Equation of State of Dense (Neutron-rich) Matter at Zero Temperature

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Christian Drischler

October 21, 2021 | N3AS: Biweekly Neutron Star Merger Meetings

These *biweekly meetings* aim to bring together researchers working on neutron star mergers.

Topics will include:

- computational astrophysics,
- **dense matter physics,**
- gravitational waves and data analysis,
- neutrino and particle astrophysics.

Meetings will include a 30-40 min talk on a related topic, and 20-30 minutes of discussion…

[A. Watts]

Today:

+ Chiral EFT + MBPT

+ Bayesian UQ

+ infinite nuclear matter

+ symmetry energy

+ nuclear saturation

+ N^{3}LO NN + 3N forces

+ …

see also Jeremy Holt's talk (November 4)
Equation of State of Dense Matter at Finite Temperature

Equation of State of Dense (Neutron-rich) Matter at Zero Temperature

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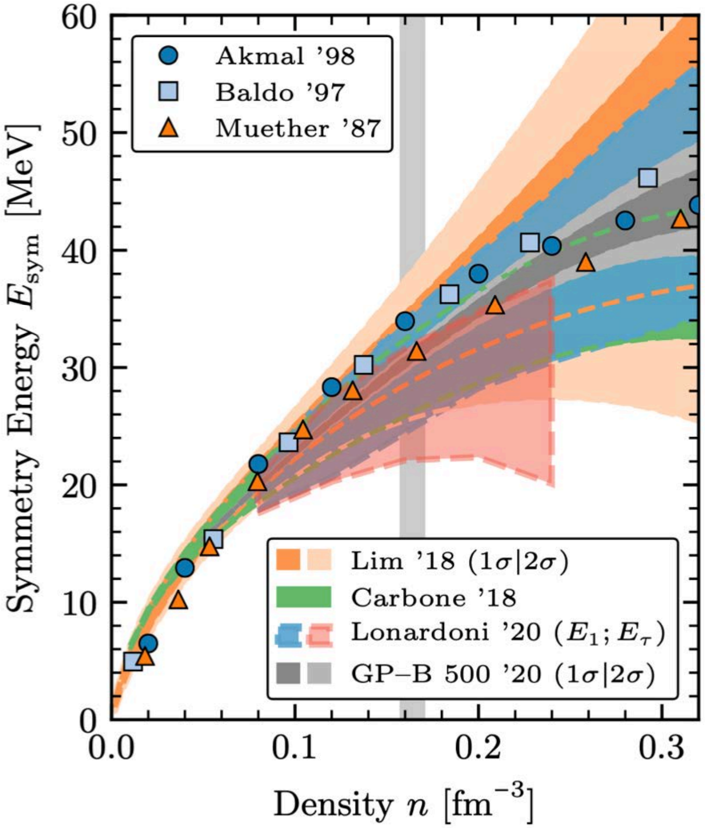
Recent review article

CD, Holt, and Wellenhofer, ARNPS **71**, 403



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

C. Drischler,[1,2,3] J. W. Holt,[4] and C. Wellenhofer,[5,6]

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[4]Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA; email: holt@physics.tamu.edu
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invited contribution to Annu. Rev. Nucl. Part. Sci. **71**, 403
see also: Lattimer, Annu. Rev. Nucl. Part. Sci. **71**, 433

see also, *e.g.*:
Tews, Front. in Phys. **8**, 153

Annu. Rev. Nucl. Part. Sci. 2021. 71:1–30

This article's doi:
10.1146/annurev-nucl-102419-041903

Annu. Rev. Nucl. Part. Sci. in press.

Keywords

chiral effective field theory, nuclear matter, neutron stars, many-body perturbation theory, bayesian uncertainty quantification

