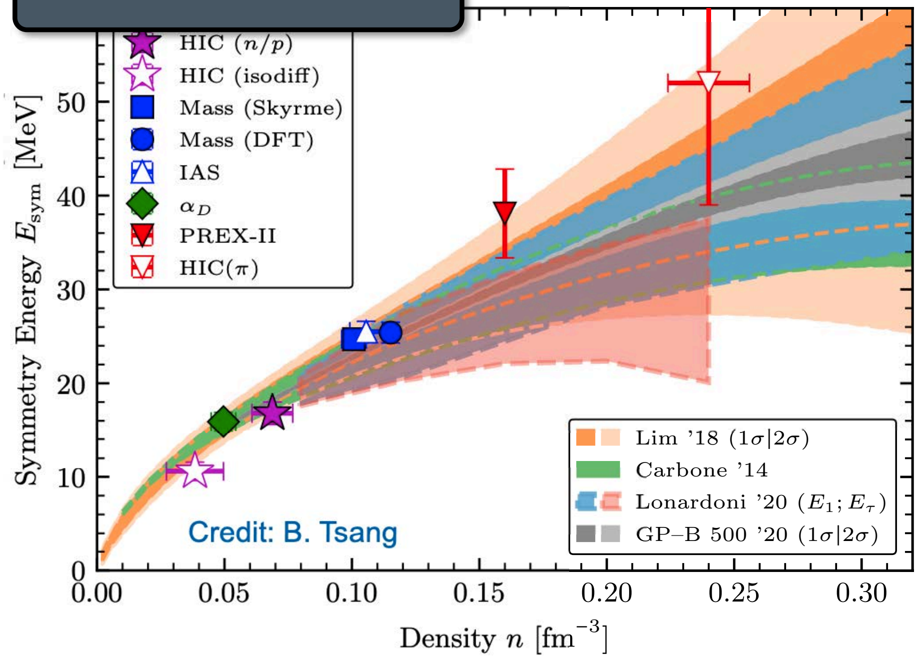
$$E_{\text{sym}}(n) \approx \frac{E}{N}(n) - \frac{E}{A}(n)$$



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

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

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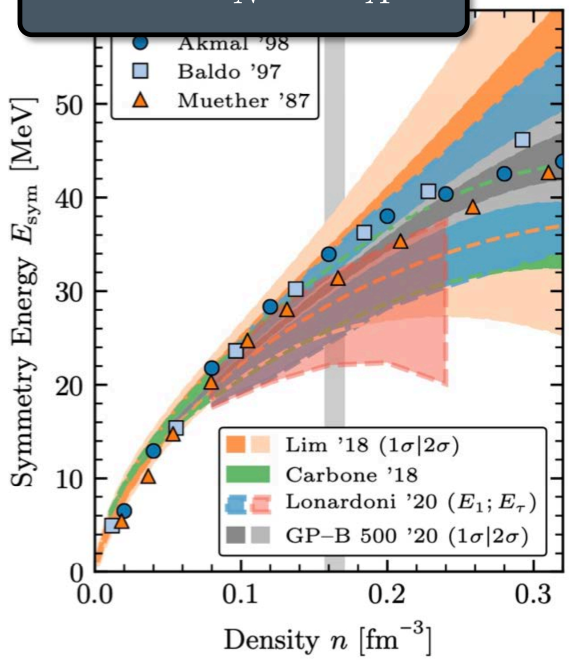

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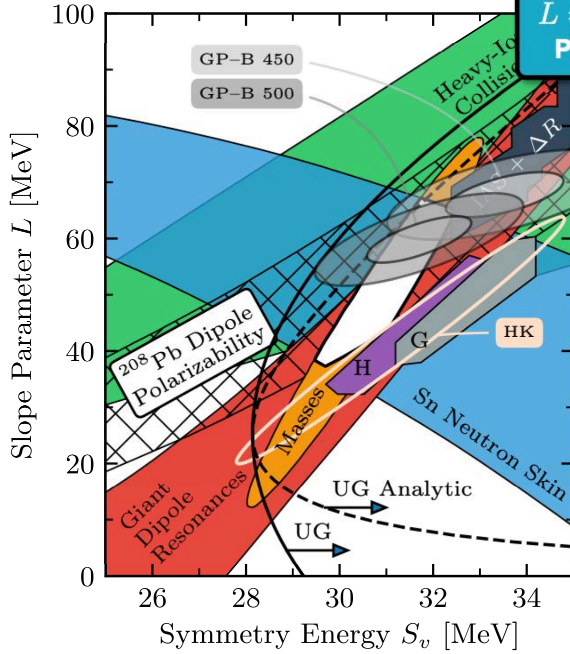
excellent agreement with experiment

