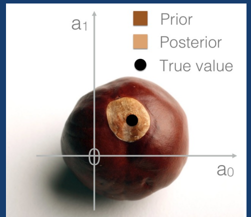
Equation of State of Neutron-Rich Matter and Implications for Neutron Stars

Christian Drischler

14th Conference on the Intersections of Particle and Nuclear Physics 2022

September 1, 2022

OHIO UNIVERSITY



BUQEYE Collaboration

Ribbon-cutting ceremony
May 2, 2022

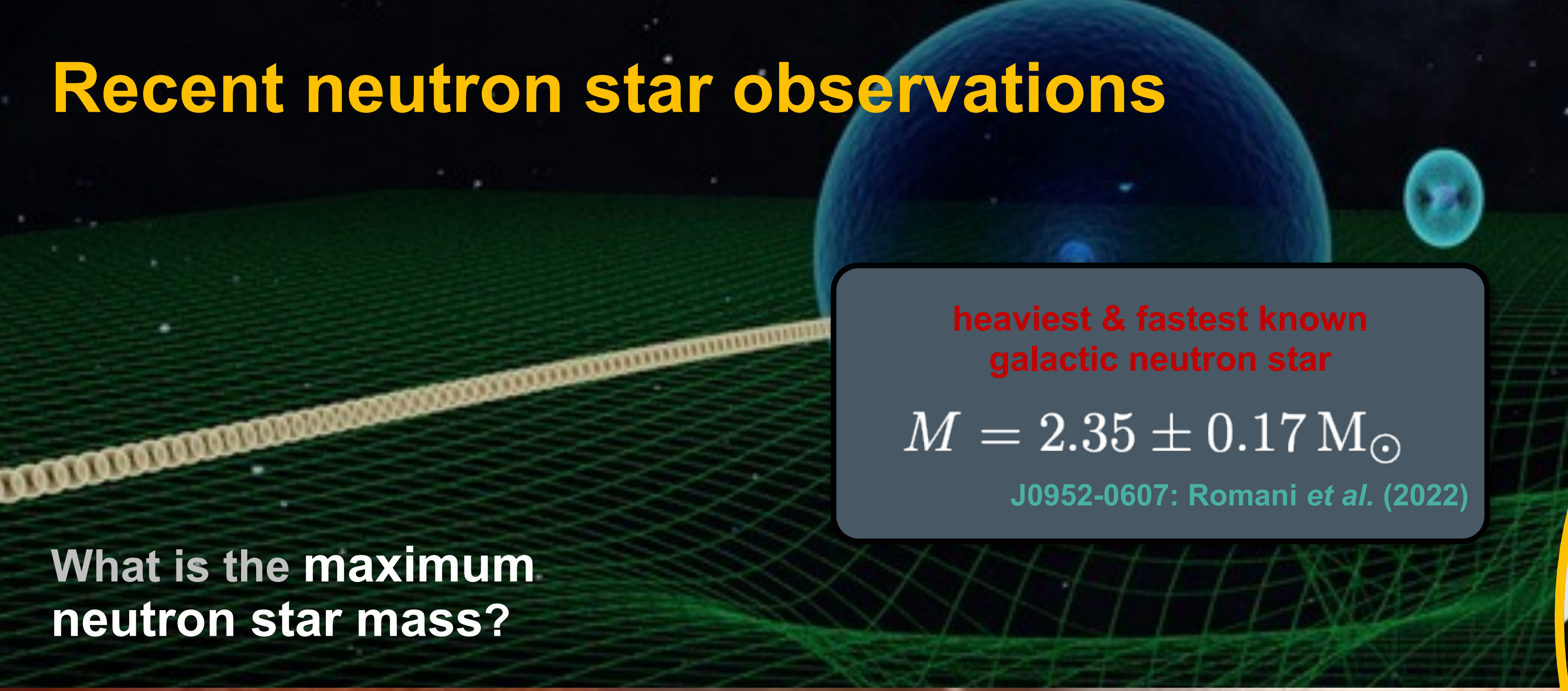
See also Brad Sherrill's talk (Friday):
Status and Prospects with FRIB

Facility for Rare Isotope Beams
at Michigan State University

Samuel L. Stanley
President of MSU

Jennifer M. Granholm
Secretary of Energy

Recent neutron star observations



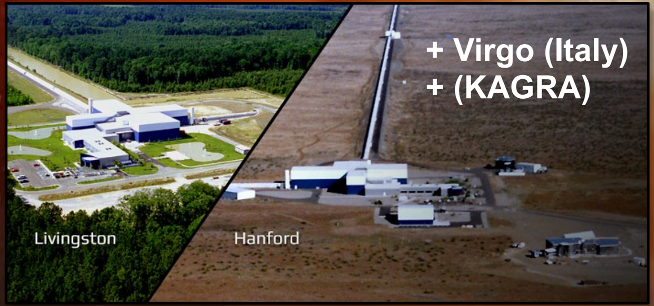
heaviest & fastest known galactic neutron star

$$M = 2.35 \pm 0.17\,\mathrm{M}_\odot$$

J0952-0607: Romani *et al.* (2022)

What is the **maximum neutron star mass?**

GW170817
GRB170817A
AT2017gfo



multi-messenger astronomy

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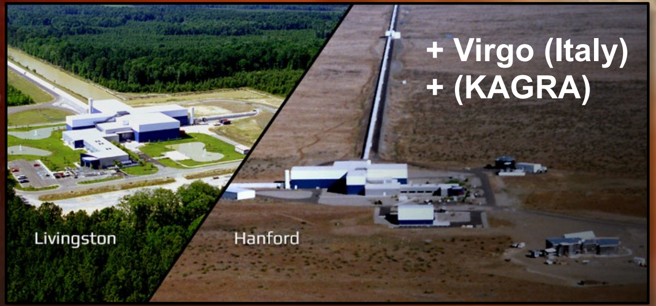
See also Ben Margalit's talk (this session):
Mergers, kilonovae, and two-solar-mass neutron stars*:*
What does astrophysics tell us about the nuclear EOS?



See also K. Chatzilioannou's talk (Saturday):
GWs from binary neutron stars and
neutron star black-hole mergers

multi-messenger astronomy

Structure of cold neutron stars

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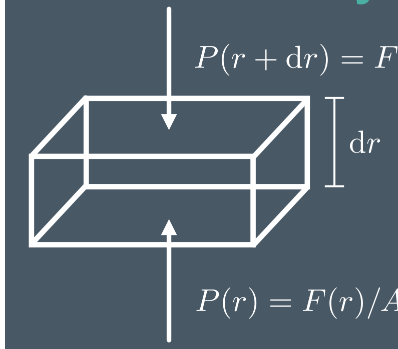
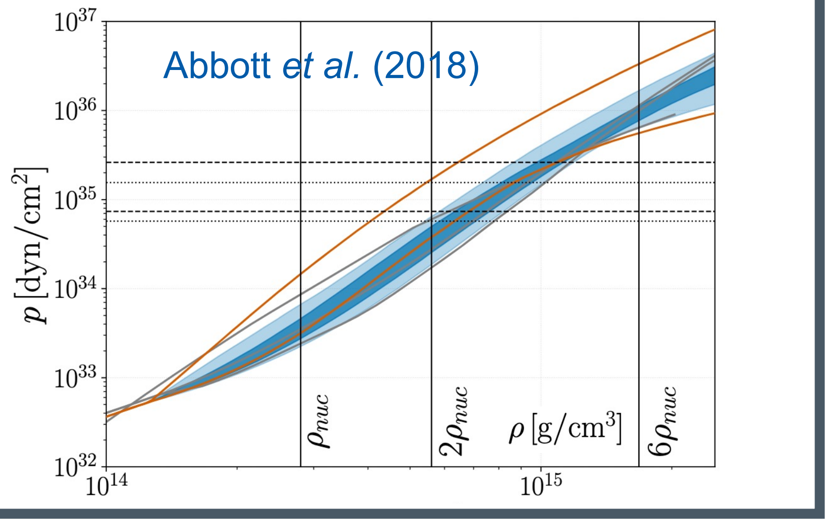
hydrostatic equilibrium

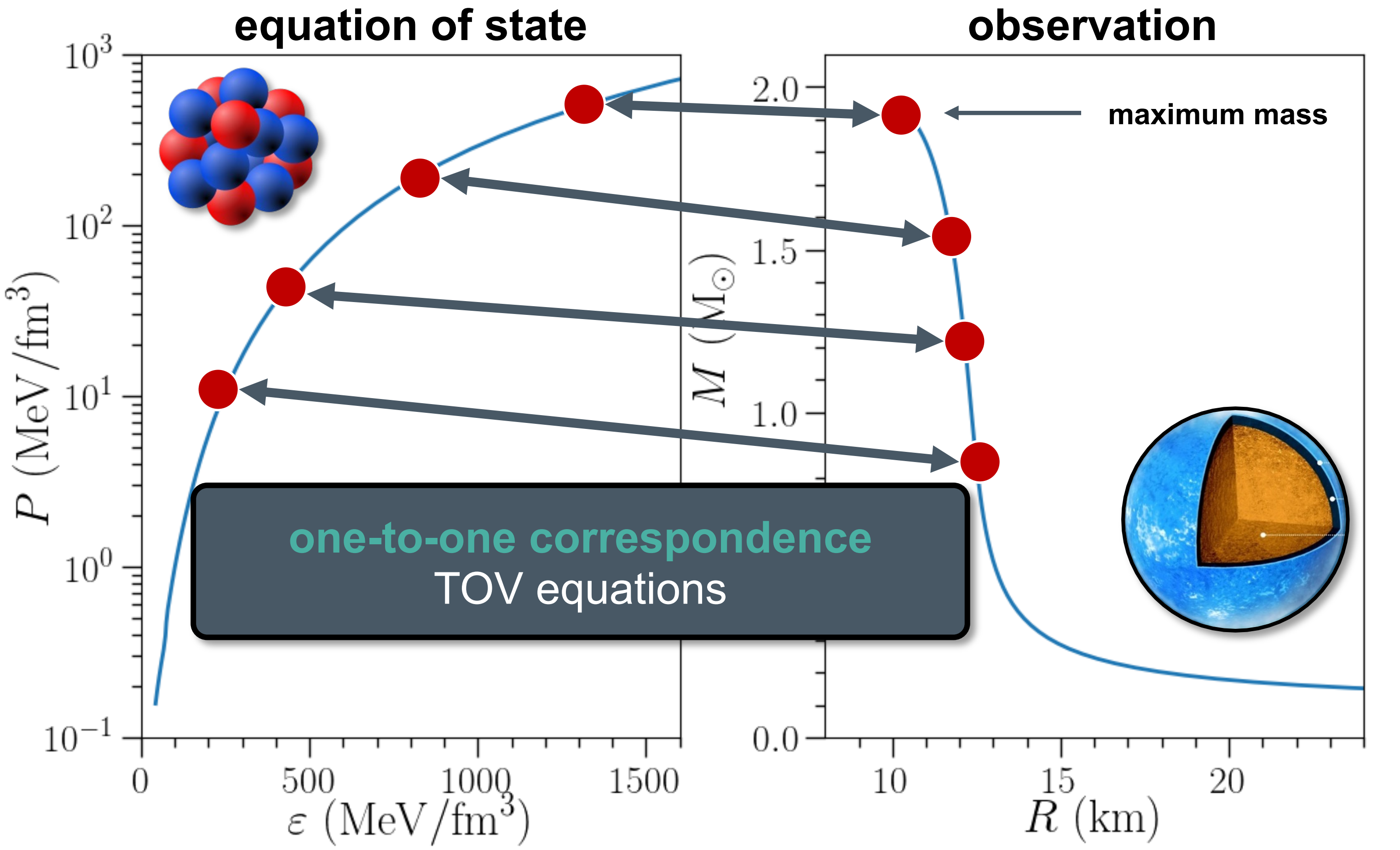


+ General Relativity

Tolman–Oppenheimer–Volkoff equation

$$\frac{dP}{dr} = -\frac{(\varepsilon + P)(m + 4\pi r^3 P)}{r(r - 2m)} \qquad \frac{dm}{dr} = 4\pi r^2 \varepsilon$$

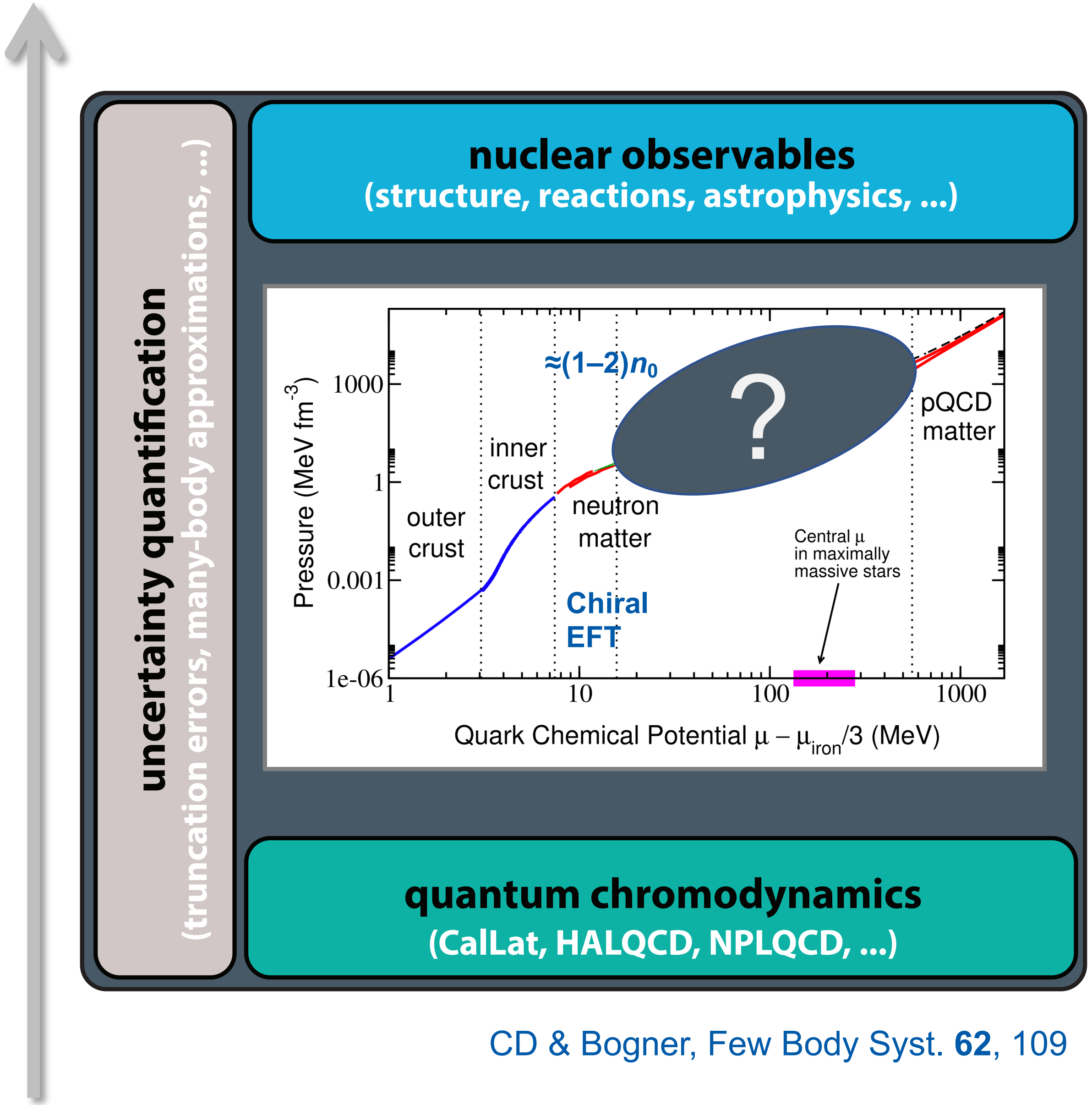




Credit: A. Steiner

The general relativistic equation for hydrostatic equilibrium determines the neutron star structure

Ab initio workflow (idealized)



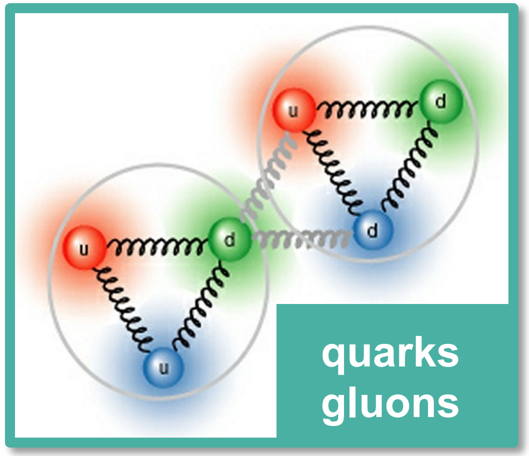
CD & Bogner, Few Body Syst. **62**, 109

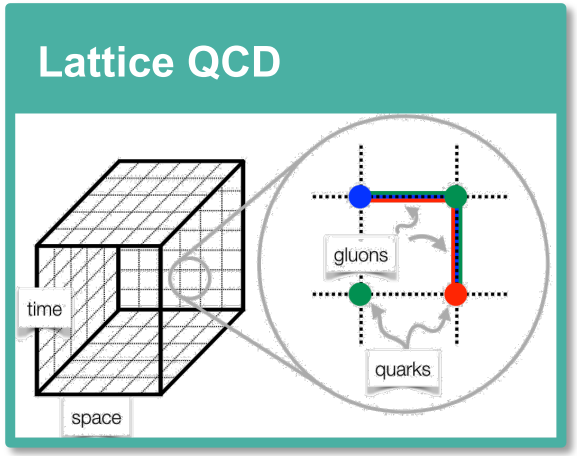
Here: nuclear equation of state (EOS)

energy per particle (and derived quantities)