Abstract

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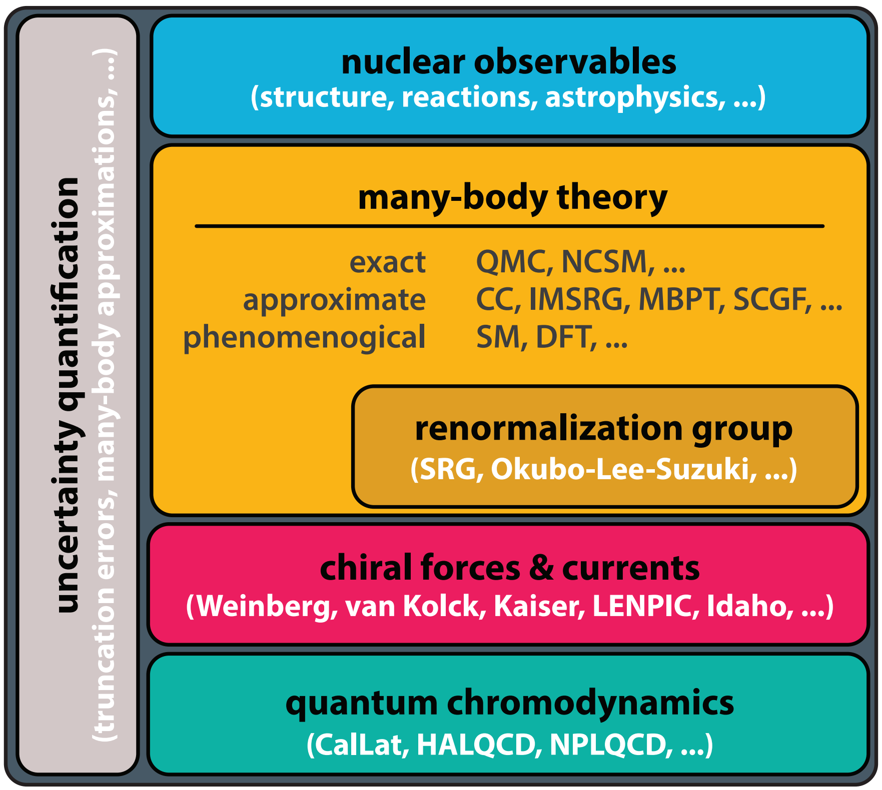
Ab initio calculations | outline

Ab initio workflow (idealized)



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

nuclear equation of state

neutron matter | symmetric matter

many-body perturbation theory

computationally efficient

many-body uncertainty estimates

chiral effective field theory

systematic expansion of nuclear forces

truncation error estimates

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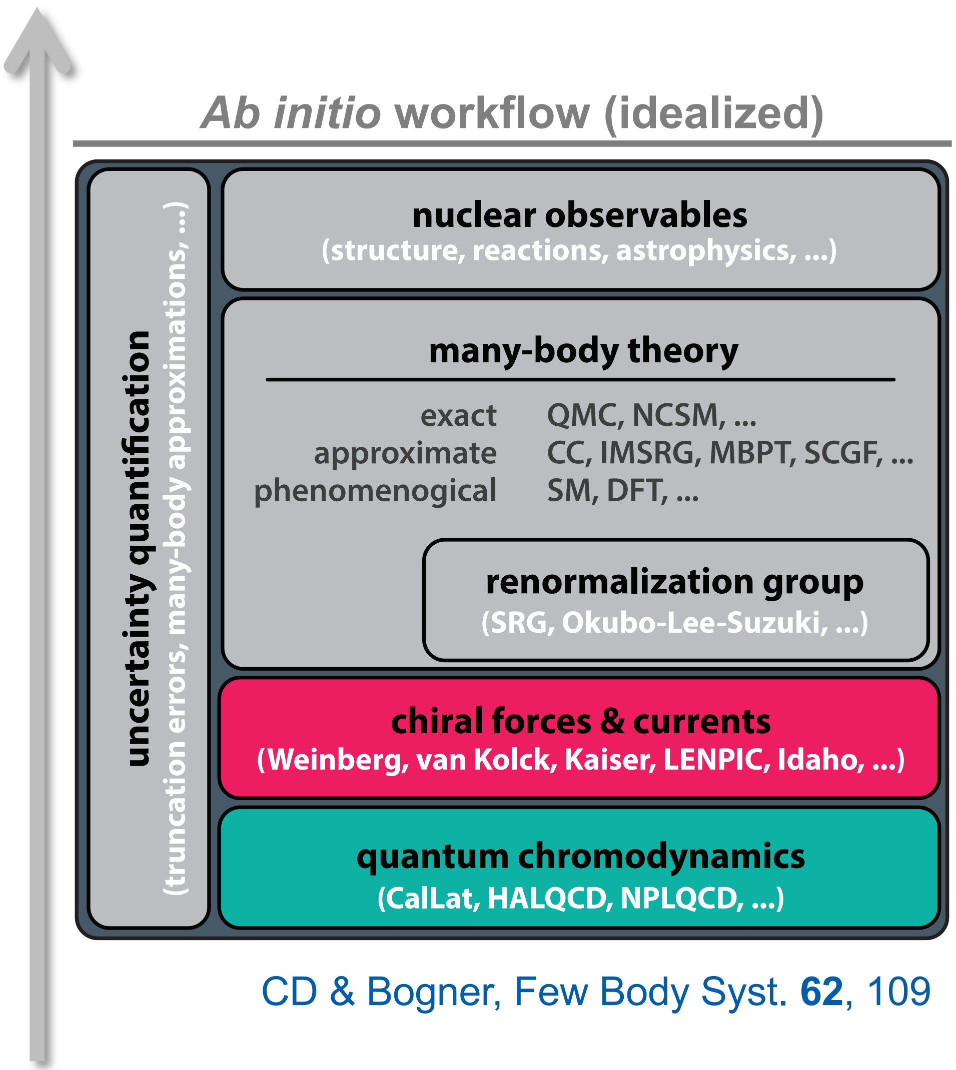