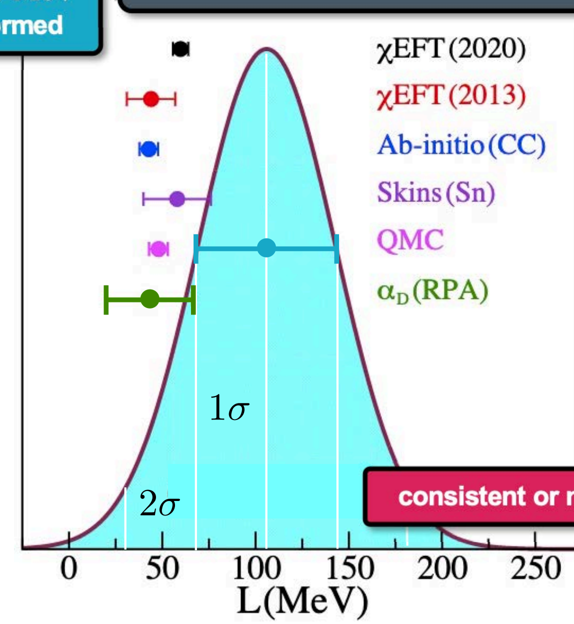


$L = 106 \pm 37\ \mathrm{MeV}$
PREX–II informed

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

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

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



consistent or not?

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

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

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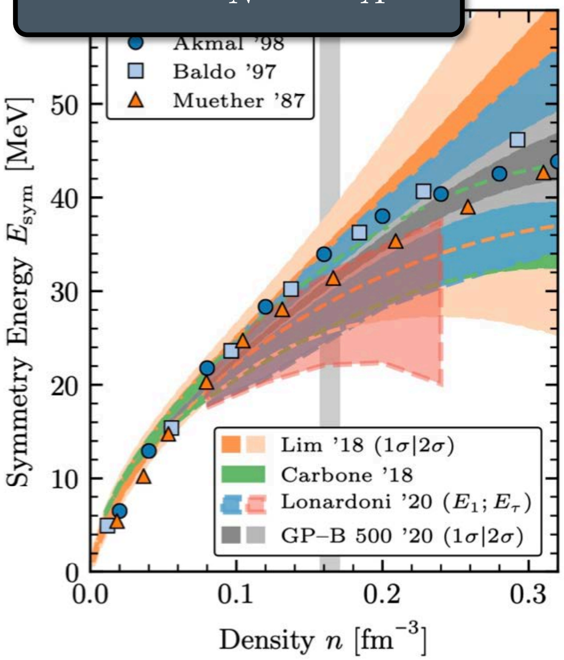

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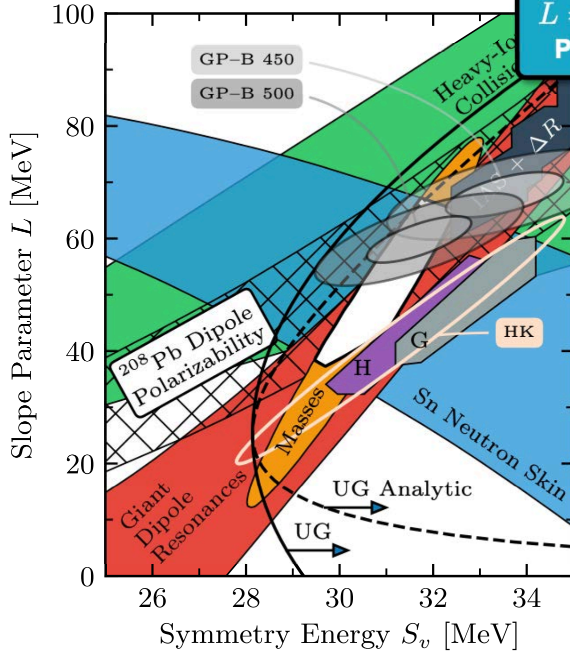