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

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





theory of strong interactions

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

CD, Haxton, McElvain, Mereghetti *et al.*, PPNP **121**, 103888

Ab initio workflow (idealized)

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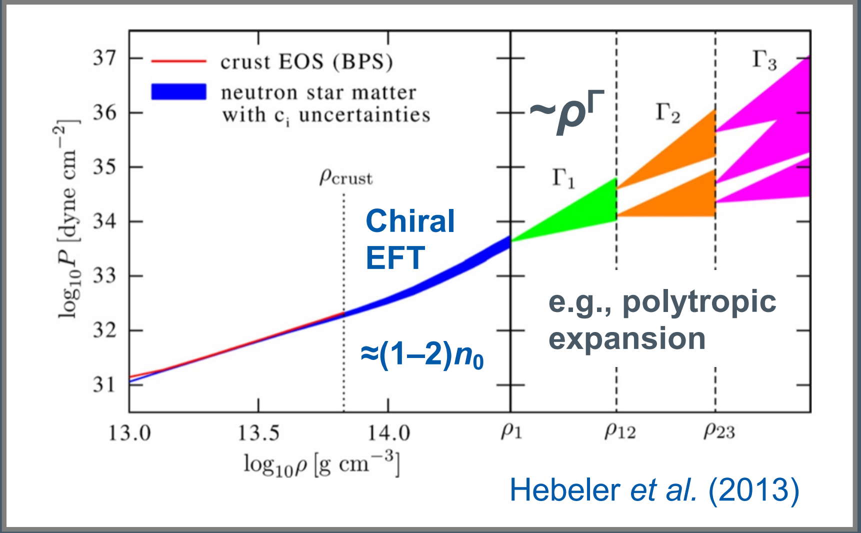
uncertainty quantification
(truncation errors, many-body approximations, …)

nuclear observables
(structure, reactions, astrophysics, …)



Hebeler *et al.* (2013)

quantum chromodynamics
(CalLat, HALQCD, NPLQCD, …)

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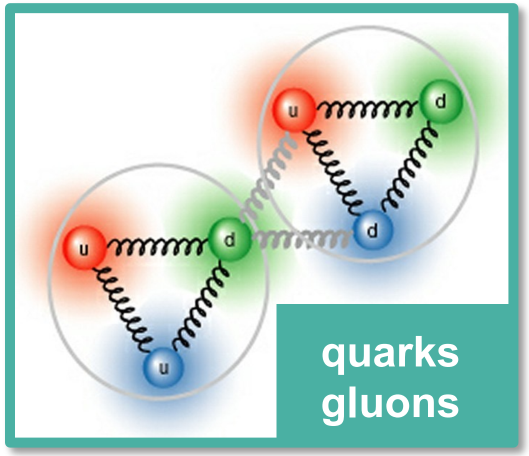

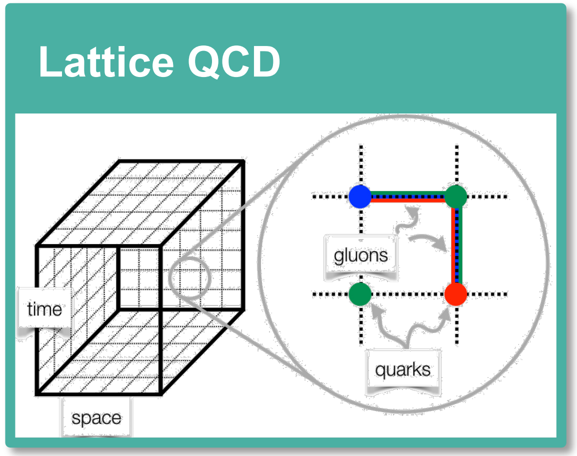

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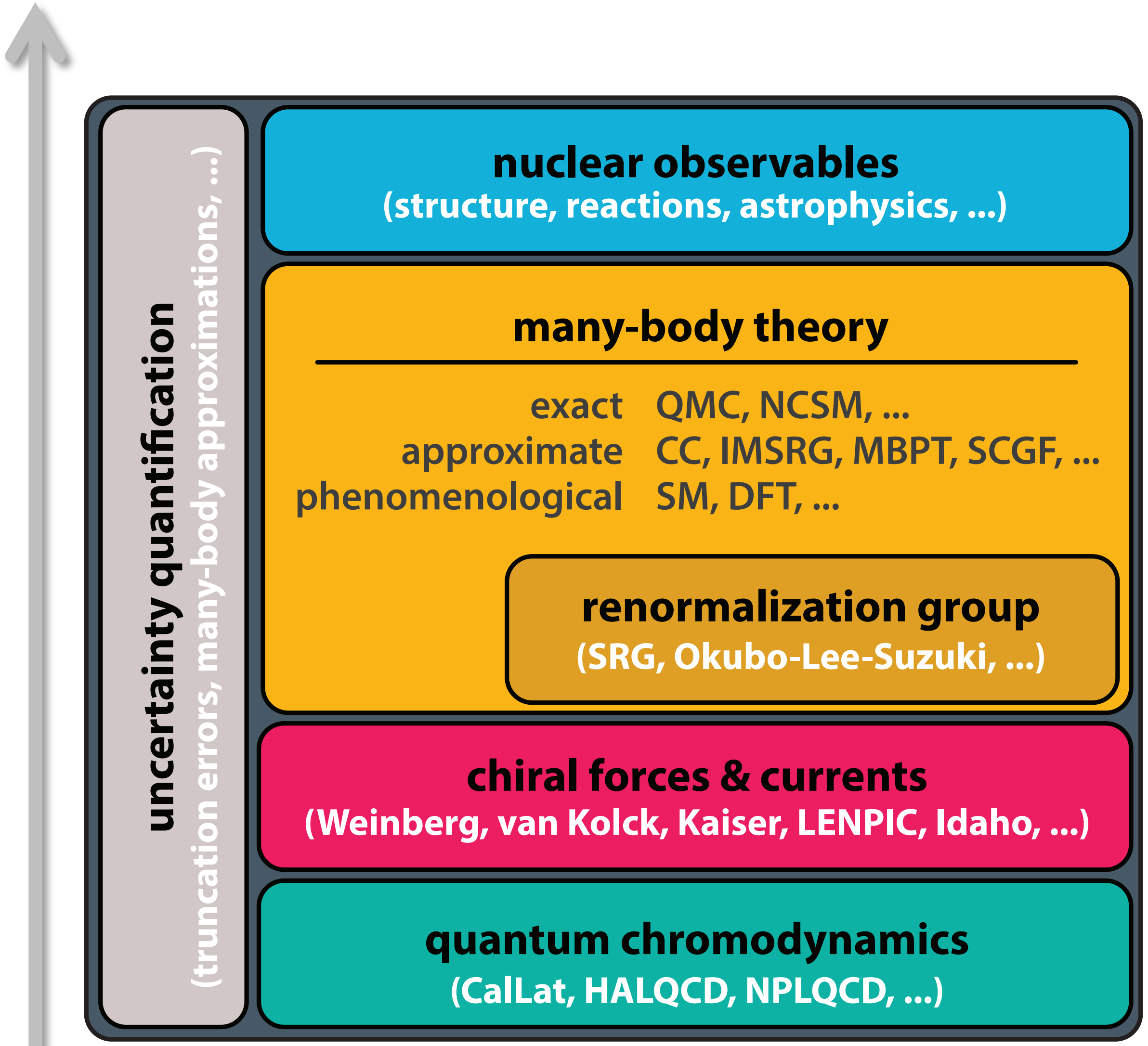

Recent highlight: *Ab initio* predictions link the neutron skin of ^{208}Pb to nuclear forces by Hu, Jiang *et al.*, arXiv:2112.01125

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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

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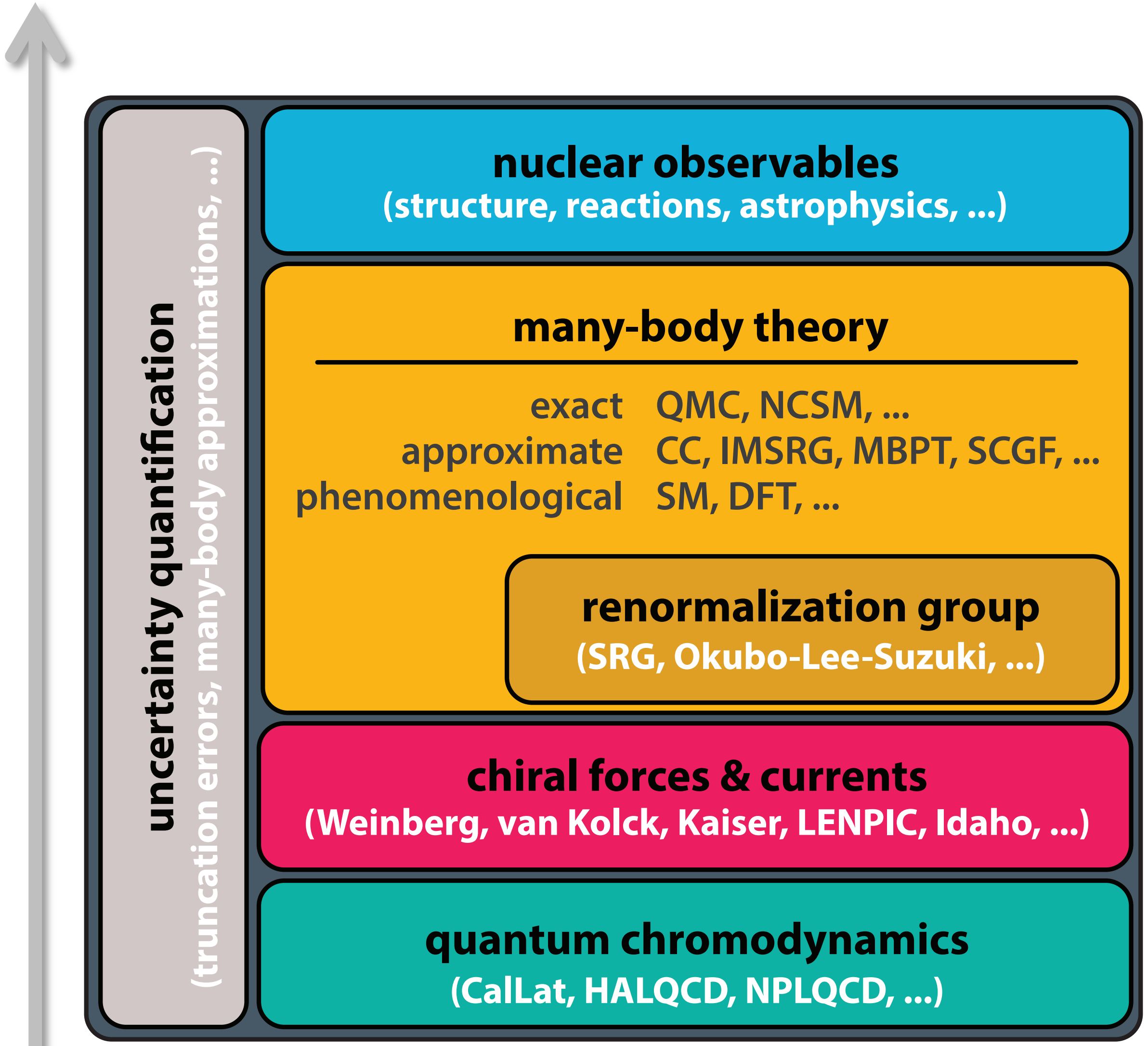

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> **See also Heiko Hergert's slides:**
> *A Status Update on*
> *Ab Initio Calculations in Nuclear Physics*

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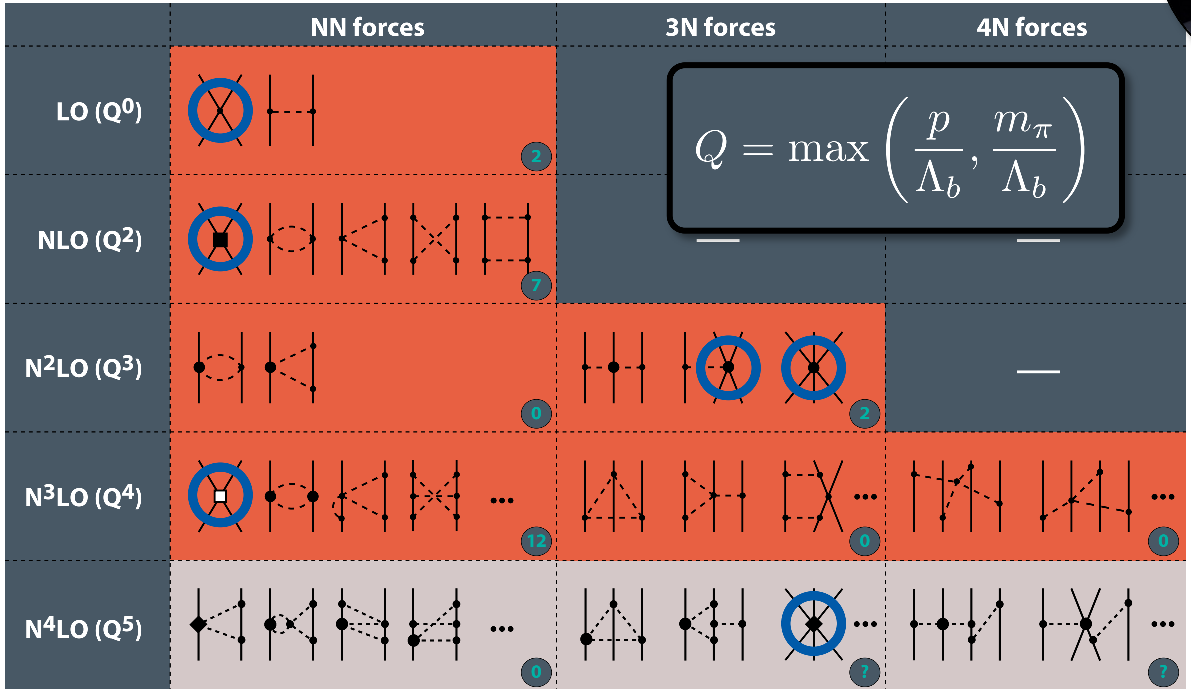
Rigorous UQ for nuclear matter

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



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^{3}LO

See also Evgeny Epelbaum's slides (LENPIC):
Chiral EFT for low-energy nuclear physics

See also Maria Piarulli's slides:
Analyzing the nuclear interaction: challenges and new opportunities

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

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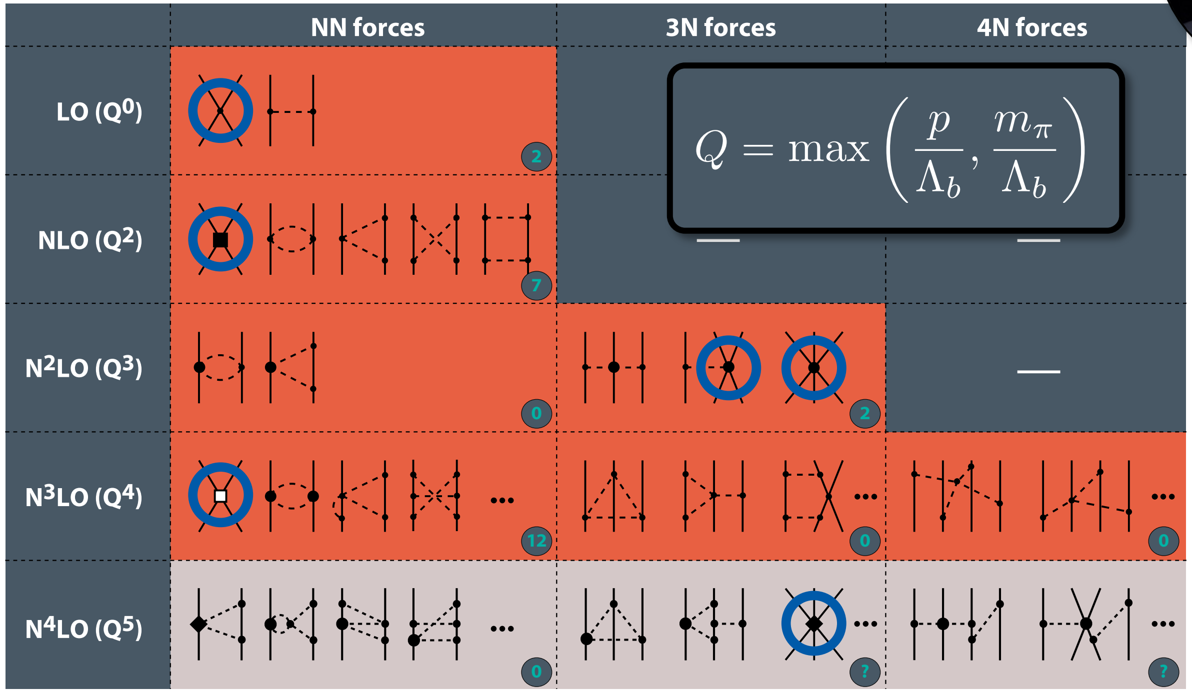