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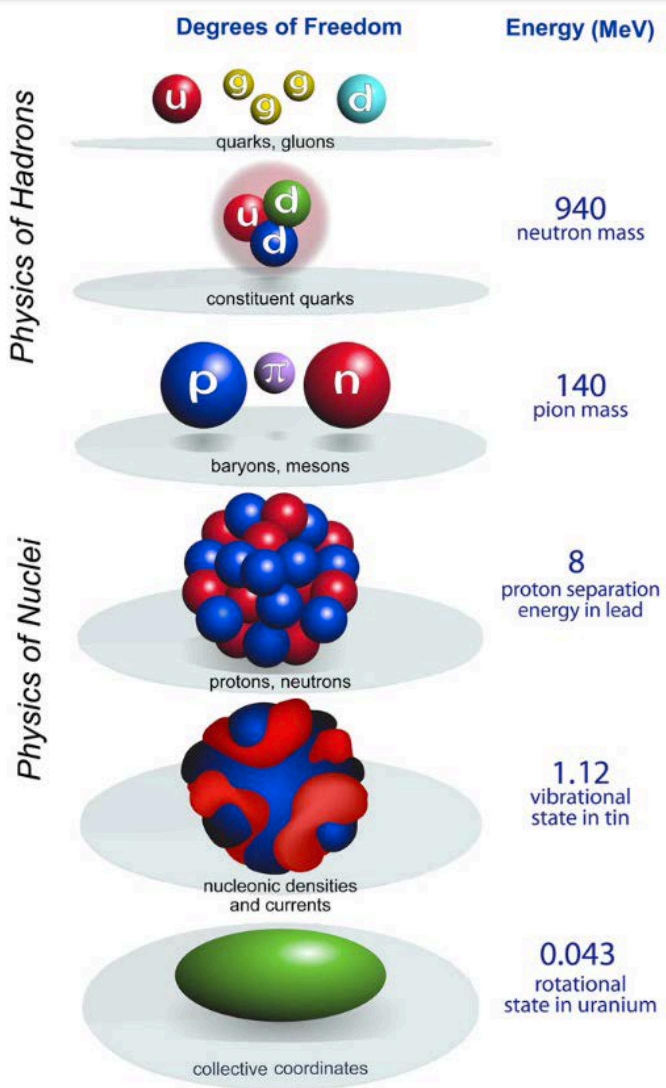
Microscopic nuclear forces

e.g., Machleidt, Entem, Phys. Rep. **503**, 1



Chiral EFT: modern approach to deriving *microscopic* nuclear forces consistent with the symmetries of low-energy QCD

- use relevant instead of the fundamental degrees of freedom: *e.g.*, **nucleons** and **pions**

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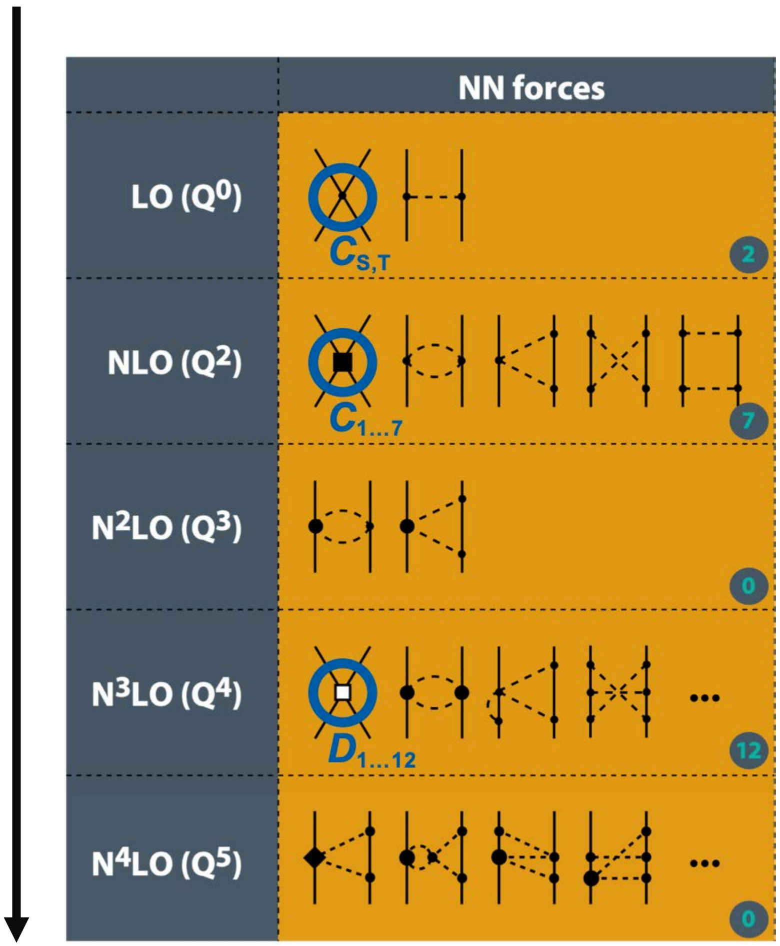