CD, Holt *et al.*, ARNPS **71**, 403
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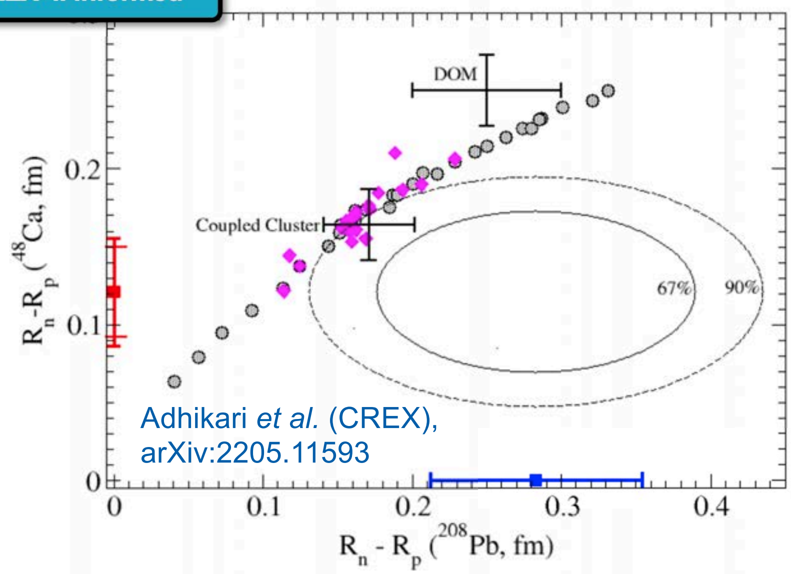

Adhikari *et al.* (CREX), arXiv:2205.11593

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

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

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

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

Incompressibility (in symmetric matter)

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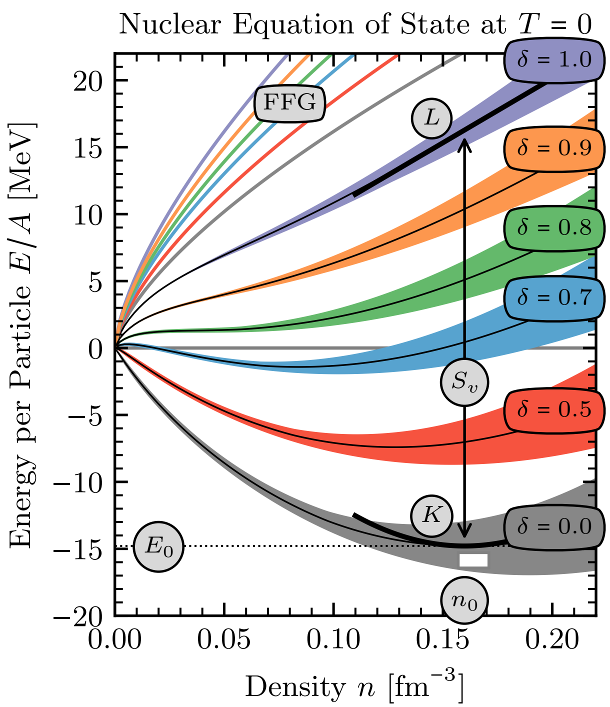
$$K = 9n_0^2 \frac{d^2}{dn^2} \frac{E}{A}(n)\Big|_{n=n_0}$$