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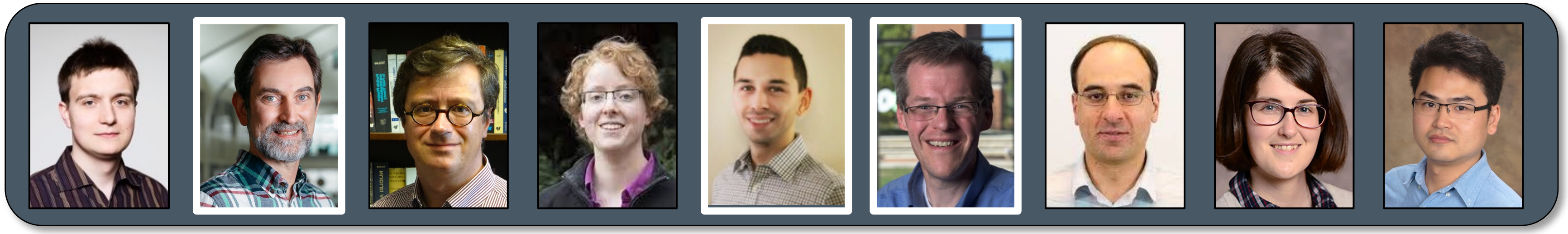
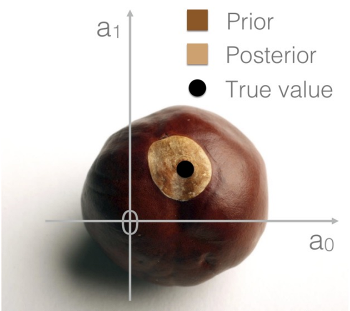
Bayesian methods are powerful tools for quantifying & propagating EFT uncertainties based on *falsifiable* model assumptions



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



Bayesian **U**ncertainty **Q**uantification: **E**rrors for **Y**our **E**FT

Rigorous UQ for nuclear matter

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

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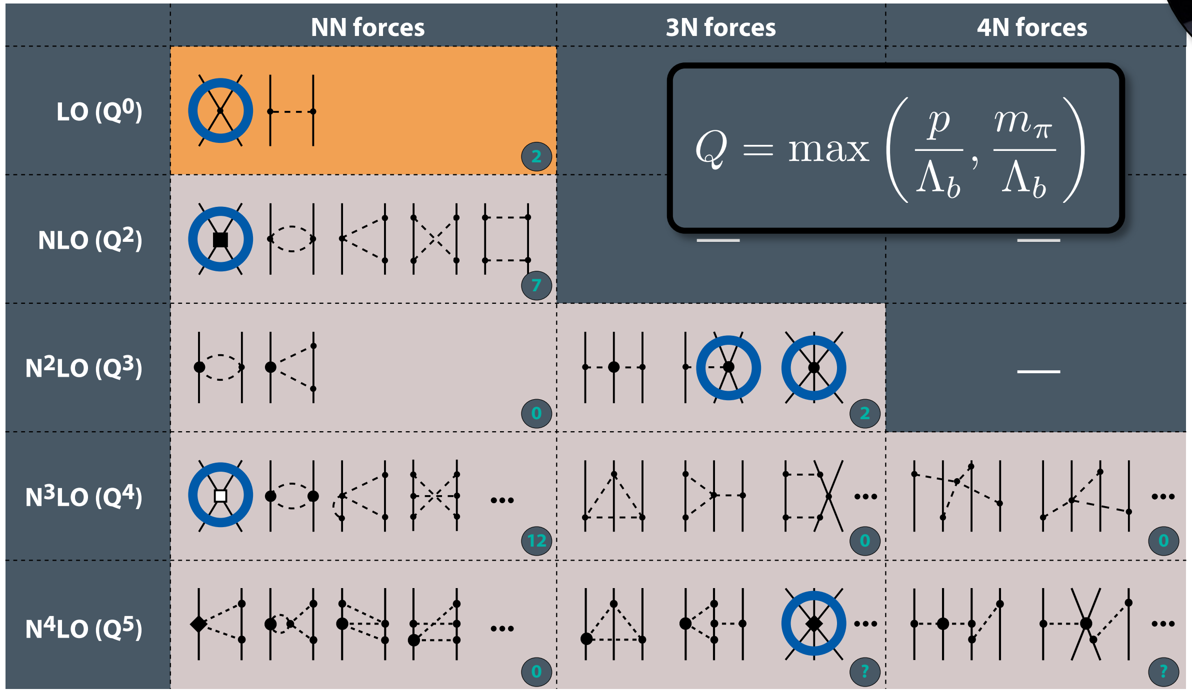

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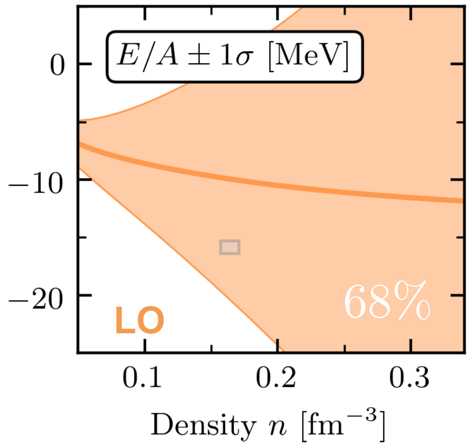
An example: symmetric matter

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

Uncertainty bands depict 68% credibility regions

$$y = y_k + \delta y_k$$



Rigorous UQ for nuclear matter

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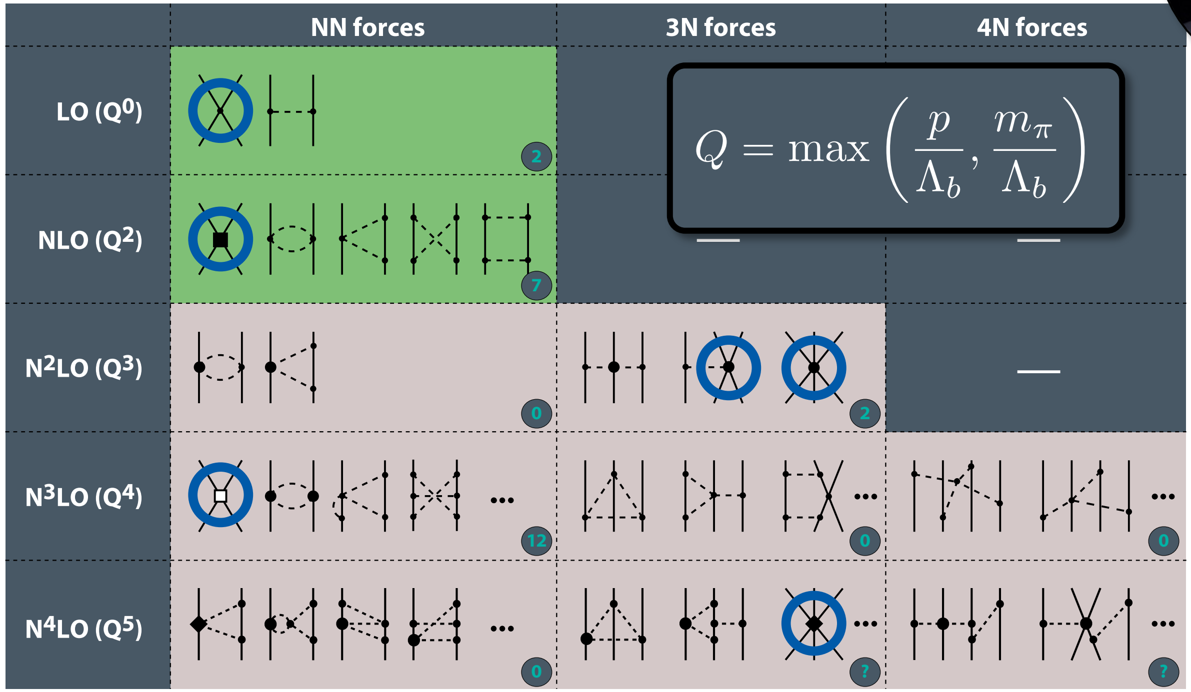

$$Q = \max\left(\frac{p}{\Lambda_b}, \frac{m_\pi}{\Lambda_b}\right)$$

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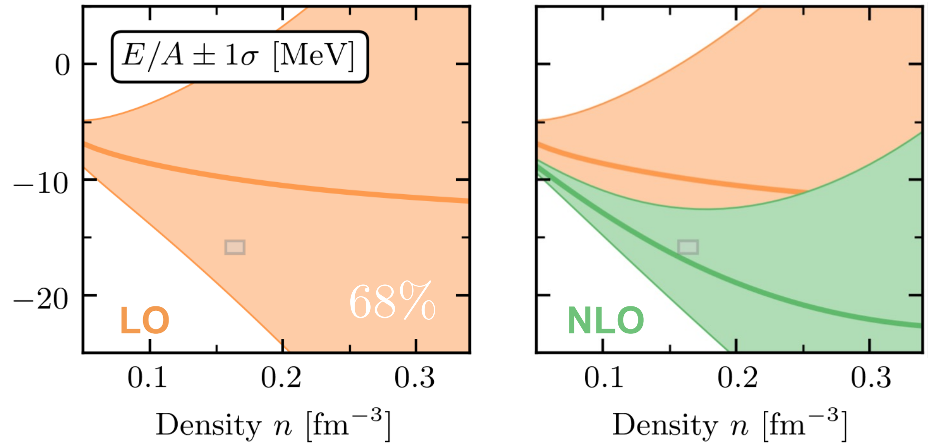

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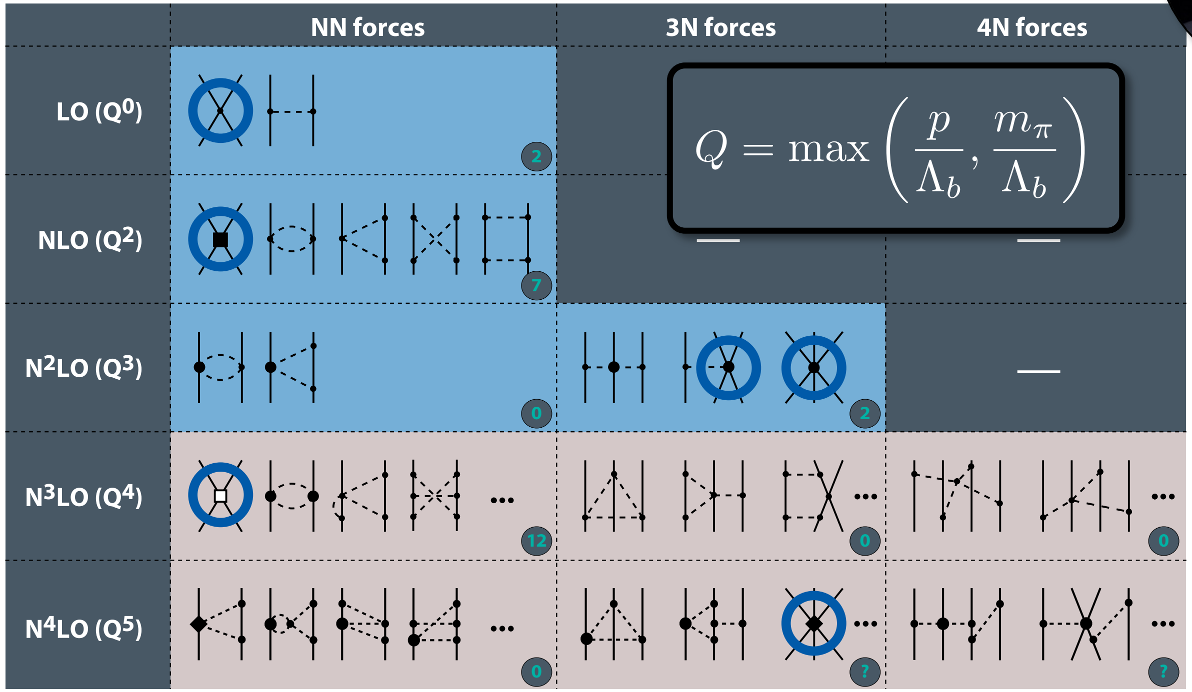

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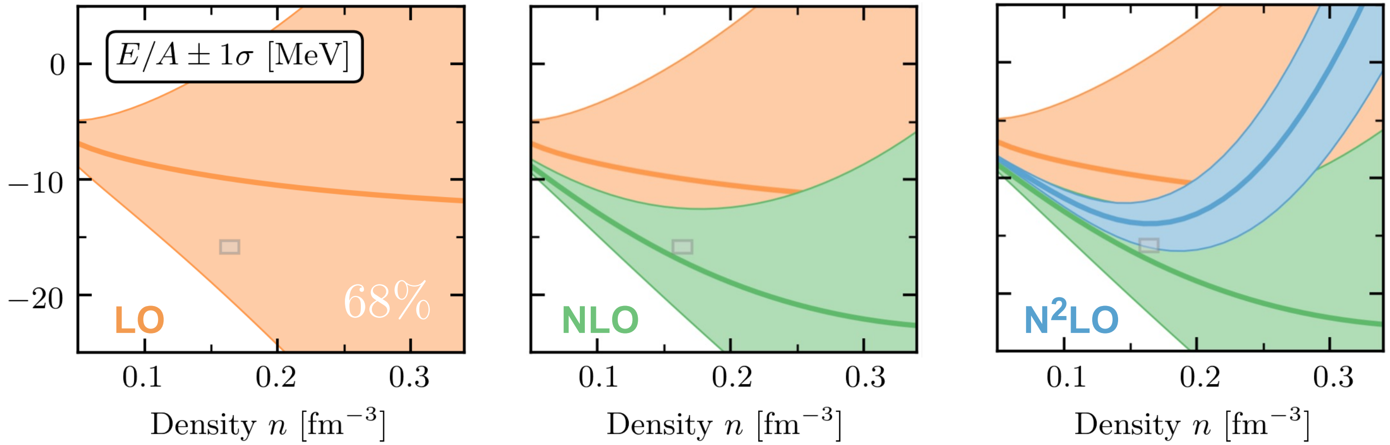

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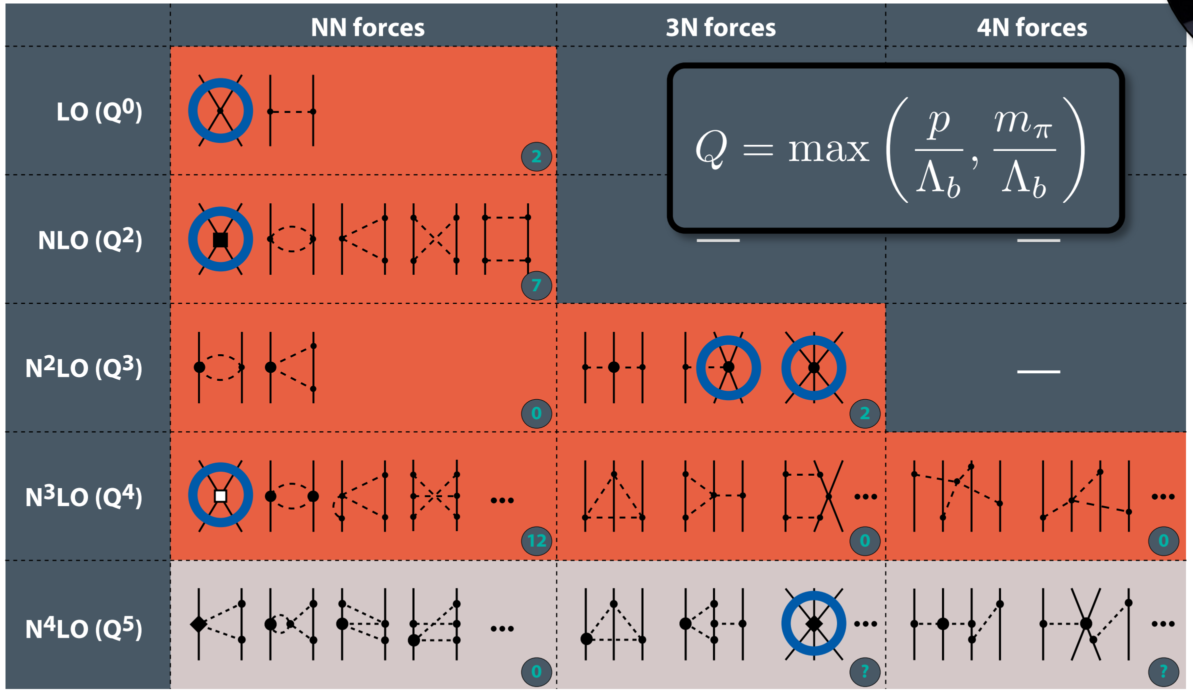