Chiral EFT: modern approach to deriving *microscopic* nuclear forces consistent with the symmetries of low-energy QCD

- use relevant instead of the fundamental degrees of freedom: *e.g.*, **nucleons** and **pions**
- **pion exchanges** and short-range **contact interactions** (∝ LECs)
- **systematic expansion** enables improvable **uncertainty estimates**

$$Q = \max\left(\frac{p}{\Lambda_b}, \frac{m_\pi}{\Lambda_b}\right) \geq \frac{1}{3}$$

Expansion

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Krebs, Machleidt, Meißner, ...

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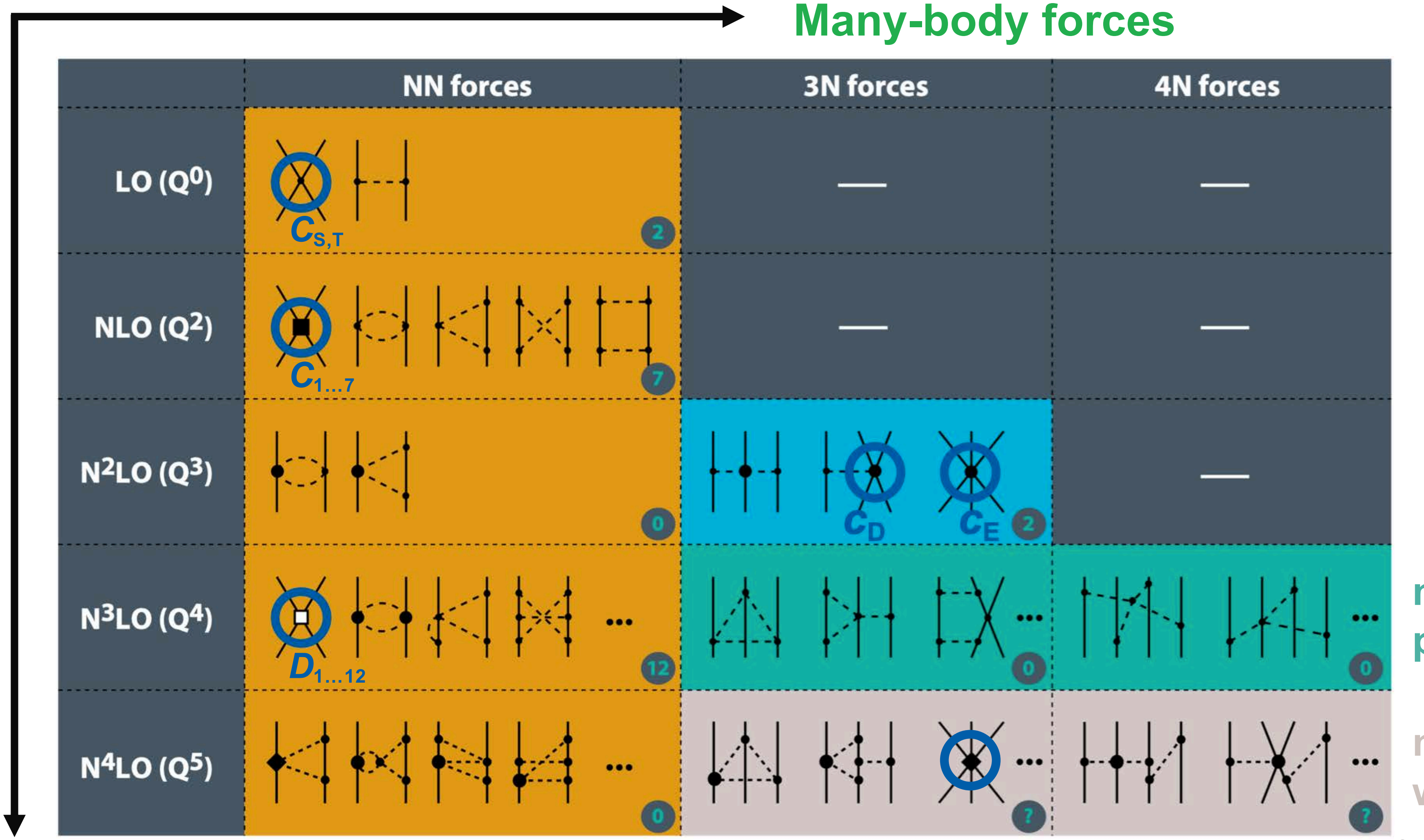
Hierarchy of nuclear forces in chiral EFT