CD, Holt *et al.*, ARNPS **71**, 403

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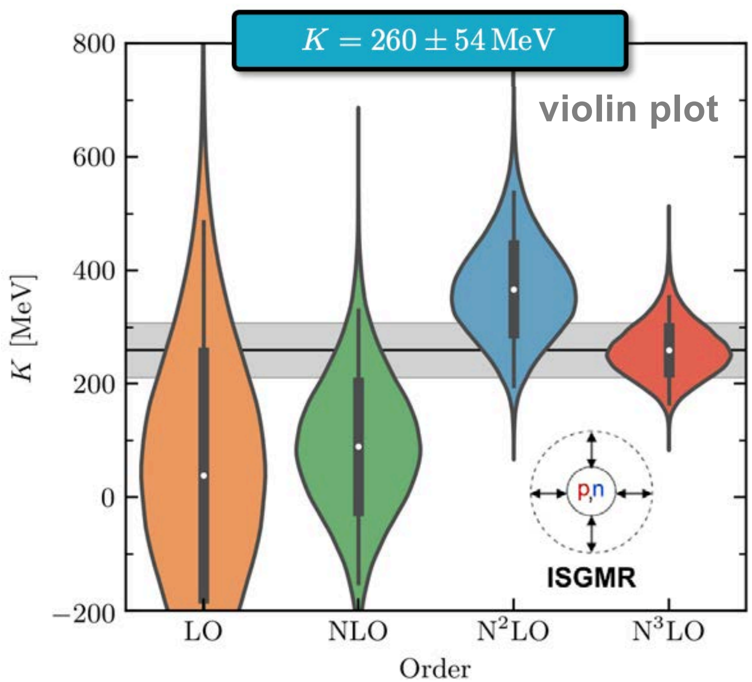
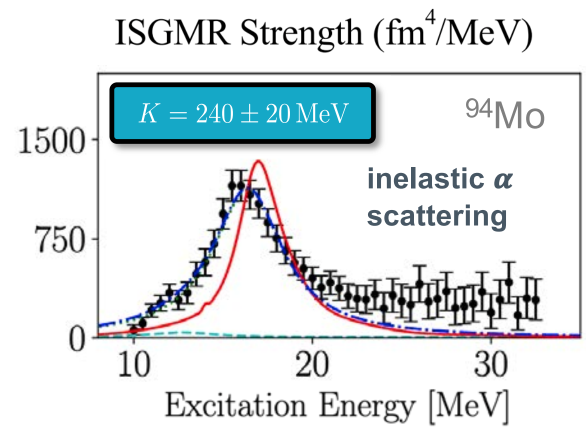


CD, Melendez *et al.*, PRC **102**, 054315

order-by-order convergence pattern

uncertainties due to the predicted saturation density included via marginalization



Howard, Garg *et al.*, PLB **807** 135608
Roca-Maza & Paar, PPNP **101**, 96

Approved FRIB experiment:
"The ISGMR in ^{132}Sn: Implications on the Nuclear Incompressibility"
Randhawa *et al.* (experiment: 21056)

new insights into $\boldsymbol{\delta}$ dependence

Automated MBPT for nuclear matter

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

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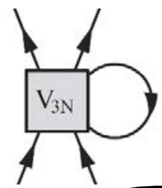
efficient MC evaluation of MBPT diagrams
with **NN**, **3N**, and **4N forces** (in a single-particle basis)



- **implementation of arbitrary diagrams** has become **straightforward** (numerically exact)
- multi-dimensional momentum integrals: improved VEGAS
- GPU-accelerated normal ordering of 3N interactions
- propagation of importance sampling distributions (*e.g.*, for mapping the EOS efficiently in density)
- **controlled evaluation of 1000s MBPT diagrams**