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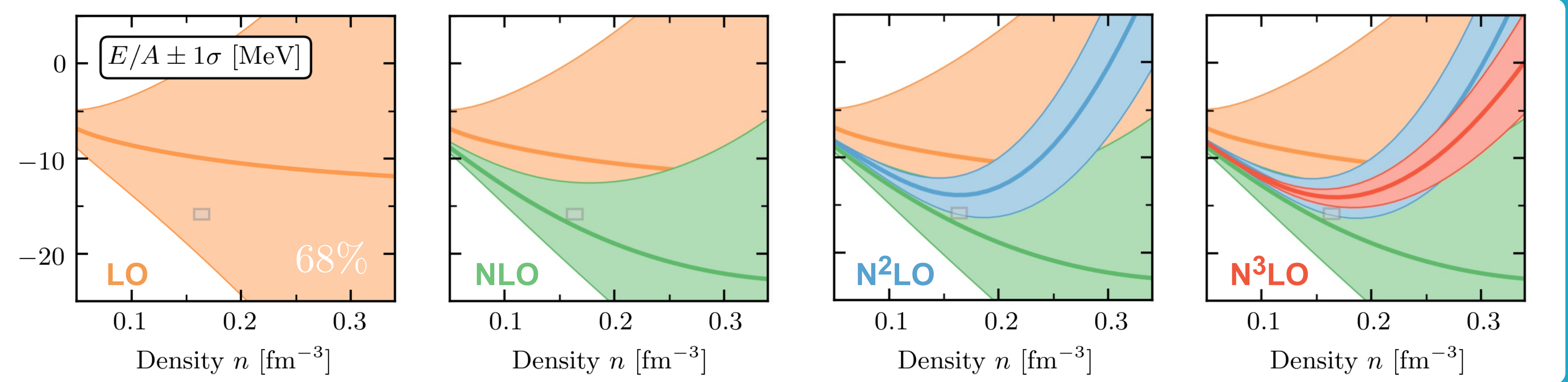

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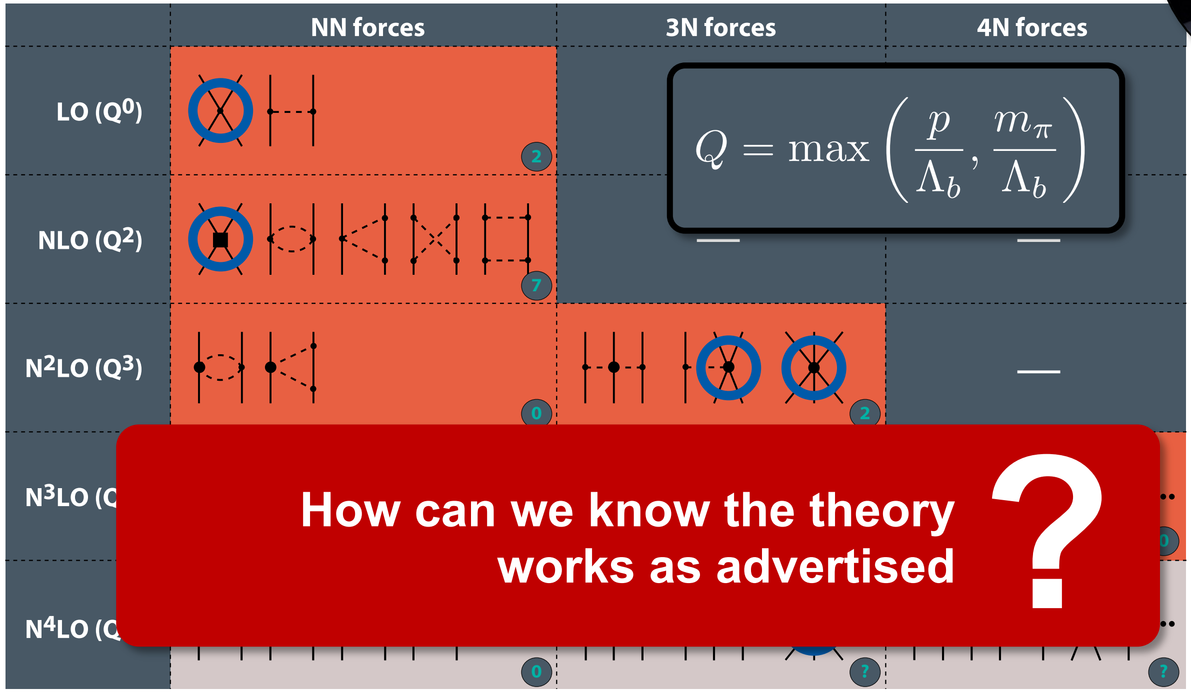

How can we know the theory works as advertised?

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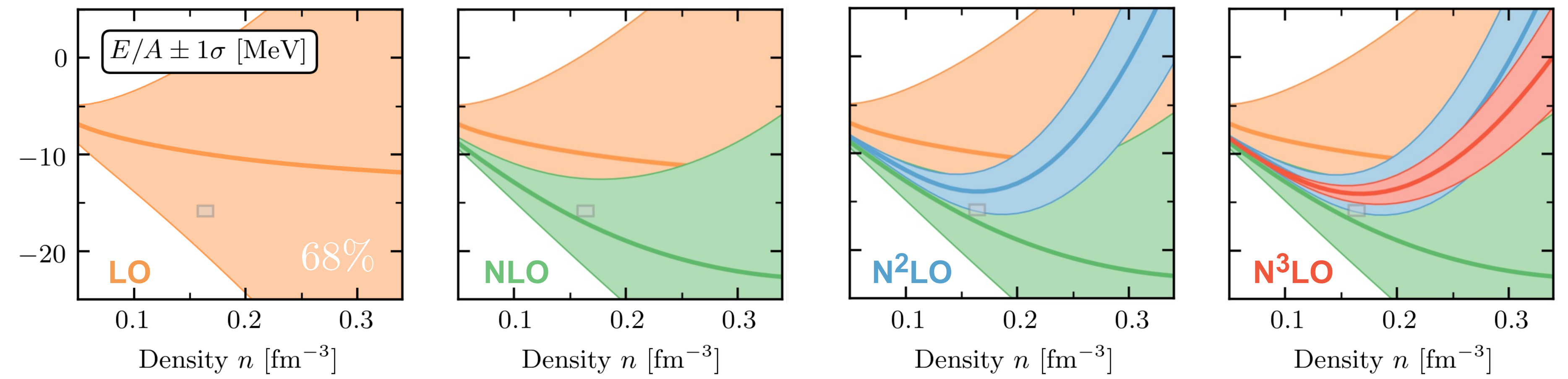

Ab initio workflow (idealized)

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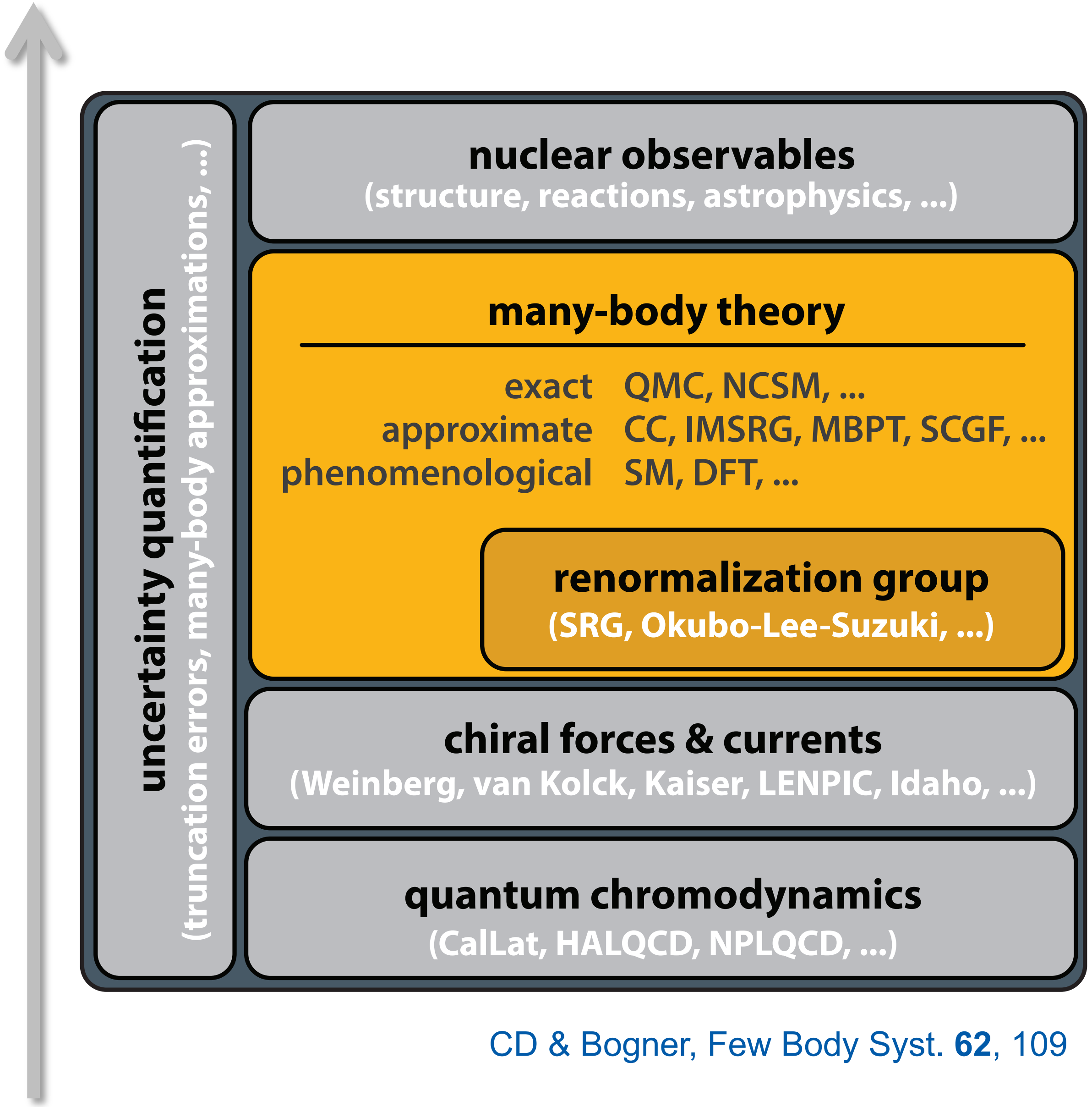

CD & Bogner, Few Body Syst. **62**, 109

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 (= 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

Ab initio workflow (idealized)

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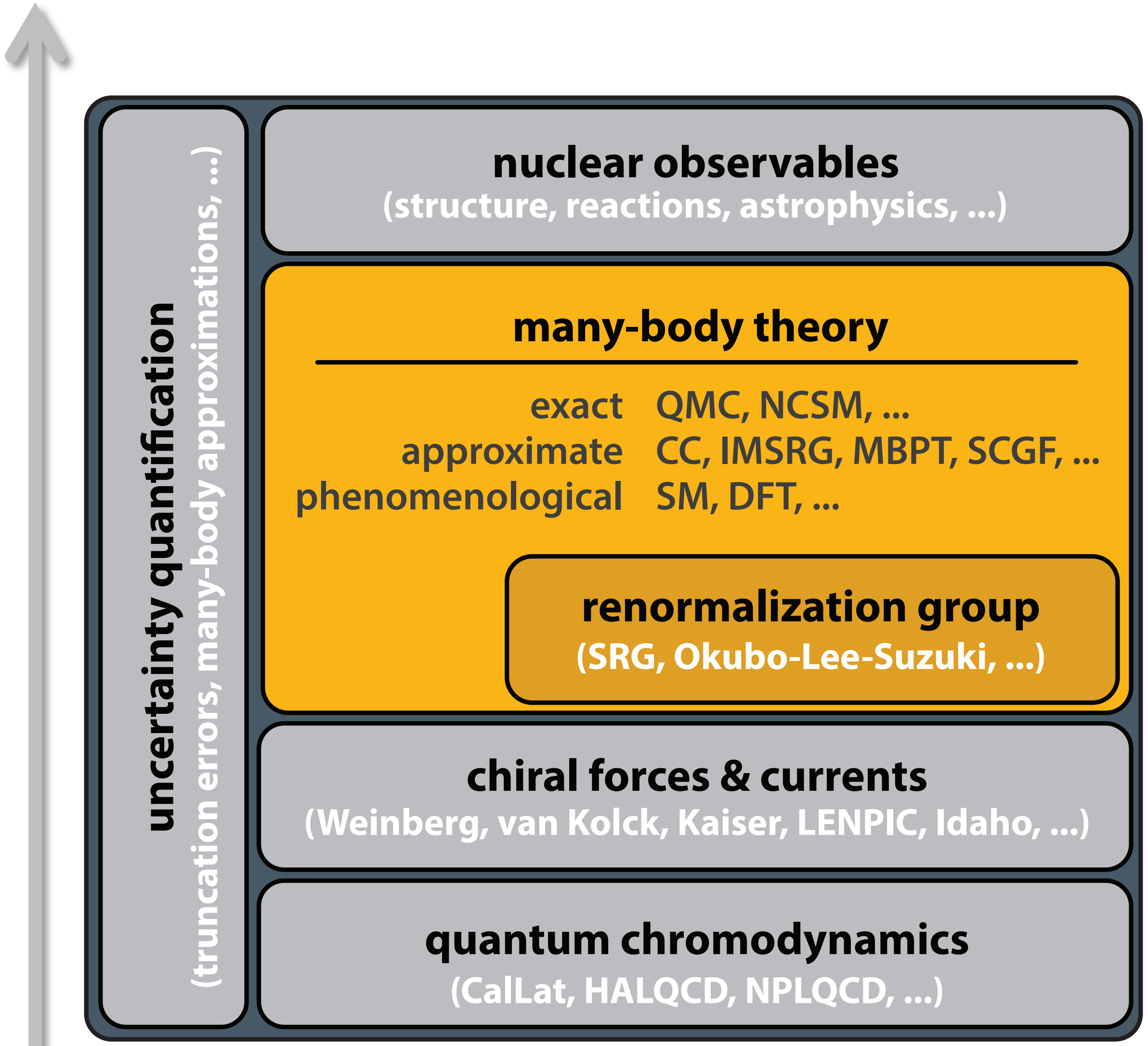

CD & Bogner, Few Body Syst. **62**, 109

Here: nuclear equation of state (EOS)

en

See also Stefano Gandolfi's slides:
Recent QMC calculations of properties of nuclei & nuclear matter

A temperature T (= 0)

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Renaissance of MBPT

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

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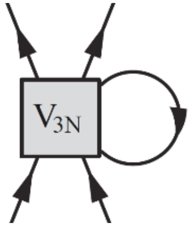
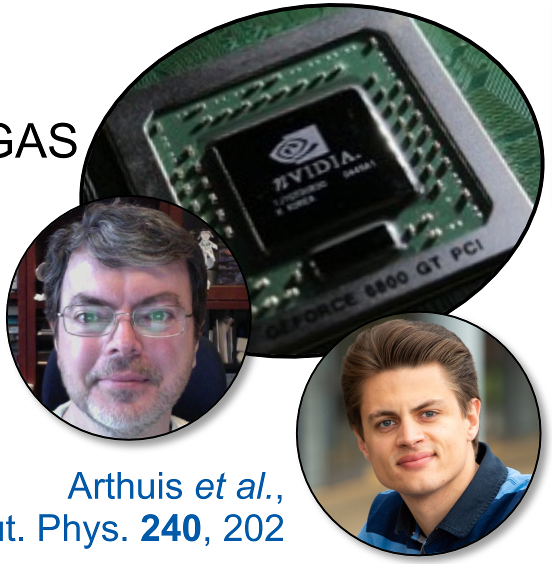
automated approach to MBPT for nuclear matter

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



- **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
- **controlled evaluation of 1000s of MBPT diagrams**



high-order MBPT calculations of the EOS

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

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

High-order MBPT for nuclear matter

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The number of diagrams increases rapidly!