e.g., Machleidt, Entem, Phys. Rep. **503**, 1

Many-body forces



S. Weinberg

no unknown parameters

not (completely) worked out

Expansion

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Krebs, Machleidt, Meißner, ...

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Many chiral potentials available!

Hoppe, CD, Furnstahl *et al.*, PRC **96**, 054002

Semilocal momentum-space regularized chiral two-nucleon potentials up to fifth

P. Reinert,[1,*] H. Krebs,[1,†]

High-quality two-nucleon potentials up to fifth order of the chiral expansion

D. R. Entem,[1,*] R. Machleidt,[2,†] and Y. Nosyk[2]

008 Salamanca, Spain

83844, USA

Uncertainty Analysis and Order-by-Order Optimization of Chiral Nuclear Interactions

B. D. Carlsson,[1,*] A. Ekström,[2,3,†] C. Forssén,[1,2,3,‡] D. Fahlin Strömberg,[1] G. R. Jansen,[3,4] O. Lilja,[1] M. Lindby,[1] B. A. Mattsson,[1] and K. A. Wendt[2,3]

[1]*Depart*

[2]*Departmen*

[3]*Phys*

Minimally nonlocal nucleon-nucleon potentials with chiral two-pion exchange including Δ resonances

M. Piarulli,[1] L. Girlanda,[2,3] R. Schiavilla,[1,4] R. Navarro Pérez,[5] J. E. Amaro,[5] and E. Ruiz Arriola[5]

rginia 23529, USA

I-73100 Lecce, Italy

23606, USA

d de Granada,

Δ isobars and nuclear saturation

A. Ekström,[1] G. Hagen,[2,3] T. D. Morris,[2,3] T. Papenbrock,[2,3] and P. D. Schwartz[2,3]

[1]*Department of Physics, C*

[2]*Physics Division, Oak*

[3]*Department of Physics and A*

Three-nucleon force in chiral EFT with explicit Δ(1232) degrees of freedom: Longest-range contributions at fourth order

H. Krebs,[1,*] A. M. Gasparyan,[1,2,†] and E. Epelbaum[1,‡]

Local chiral effective field theory interactions and quantum Monte Carlo applications

A. Gezerlis,[1,*] I. Tews,[2,3,†] E. Epelbaum,[4,‡] M. Freunek,[4] S. Gandolfi,[5] K. Hebeler,[2,3] A. Nogga,[6] and A. Schwenk[2,3,§]

[1]*Department of Physics, University of Guelph, Guelph, Ontario, Canada N1G 2W1*

[2]*Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*

[3]*ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*

e.g., Carlsson, Ekström, Entem, Epelbaum, Forssén, Gezerlis, Krebs, Machleidt, Piarulli, Reinert, Tews