systematic EOS calculations in MBPT

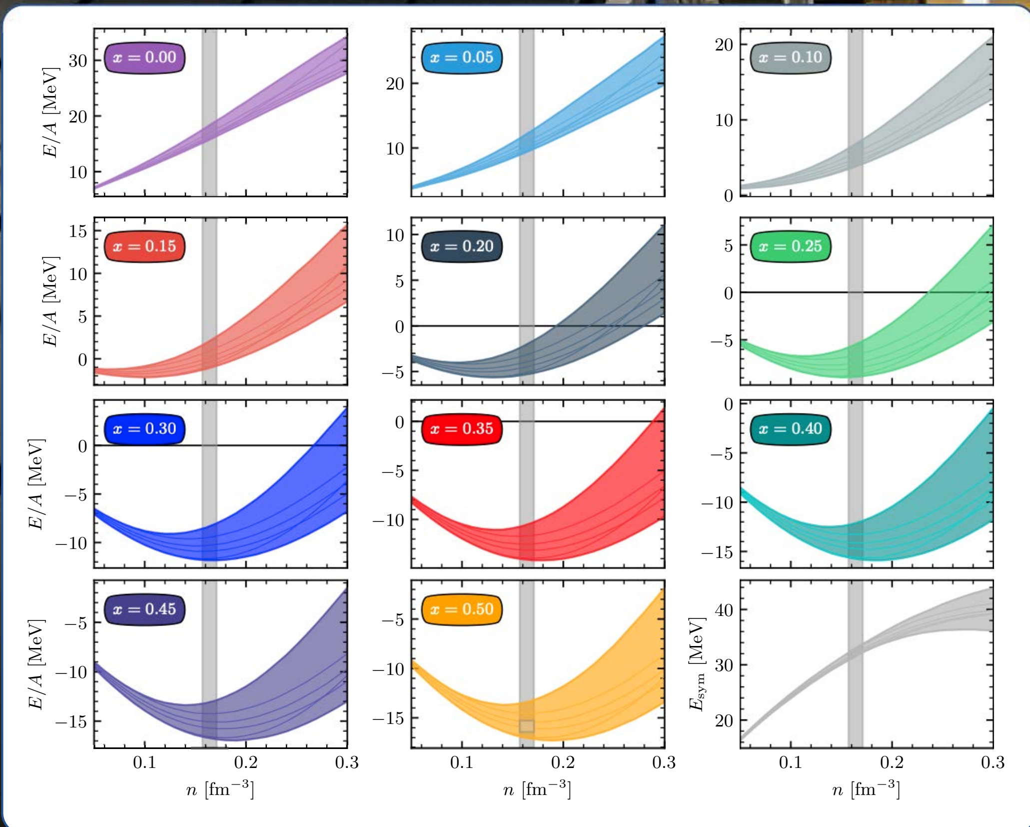
automated code generation

analytic expressions
interaction & MBPT diagrams

automated diagram generation

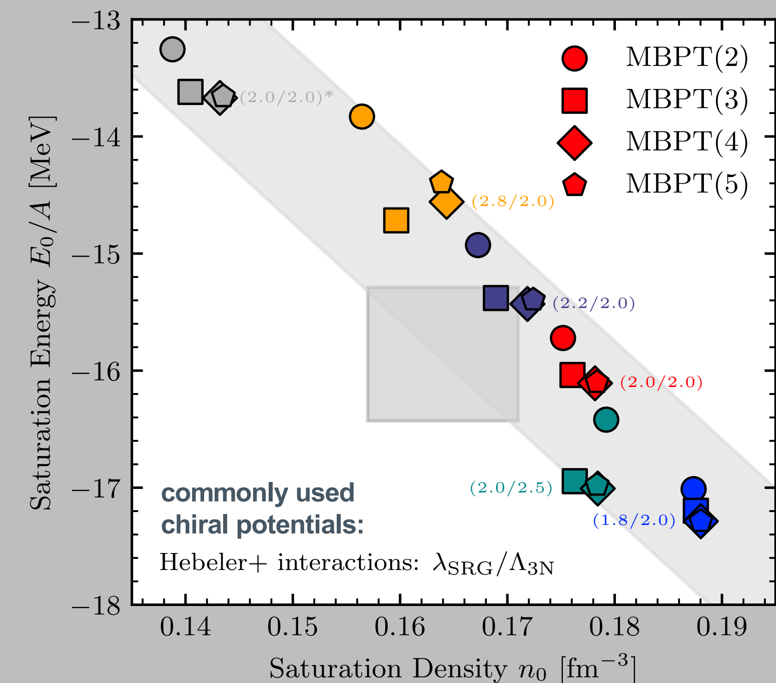
Application to dilute Fermi gas: Wellenhofer, CD, Schwenk, PRC **104**, 014003 & PLB **802**, 135247

MBPT: an HPC application



MBPT(*n*)	2	3	4	5
NN+3N norm. ord.	✓	✓	✓	✓
residual 3N	✓ (1)	✓ (14)	✗	✗

(new)



nuclear saturation | see also Hu, Li, Xu, arXiv:1810.08804

#2 (U.S.)