	1,	**3,**	**39,**	**840,**	**27 300,**	**1 232 280,**	**…**
n =	2	3	4	5	6	7	

Integer sequence A064732:
Number of labeled Hugenholtz diagrams with n nodes.

with automated diagram generation » **automated approach to MBPT for nuclear matter**

Stevenson, Int. J. Mod. Phys. C **14**, 1135
Arthuis *et al.*, Comput. Phys. **240**, 202

for residual 3N contributions, see Xu, Li, and Xu, arXiv:1810.08804

MBPT: an HPC application

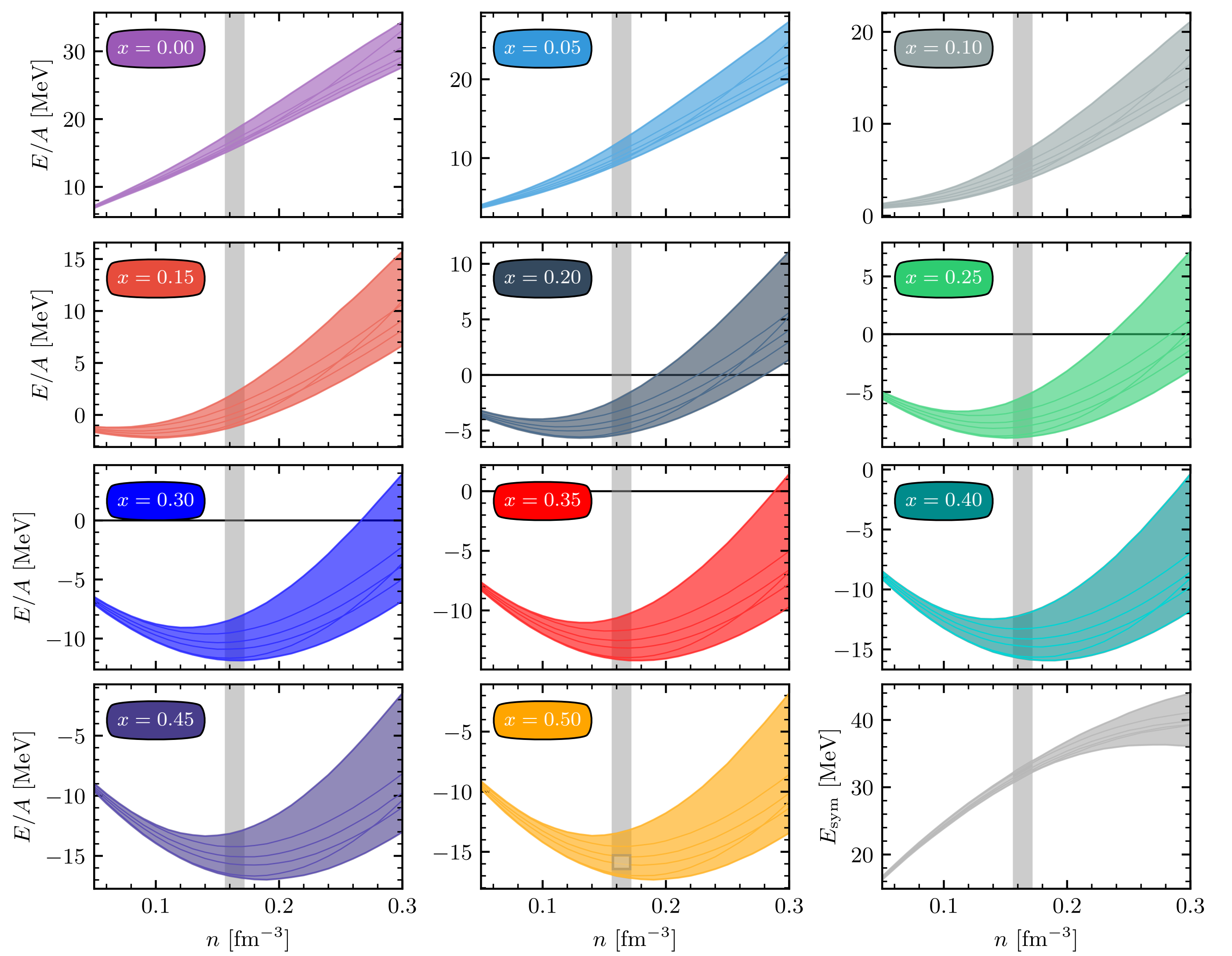
#2 (U.S.)

Summit @ Oak Ridge Leadership Computing Facility

202 752 CPU Cores
27 648 Nvidia GPUs

122.3 peta flops

MBPT: an HPC application



Drischler, McElvain *et al.*, in prep.

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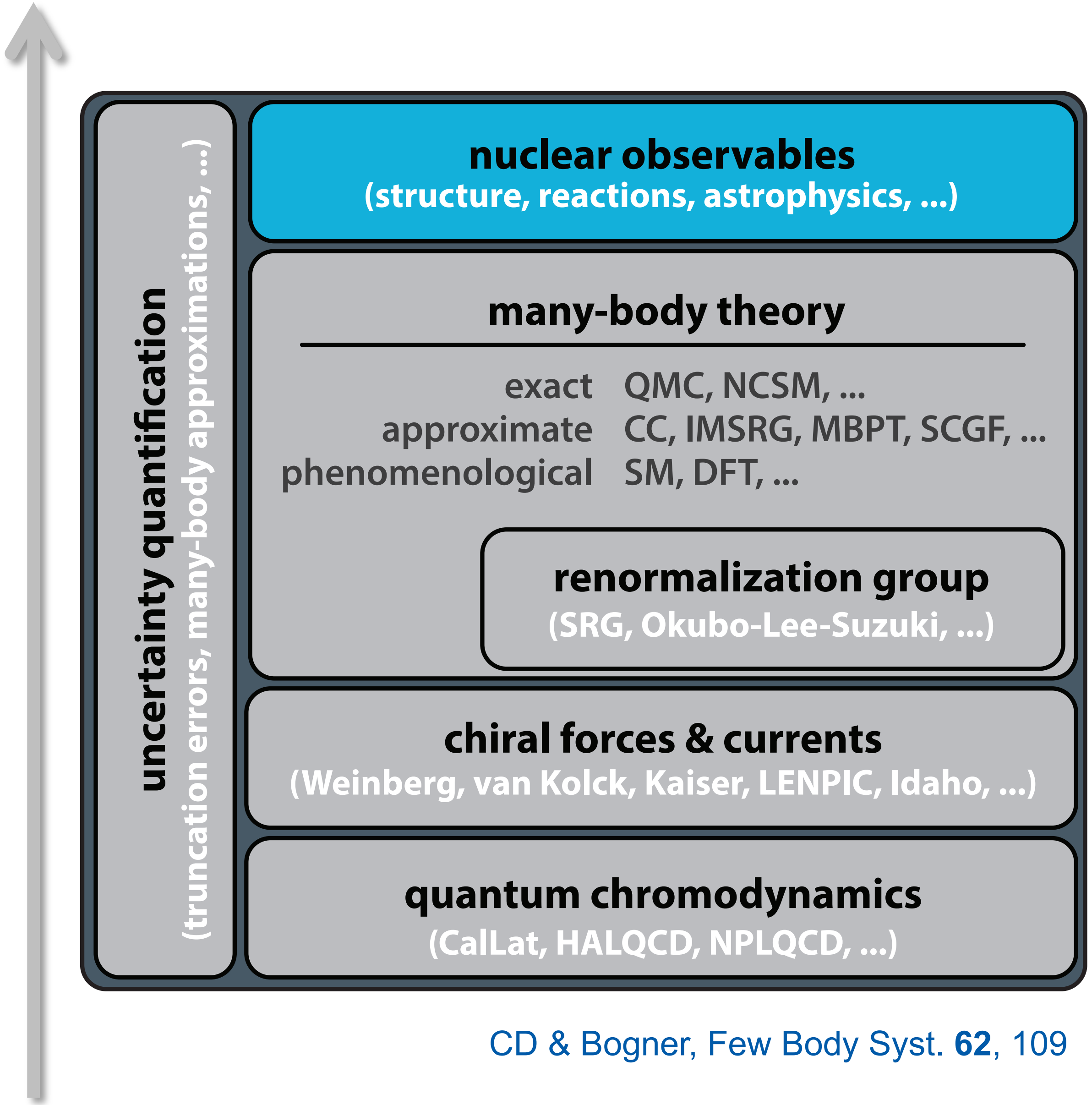

CD & Bogner, Few Body Syst. **62**, 109

nuclear EOS with quantified uncertainties

energy per particle (and derived quantities)

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temperature T (= 0)

Uncertainty quantification

robust estimates of theoretical uncertainties using Bayesian machine learning via Gaussian Processes

uncertainties in EFT-based calculations due to:

- **truncating the EFT expansion**
- **applying many-body (and other) approximations**
- **fitting LECs to experimental data**

First chiral potentials with uncertainties fully quantified and their applications:
Wesolowski, Svensson *et al.*, PRC **104**, 064001
Djärv, Ekstöm *et al.*, PRC **105**, 014005

Neutron matter | saturation in symmetric matter

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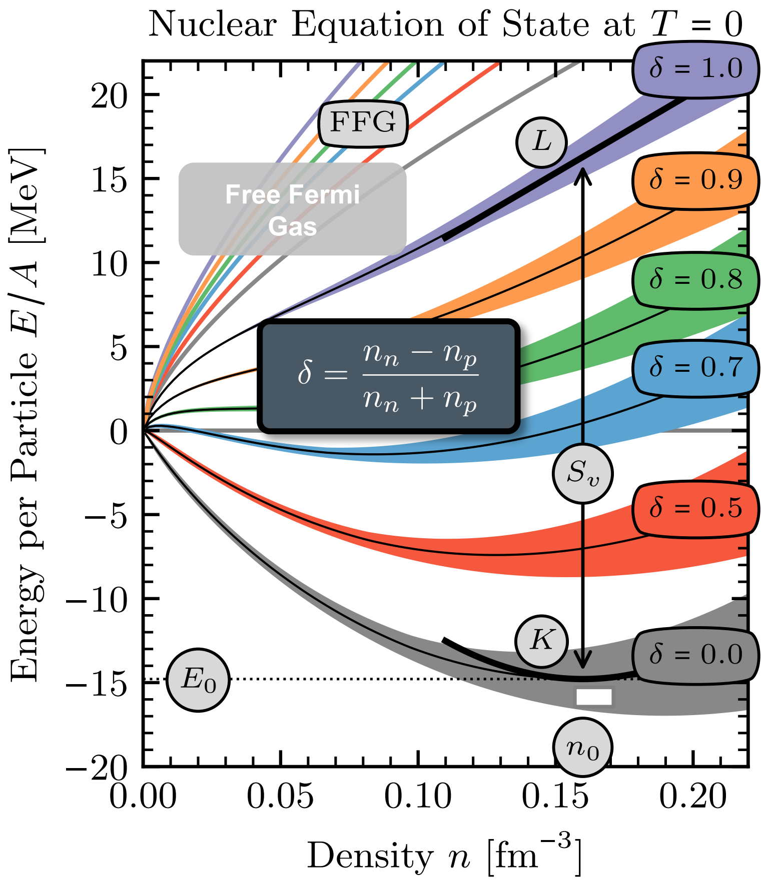
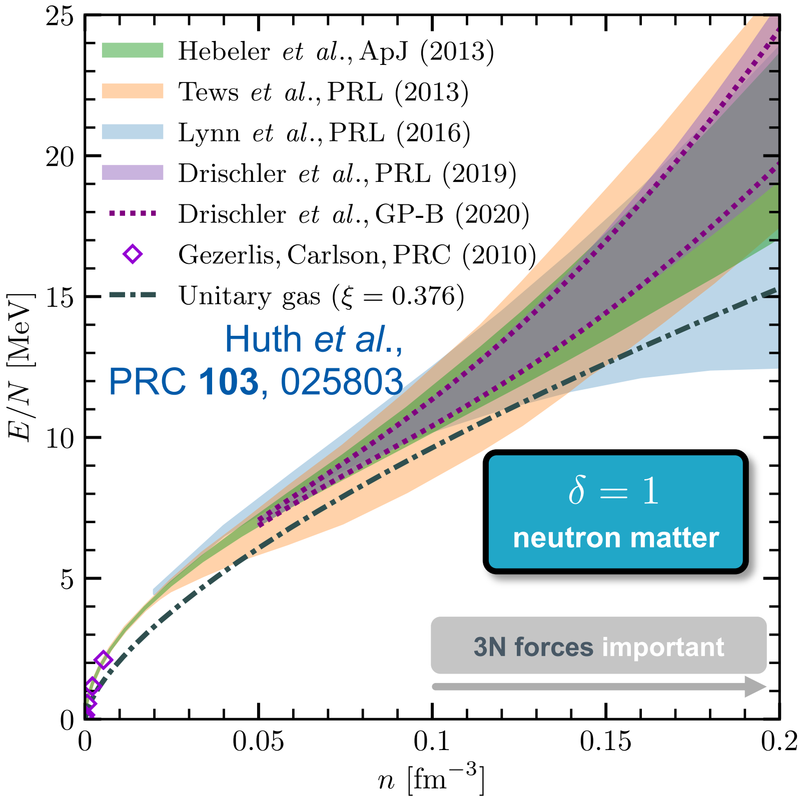
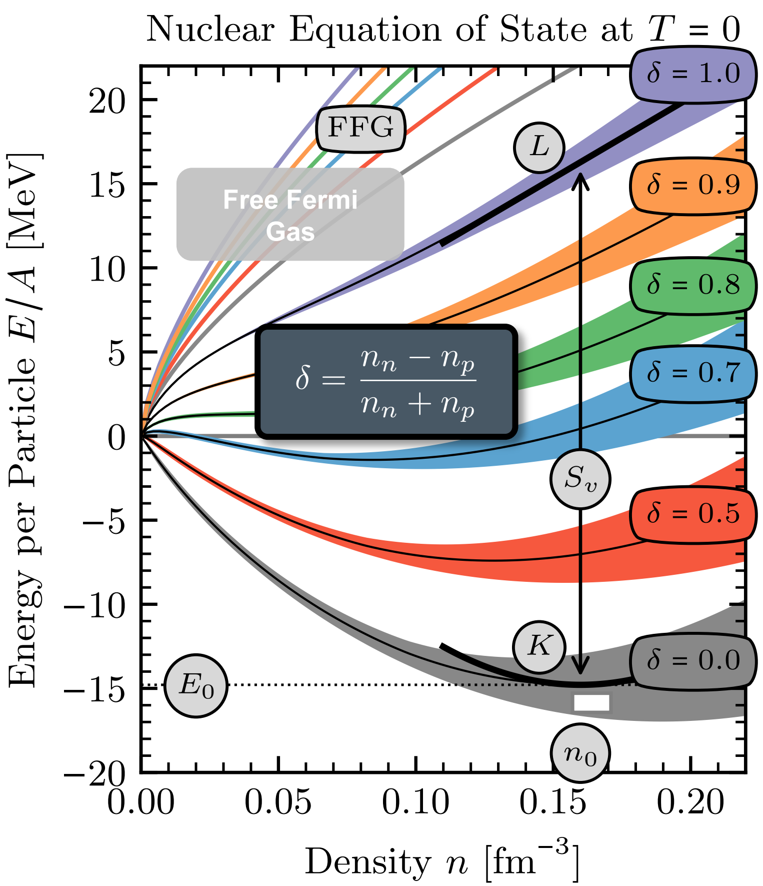
$$\frac{\mathrm{d}}{\mathrm{d}n}\frac{E}{A}(n,0)\Big|_{n=n_0} = 0$$