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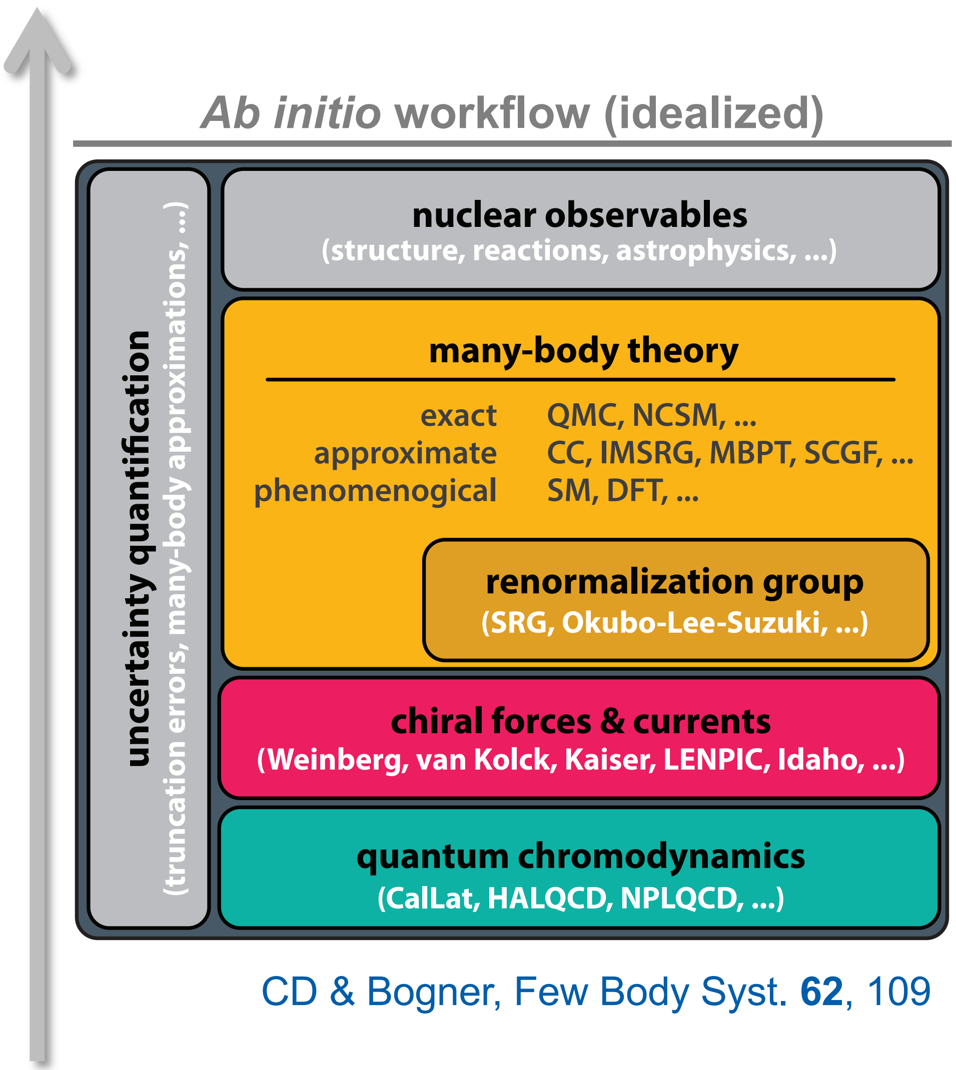
Outline



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

many-body perturbation theory
computationally efficient
many-body uncertainty estimates

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systematic expansion of nuclear forces
truncation error estimates

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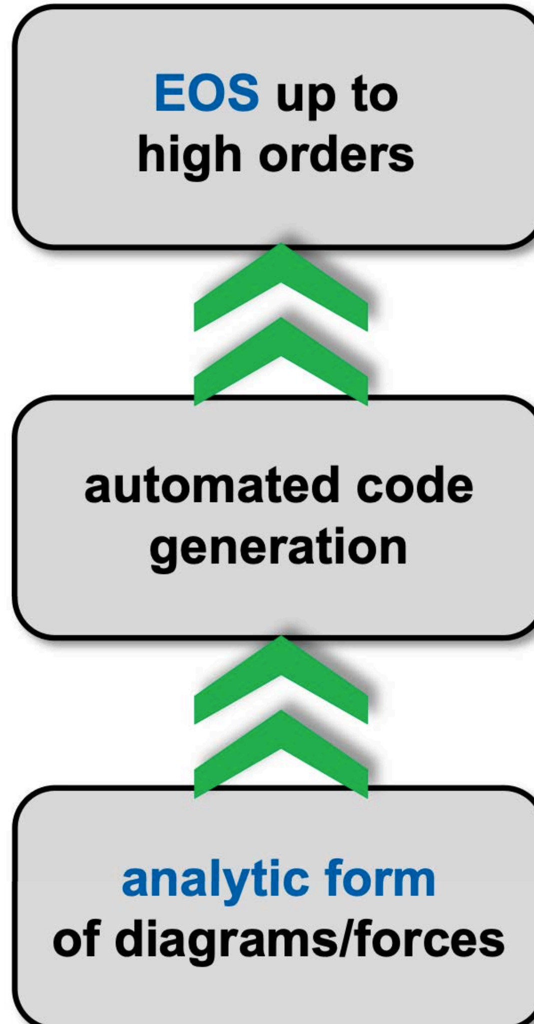
Efficient Monte Carlo framework

CD, Hebeler, Schwenk, PRL **122**, 042501

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

- **implementing diagrams** has become **straightforward** (incl. particle-hole terms)
- multi-dimensional momentum integrals: (improved) VEGAS algorithm
- acceleration: openMP, MPI, and CUDA
- **controlled computation** of arbitrary interaction and many-body diagrams

improved sampling: Brady, Wen, and Holt, PRL **127**, 062701



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.