Summit @ Oak Ridge Leadership Computing Facility

New predictions in SNM at intermediate densities

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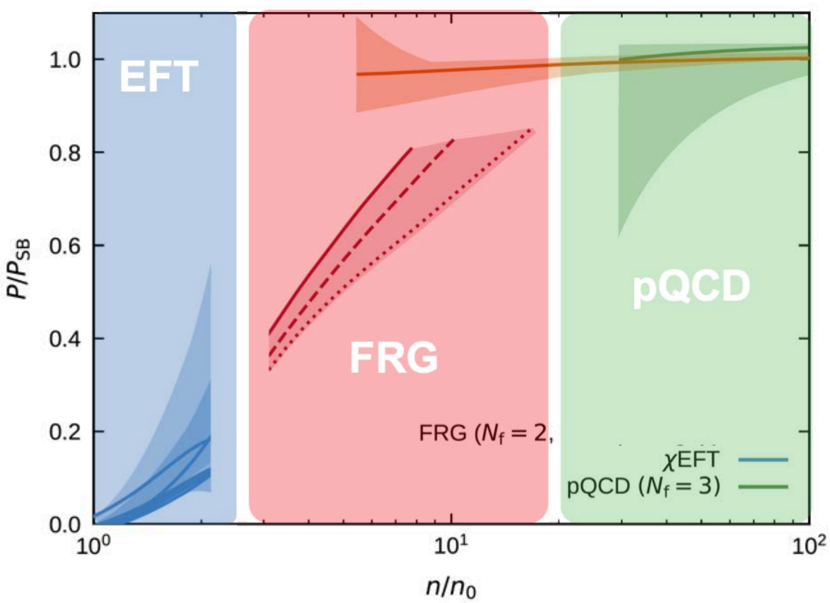
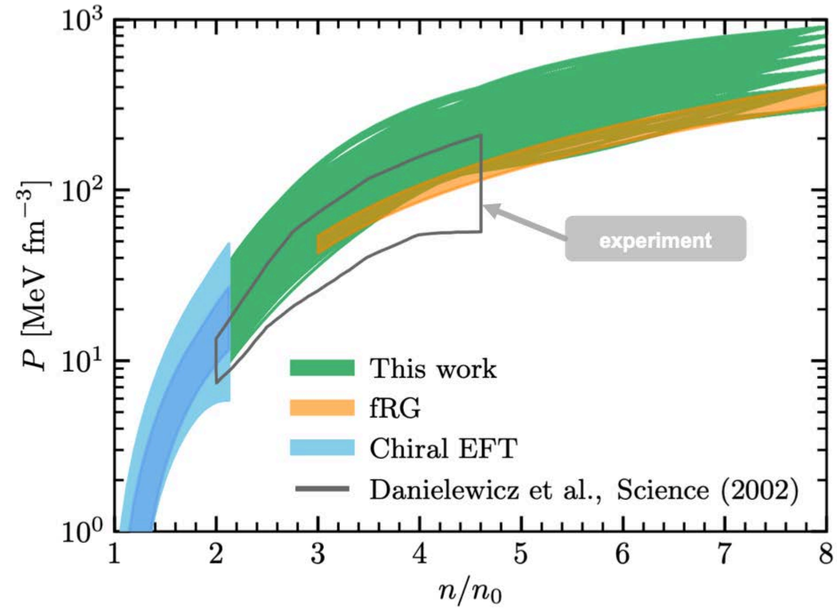


Leonhardt, Pospiech, Schallmo, Braun, CD, Hebeler, and Schwenk, PRL **125**, 142502



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 combined (Bayesian model mixing?)