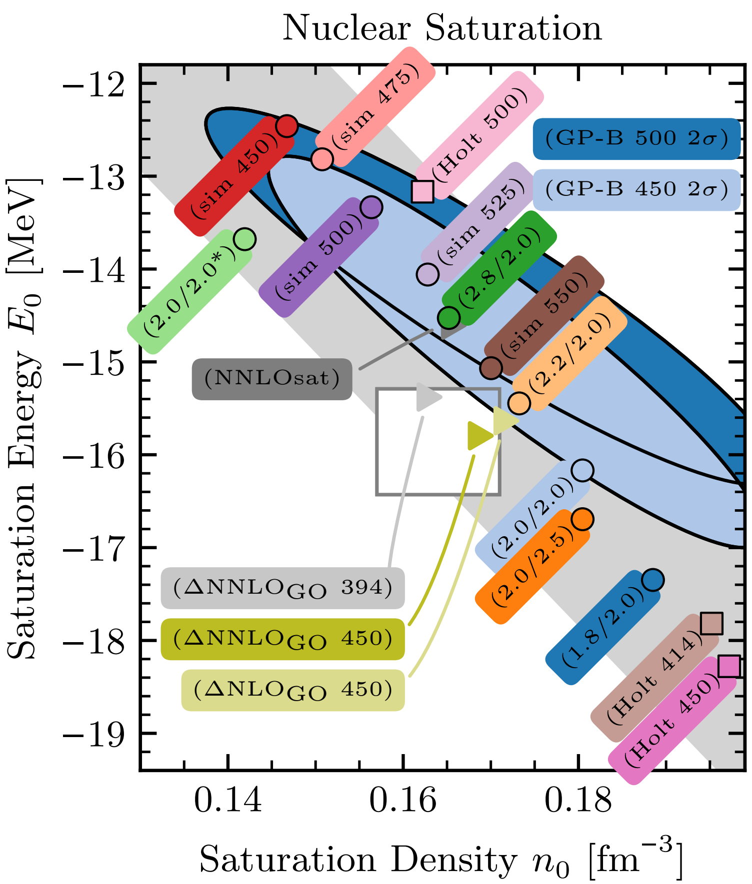




CD, Holt, and Wellenhofer, Annu. Rev. Nucl. Part. Sci. **71**, 403

Neutron matter | saturation in symmetric matter





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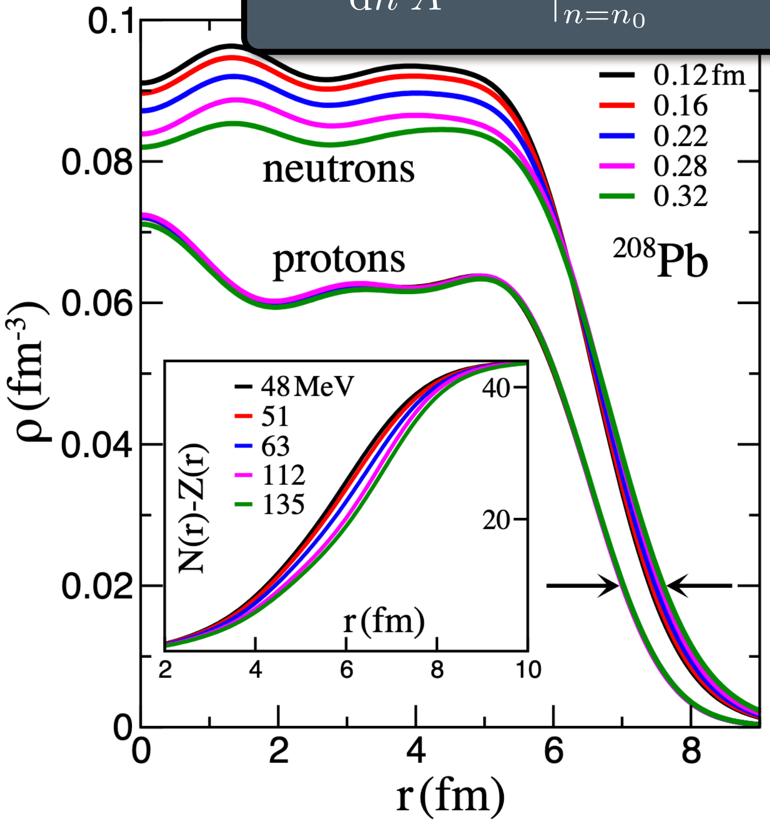

Piekarewicz & Fattoyev, Phys. Today **72**, 7

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

needed: improved predictions with novel NN+3N interactions and robust uncertainty quantification

Nuclear symmetry energy

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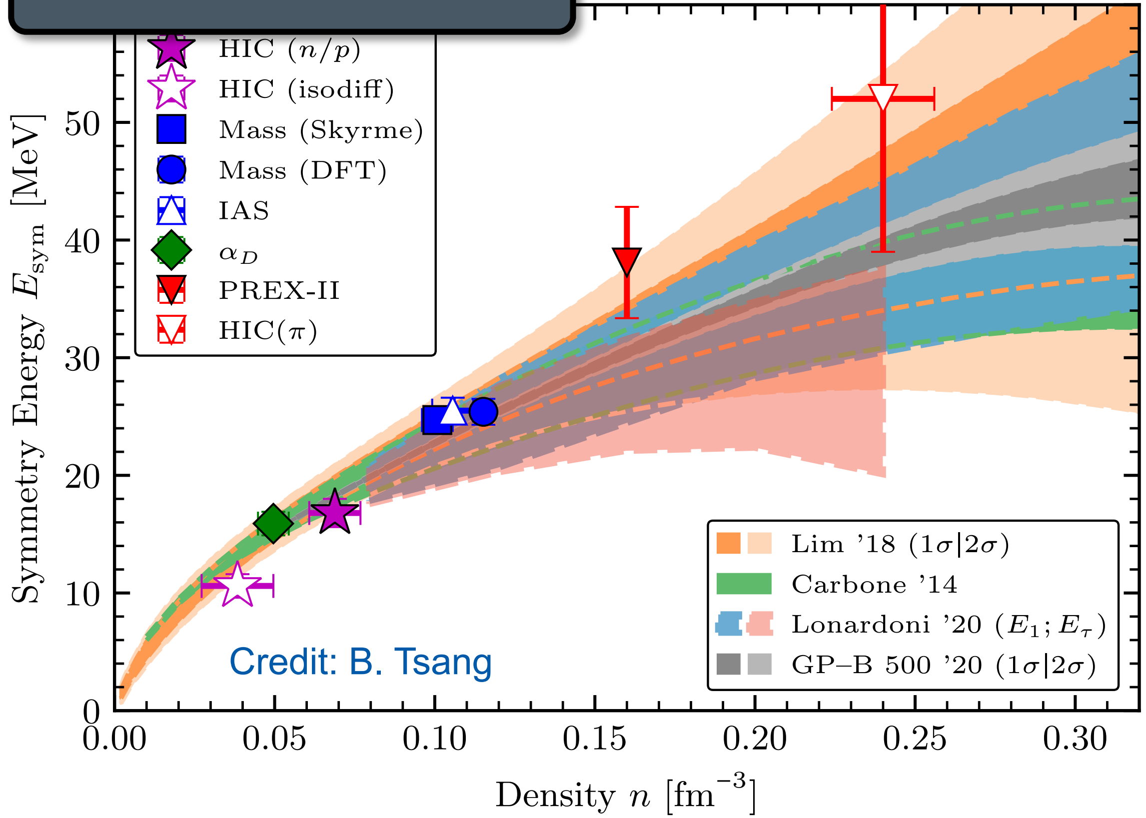
$$E_{\text{sym}}(n) \approx \frac{E}{N}(n) - \frac{E}{A}(n)$$



See also Betty Tsang's talk:
Symmetry Energy (Saturday)

Nuclear symmetry energy

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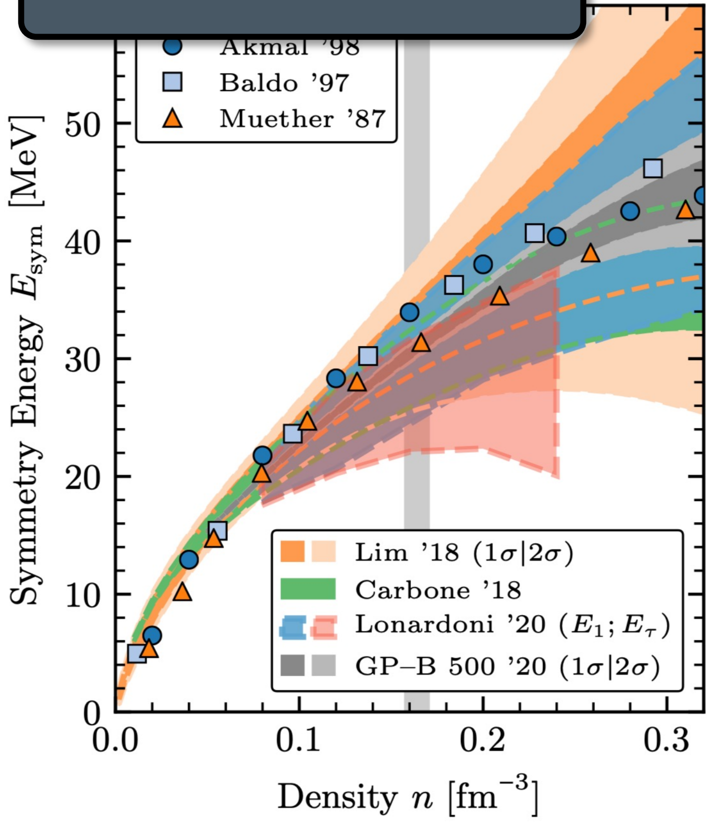
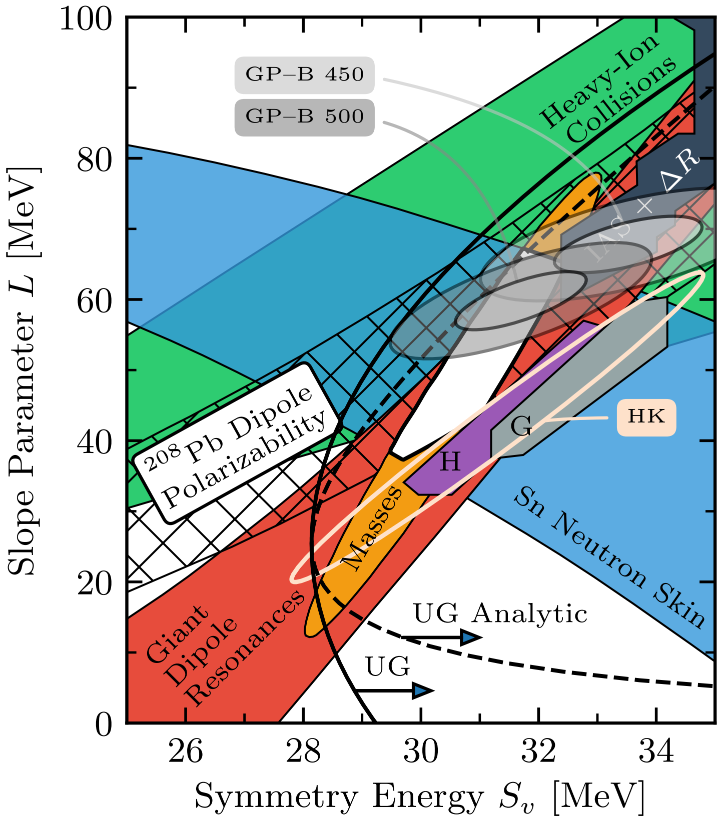


excellent agreement with experiment



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

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

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

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

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

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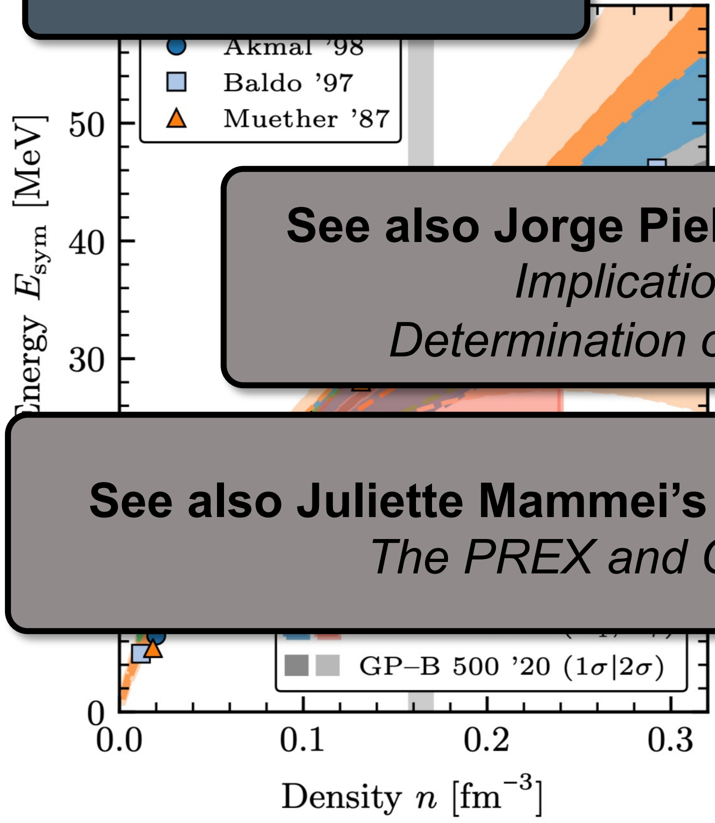

See also Jorge Piekarewicz's slides:
Implications of PREX for the Determination of the Nuclear EOS

See also Juliette Mammei's slides (next talk):
The PREX and CREX Experiments

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

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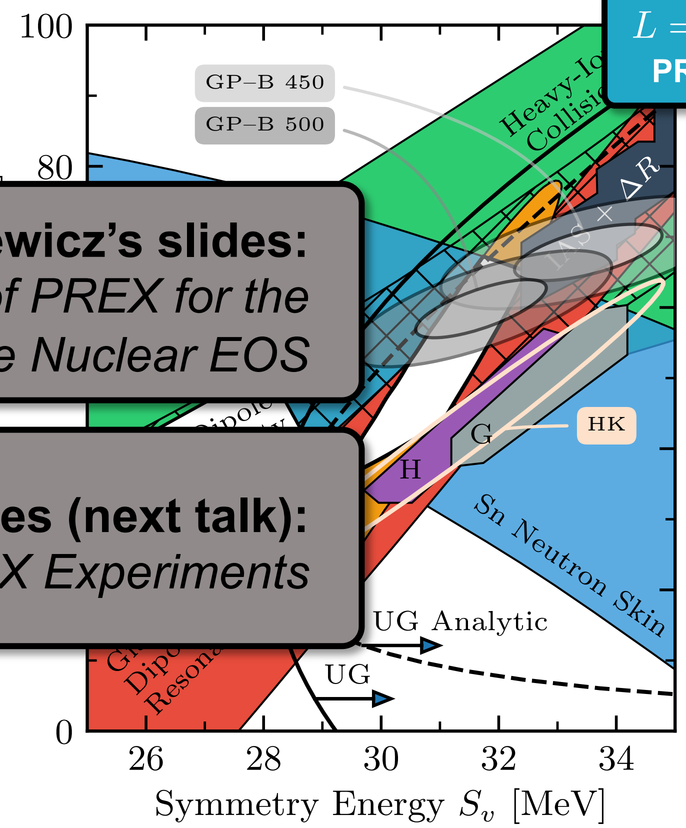
$L = 106 \pm 37$ MeV
PREX–II informed



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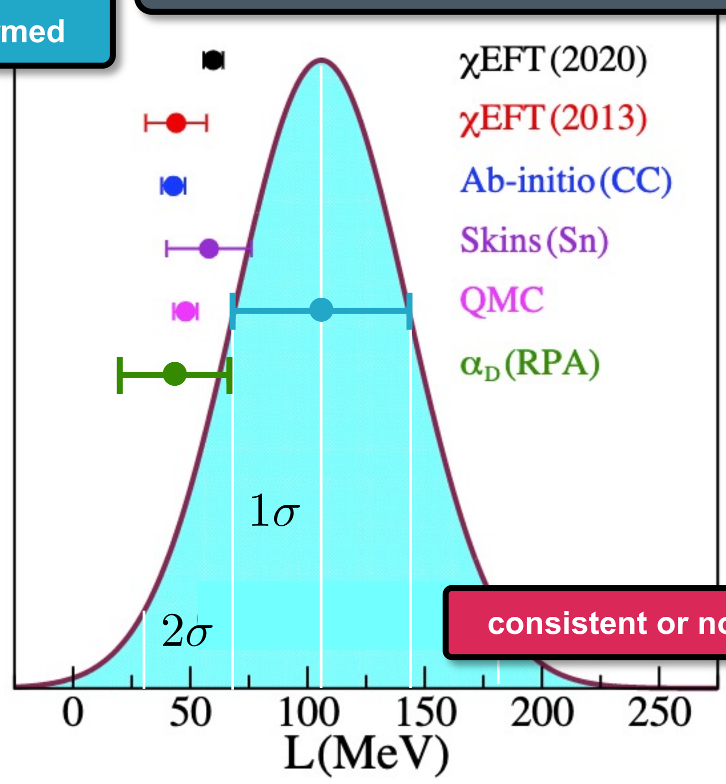

consistent or not?