ADG: Automated generation and evaluation of many-body diagrams I. Bogoliubov many-body perturbation theory

Pierre Arthuis, Thomas Duguet, Alexander Tichai, Raphaël-David Lasseri, Jean-Paul Ebran

Comput. Phys. **240**, 202

fully automated approach to MBPT

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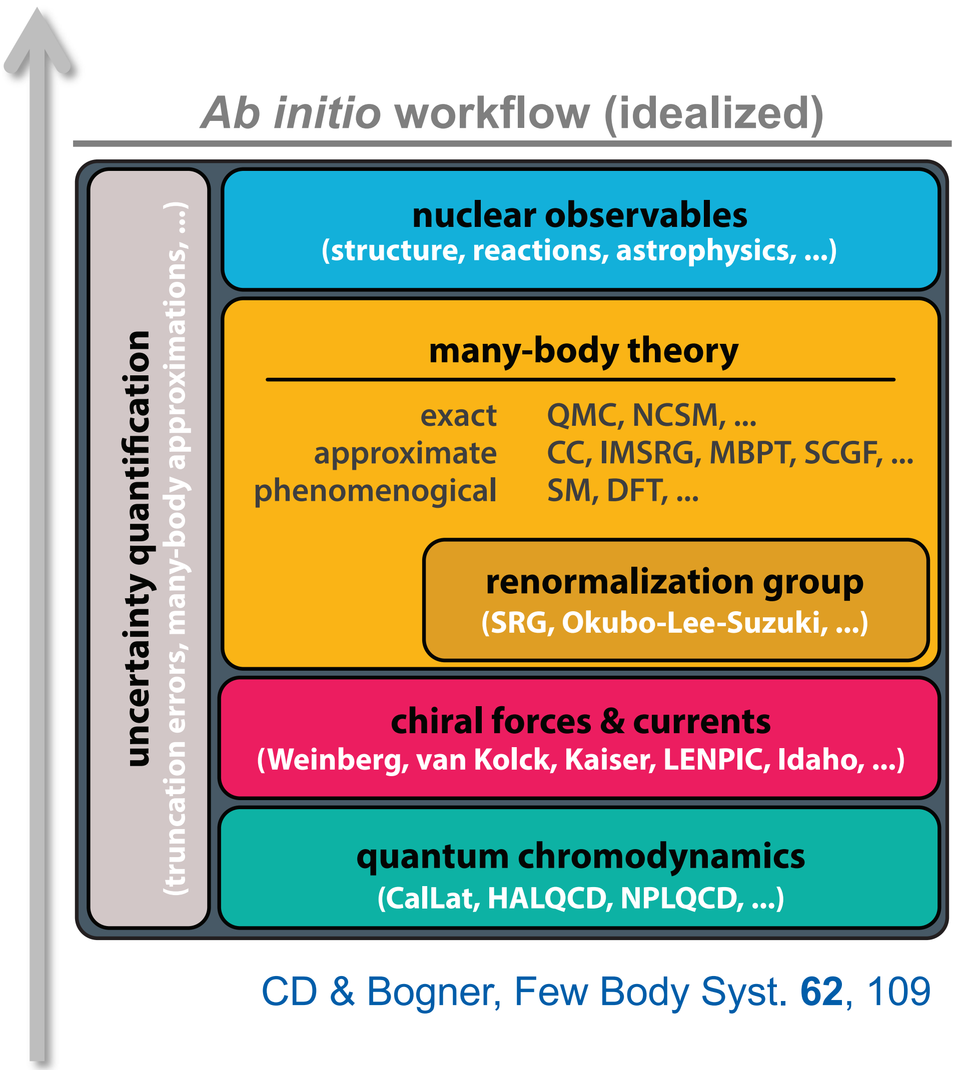