for PNM see: Braun & Schallmo; arXiv:2204.00358

remarkable consistency between theory predictions, experiment, and astrophysics

BAND
Bayesian Analysis of Nuclear Dynamics

BAND Manifesto,
Phillips, Furnstahl, Heinz *et al.*,
JGP: NP **48** 072001

More details? Recent review article

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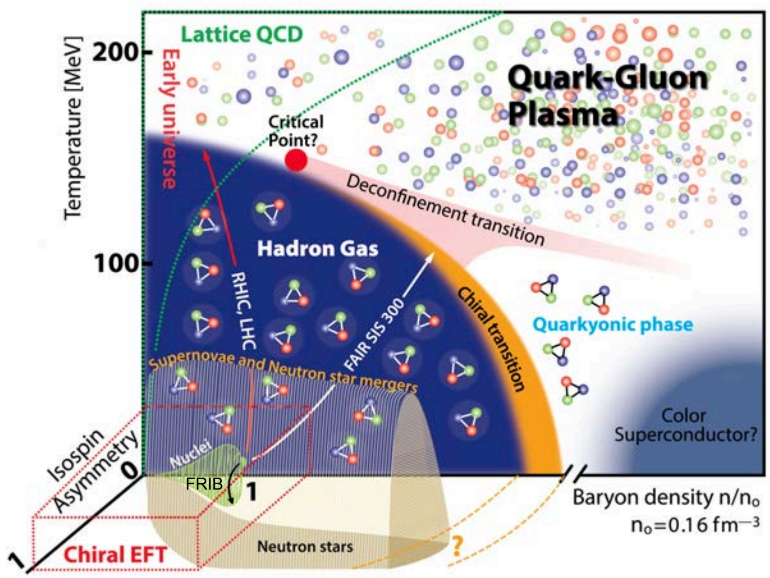

Chiral Effective Field Theory and the High-Density Nuclear Equation of State

Annual Review of Nuclear and Particle Science

Vol. 71:403-432 (Volume publication date September 2021)
First published as a Review in Advance on July 6, 2021
https://doi.org/10.1146/annurev-nucl-102419-041903

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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

Open Access

Emulators: mining scattering & reaction data

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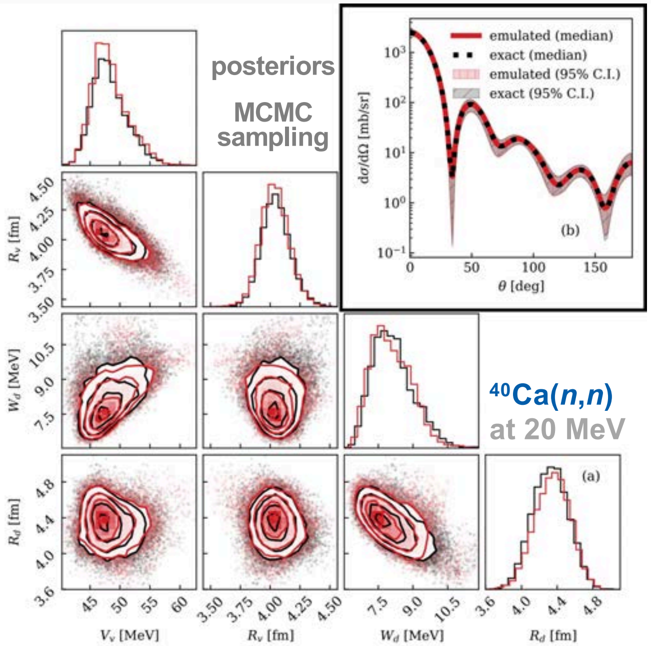
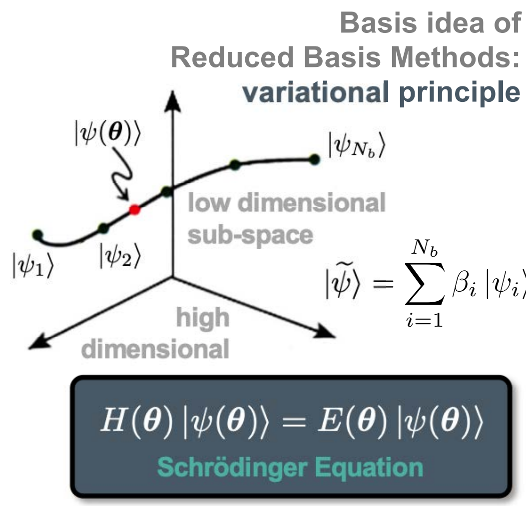


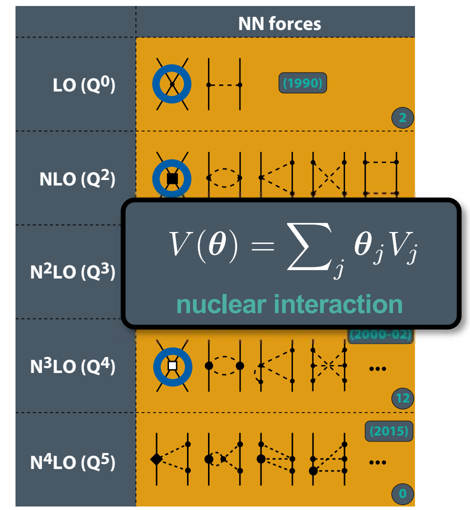
CD, Quinonez *et al.*, PLB **823**, 136777