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

Exploring the limits of chiral EFT

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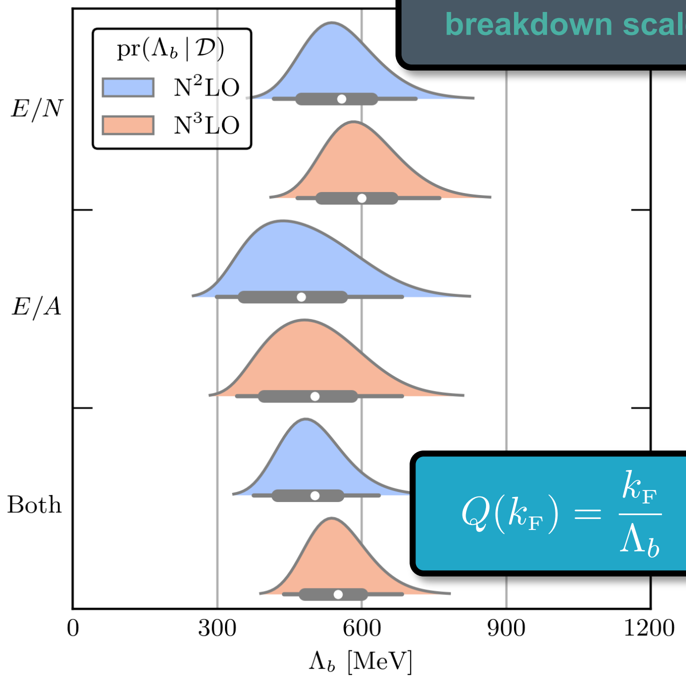


$\mathrm{pr}\,(\Lambda_b \,|\, \mathcal{D})$

breakdown scale

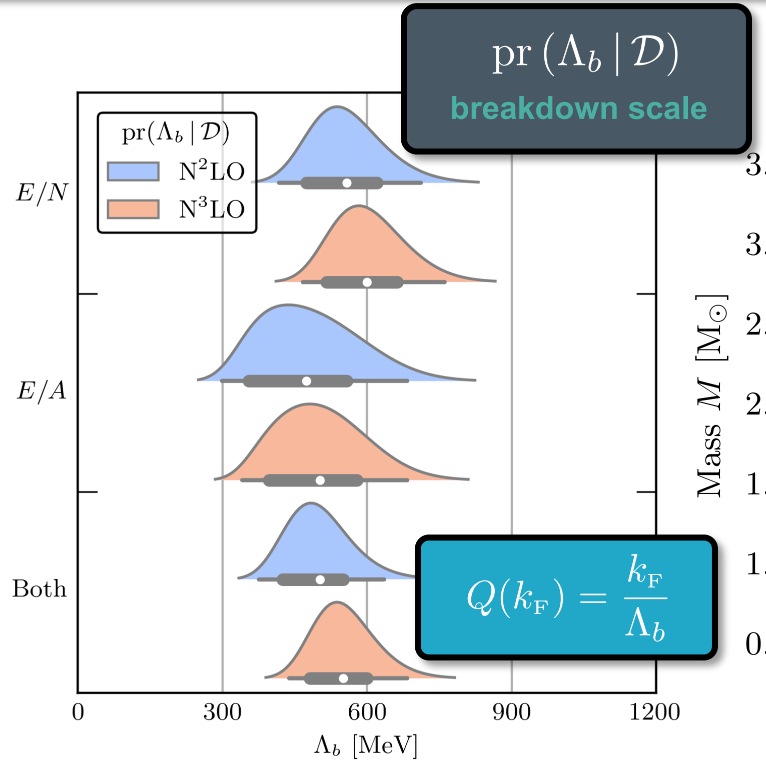
$$Q(k_F) = \frac{k_F}{\Lambda_b}$$

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

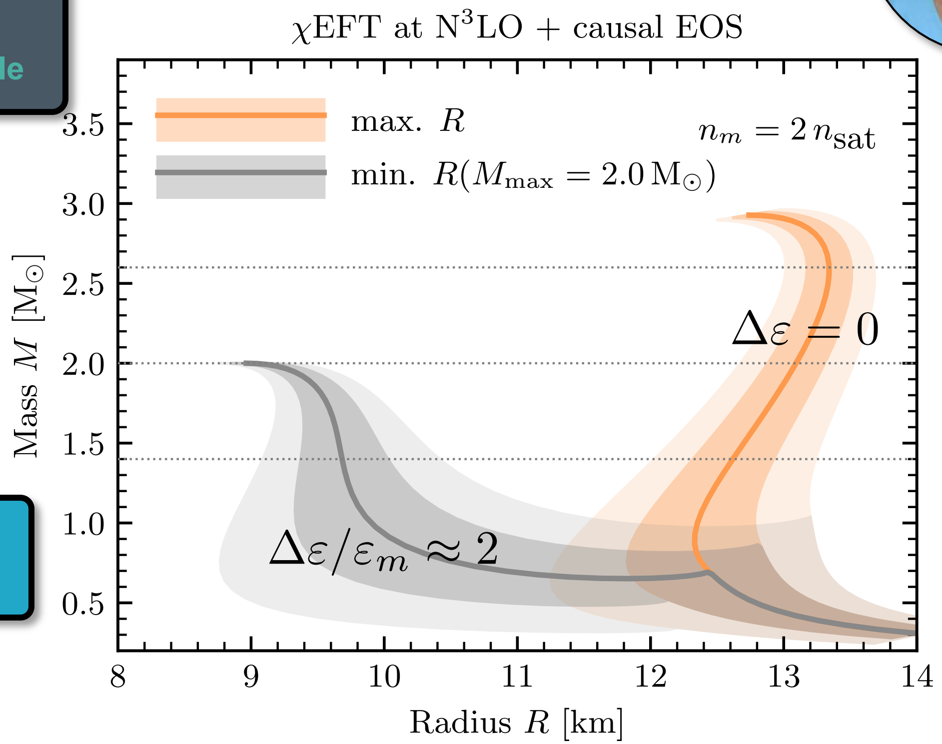
Bayesian inference of the in-medium breakdown scale

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

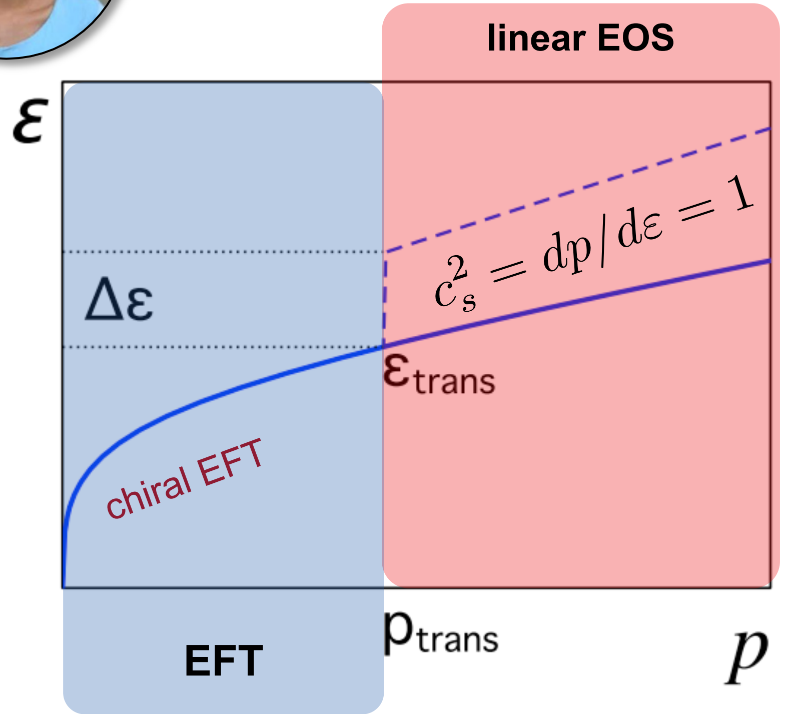
Exploring the limits of chiral EFT



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



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



Han & Prakash, APJ **899**, 2
Alford *et al.*, JPG: NPP **46**, 114001

Bayesian inference of the in-medium breakdown scale

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

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

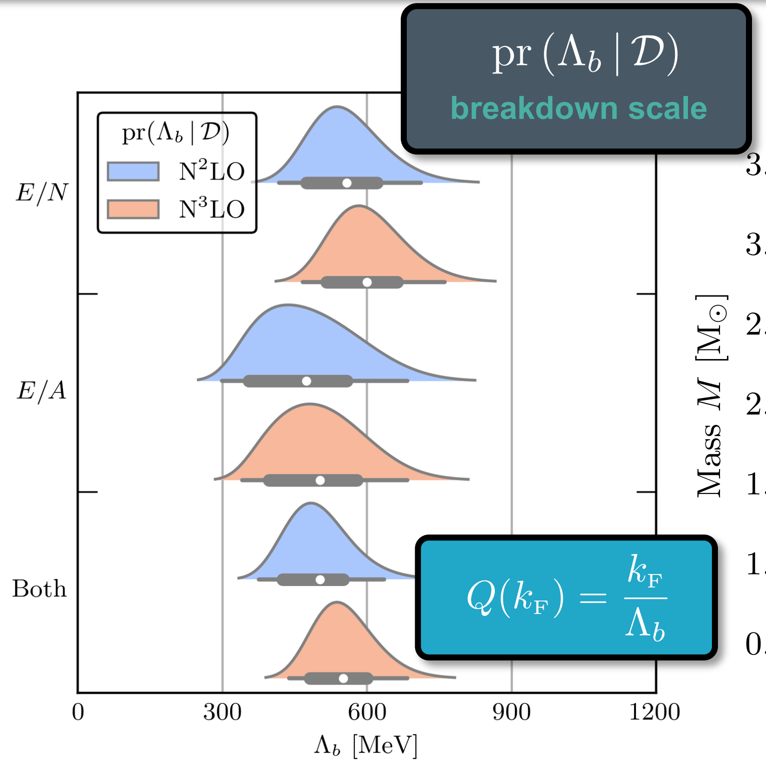
Riley *et al.*, AJL **918**, L27
Miller *et al.*, AJL **918**, L28

extend EFT EOS at n_m to linear EoS with finite discontinuity (softening)

continuous match sets upper bound

use **lower limit on M_{max}** from observation to adjust $\boldsymbol{\Delta\varepsilon}$ and constrain R_{min}

Exploring the limits of chiral EFT



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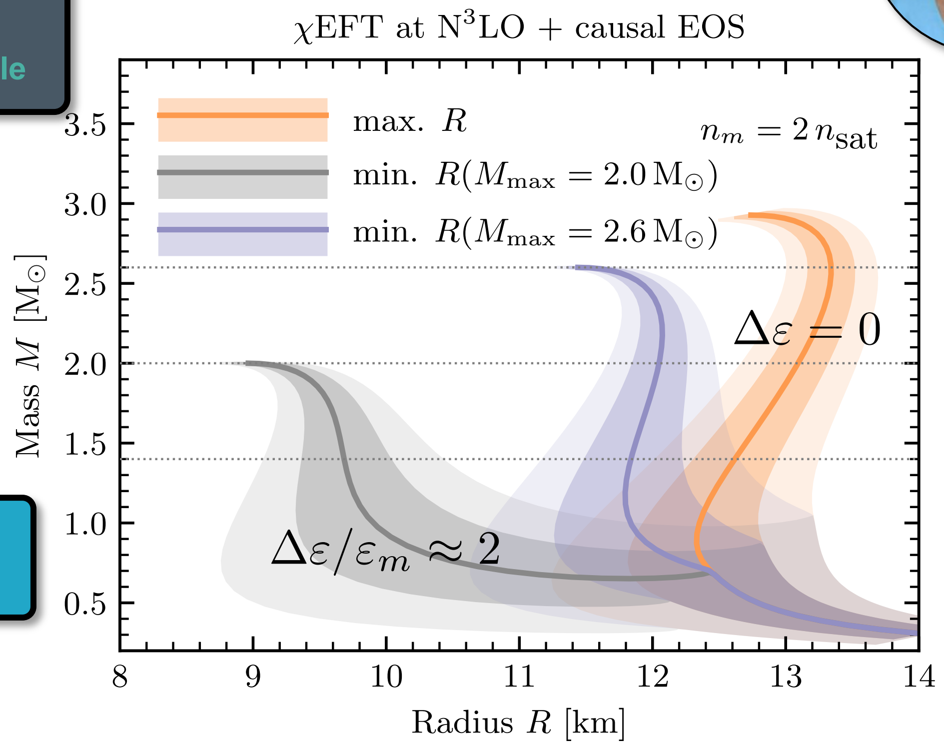

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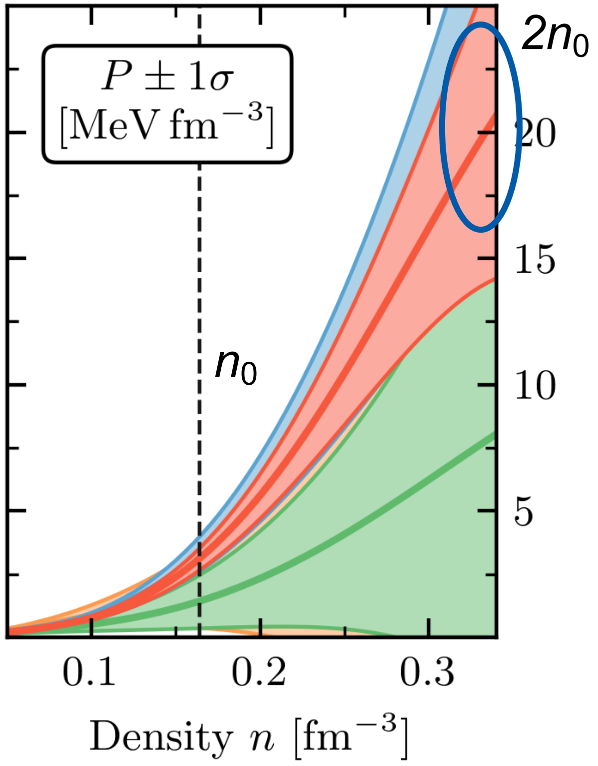
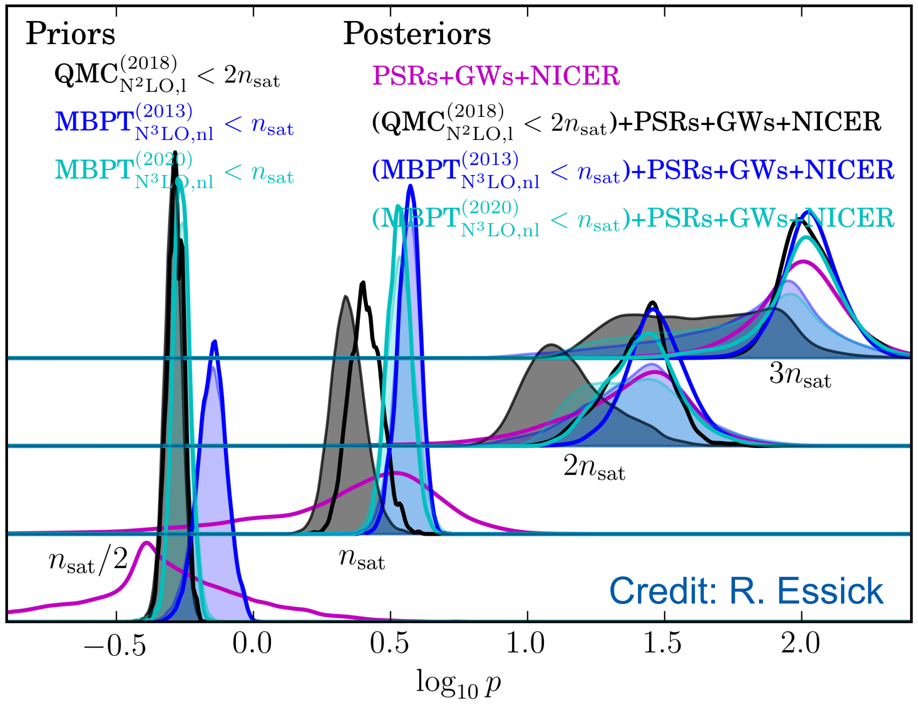
Direct astrophysical tests at supranuclear densities





CD, Furnstahl *et al.*, PRL **125**, 202702

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

Neutron star observations could be used for:

Model checking & selection of chiral interactions

Constraints on coupling constants in nuclear forces

$$P(n = 0.32\,\mathrm{fm}^{-3}) \approx \begin{cases} 20 \pm 6\,\mathrm{MeV\,fm}^{-3} & \text{MBPT: nonlocal} \\ 15 \pm 5\,\mathrm{MeV\,fm}^{-3} & \text{QMC: local } V_{E,\mathbb{1}} \end{cases}$$