Kohn VP: spurious *singularities* can be mitigated

Proof of principle: fast & accurate emulation of scattering observables for parameter estimation

Goal: improving next-generation optical models & chiral interactions in the FRIB era





Frame *et al.*, PRL **121**, 032501
Melendez, CD *et al.*, arXiv:2203.05528 (literature guide)
Melendez, CD *et al.*, PLB **821**, 136608 (Newton's VP)

Construct **reduced-order models** by removing superfluous information in high-fidelity models

Emulators enable applications *thought* to be prohibitively slow

For bound-state emulators, see König, Ekström *et al.*, PLB **810**, 135814, Ekström & Hagen, PRL **123**, 252501, and more

Model reduction for nuclear emulators

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Emulators
(surrogate models)

data-driven (non-intrusive)
Gaussian Processes, Artificial Neural Networks, etc.

model-driven (intrusive)
reduced-order equations from high-fidelity models

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Many pointers to the MOR literature: arXiv:2203.05528 (J. Phys. G Nucl. Part. in press)

The field of model order reduction (MOR) is growing in importance due to its ability to extract the key insights from complex simulations while discarding computationally burdensome and superfluous information. We provide an overview of MOR methods for the creation of fast & accurate emulators of memory- and compute-intensive nuclear systems. As an example, we describe how "eigenvector continuation" is a special case of a much more general and well-studied MOR formalism for parameterized systems. We continue w
projection methods that underpin many such emulato
and its successful applications along the way. We be
applications in nuclear physics and facilitate commun

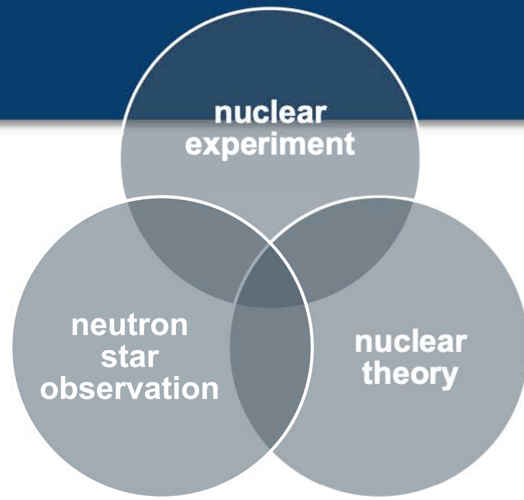
See also Xilin Zhang's talk:
Recent developments in the emulations of quantum continuum states

see also: CD & Zhang, Chap. 8, pp. 29–36, in arXiv:2202.01105 (collec
for RBMs applied to DFT, see Melendez's GitHub; Bonilla, Giuliani *et al.*, arXiv:2203.05284; Anderson *et al.*, arXiv:2206.14889

Take-away points

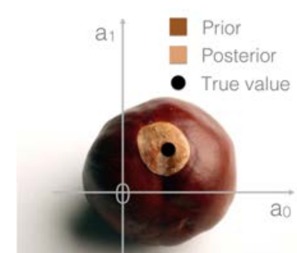
multi-messenger
nuclear precision
FRIB

} era



unique opportunity to obtain a **fundamental understanding** of strongly interacting matter, with great **potential for discoveries**

1. Upcoming observational (and experimental) campaigns will provide **stringent constraints** on the properties of neutron stars
2. Chiral EFT enables **microscopic predictions** of nuclear matter (and nuclei) **with quantified uncertainties** to interpret these empirical constraints
3. Bayesian methods are powerful tools for quantifying & propagating **correlated uncertainties** in EFT-based calculations (*model checking* is important)
4. Emulators have been **game changers in nuclear physics**; and much can be learned from the well-established MOR field in applied mathematics.



BUQEYE Collaboration

Many thanks to: R. Furnstahl A. Garcia P. Guiliani S. Han J. W. Holt J. Lattimer A. Lovell K. McElvain J. Melendez F. Nunes D. Phillips M. Prakash S. Reddy C. Wellenhofer X. Zhang T. Zhao