Direct astrophysical tests at supranuclear densities

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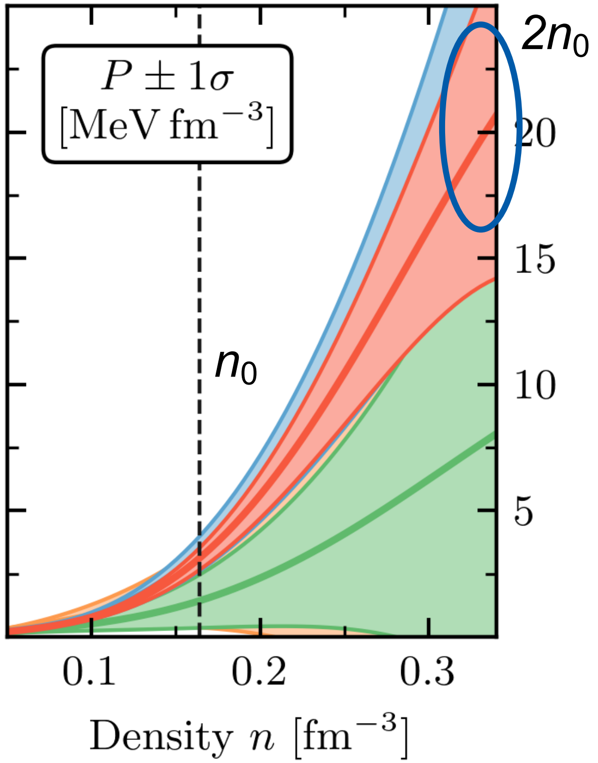
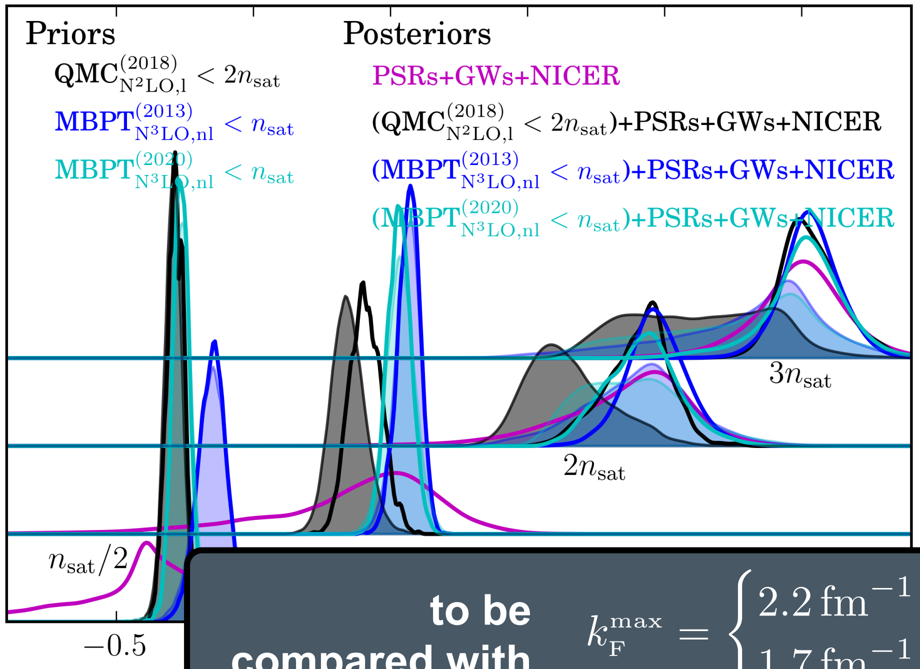
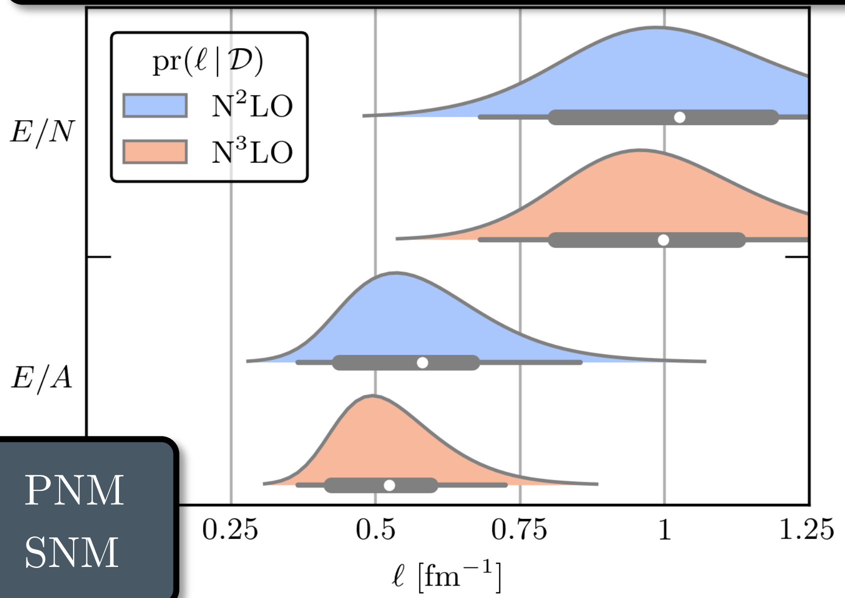




How correlated is nuclear matter ? $\mathrm{pr}(\ell \mid \mathcal{D})$ correlation length



to be compared with $k_{\mathrm{F}}^{\max} = \begin{cases} 2.2\,\mathrm{fm}^{-1} & \mathrm{PNM} \\ 1.7\,\mathrm{fm}^{-1} & \mathrm{SNM} \end{cases}$

CD, Furnstahl *et al.*, PRL **125**, 202702

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

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

EFT truncation error is *highly* correlated

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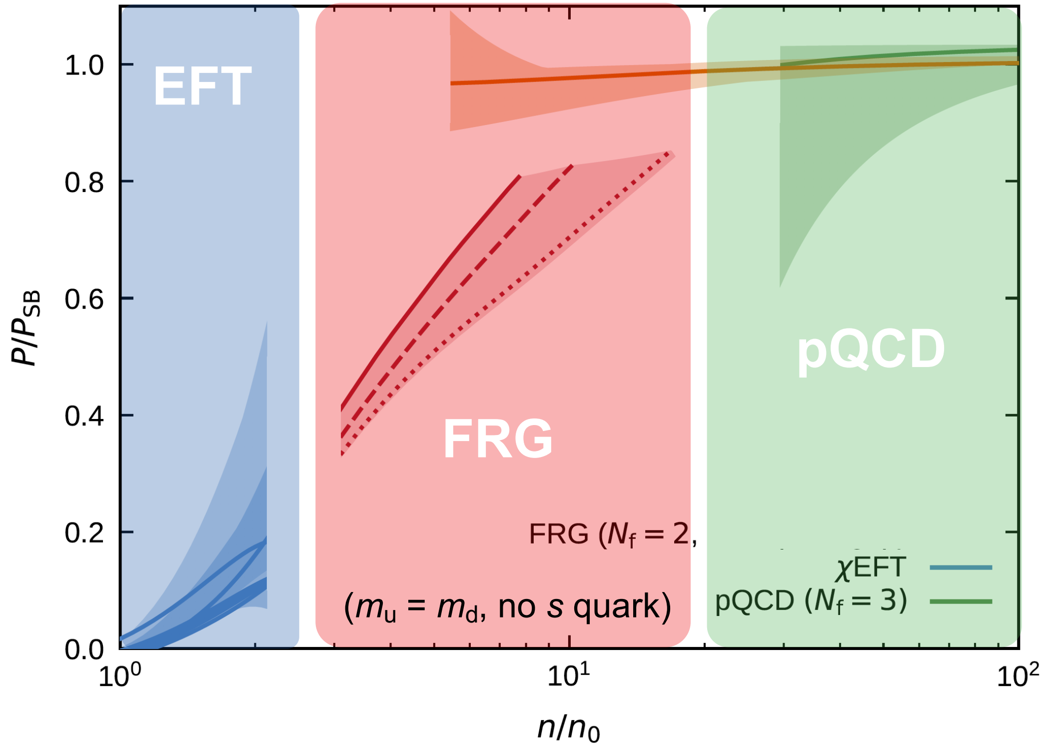
New predictions in SNM at intermediate densities



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

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

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

Bayesian Analysis of Nuclear Dynamics

BAND Manifesto,
Phillips, Furnstahl, Heinz *et al.*,
JGP: NP **48** 07200

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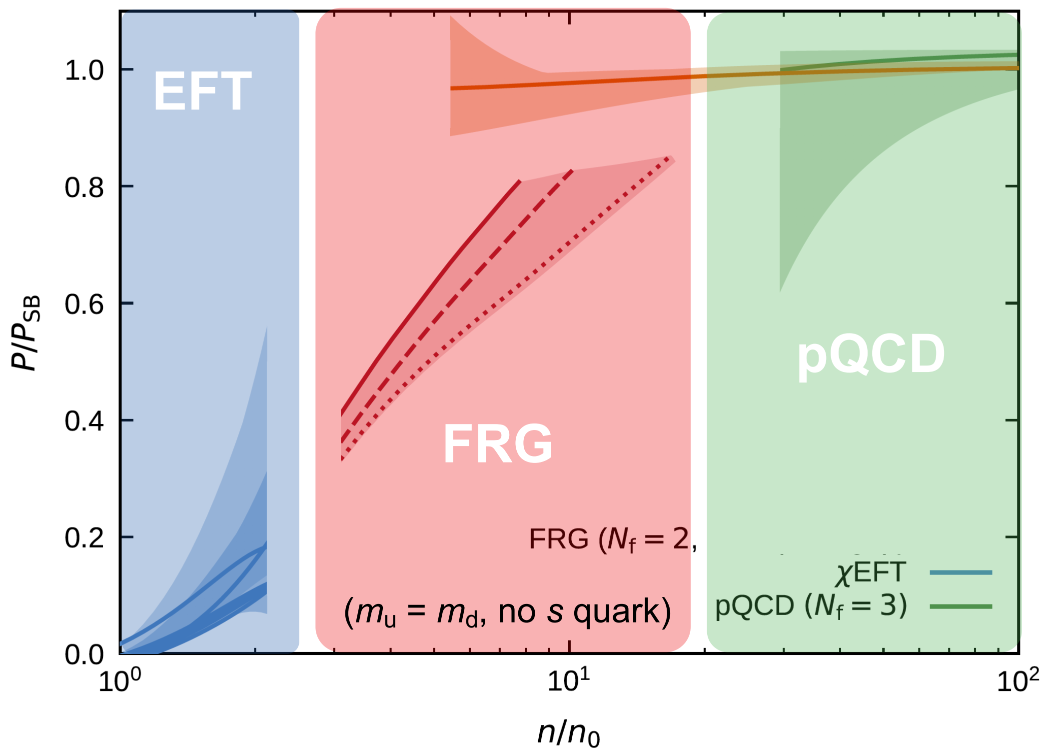
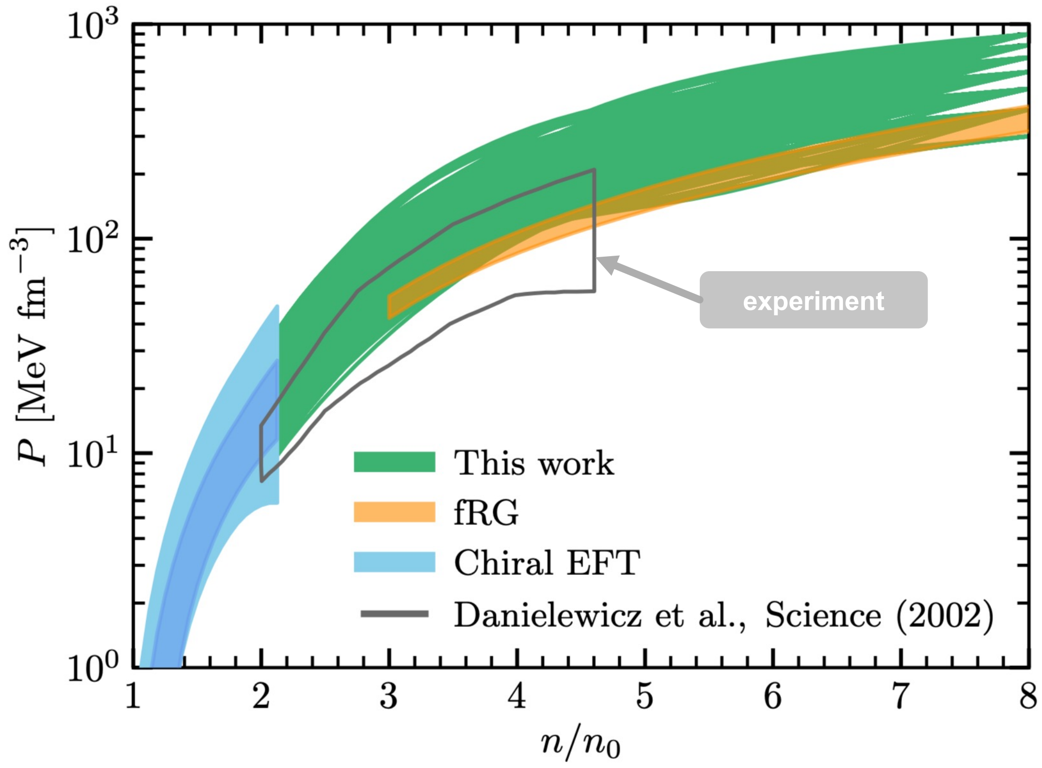


Leonhardt, Pospiech, Schallmo, Braun, CD, Hebeler, and Schwenk, PRL **125**, 142502



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

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for neutron star matter, 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** 07200

More details? Recent review article

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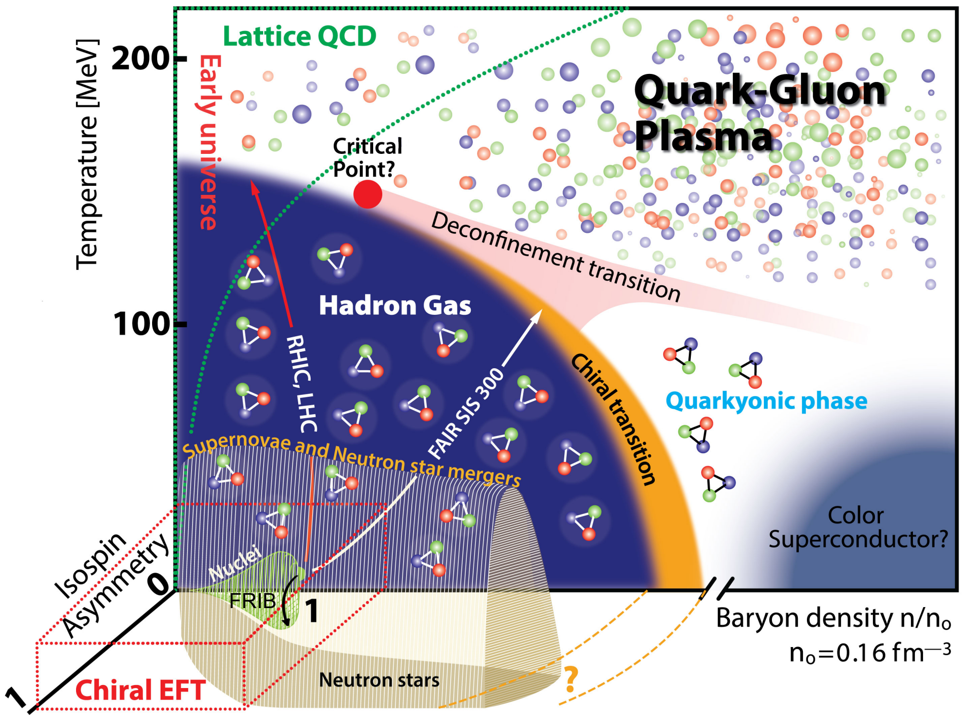

Keywords:

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

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

Annual Review of Nuclear and Particle Science

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Take-away points

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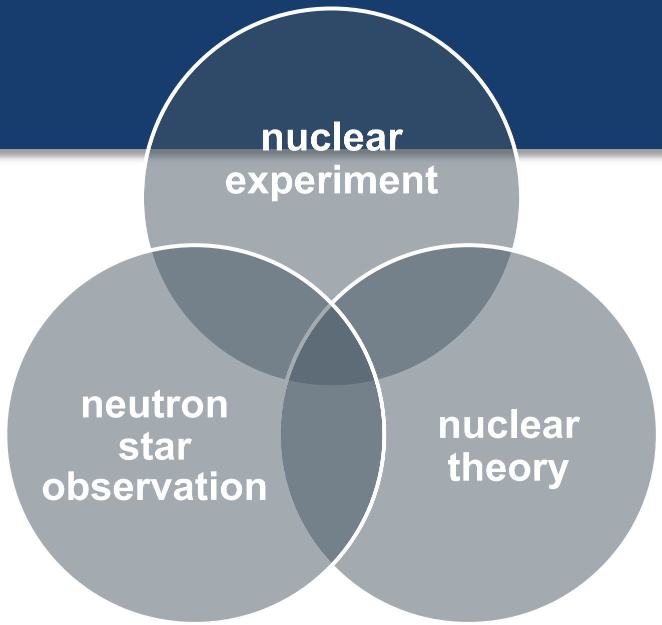
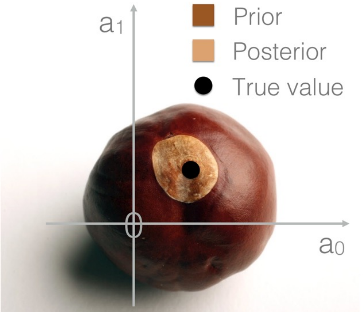
multi-messenger
nuclear precision
FRIB
} era



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

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. **Automated MBPT**: efficient EOS calculations across a wide range of densities, isospin asymmetries, and temperatures, as well as nuclear interactions.
4. Bayesian methods: powerful tools for quantifying & propagating **correlated uncertainties** in EFT-based calculations (*model checking* is important).



BUQEYE Collaboration

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