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nuclear equation of state

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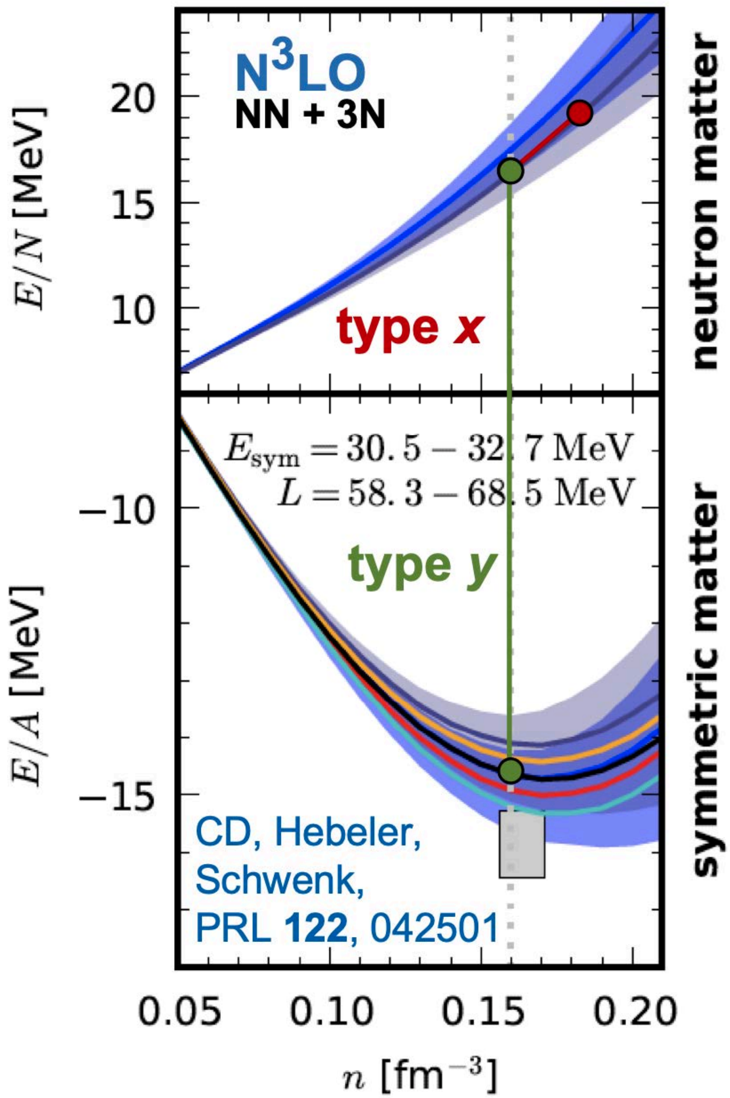
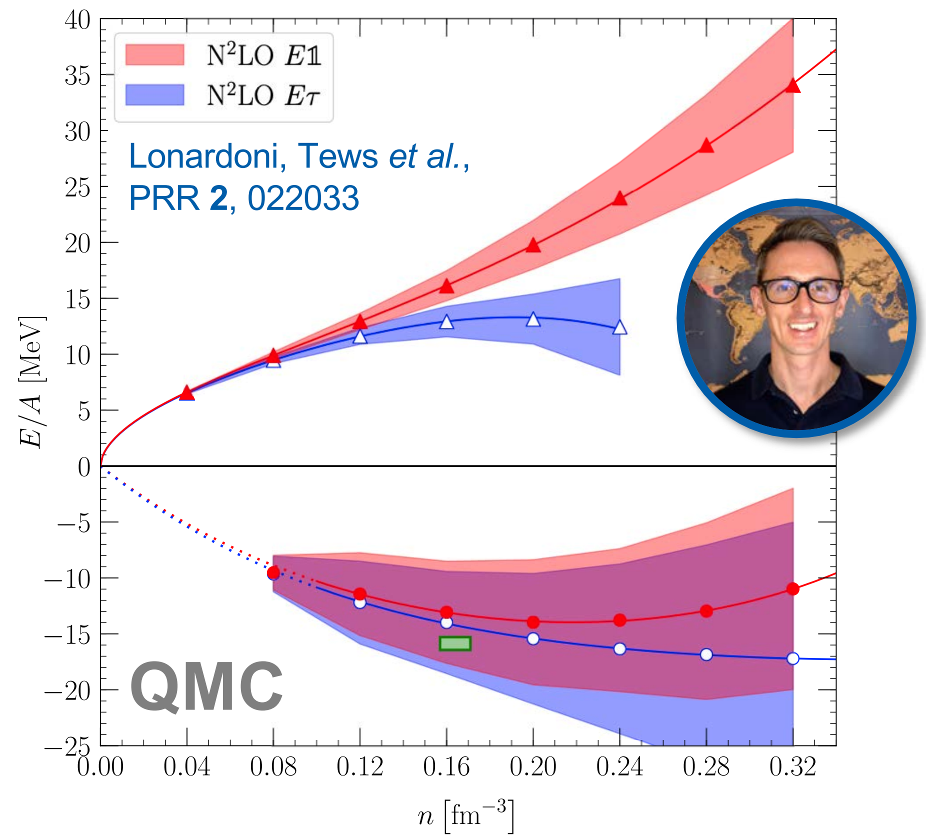
Nuclear matter calculations

e.g., Hebeler, Holt *et al.*, ARNP **65**, 457



great progress in predicting the **EOS** of infinite matter and the structure of **neutron stars** at densities $\lesssim n_0$



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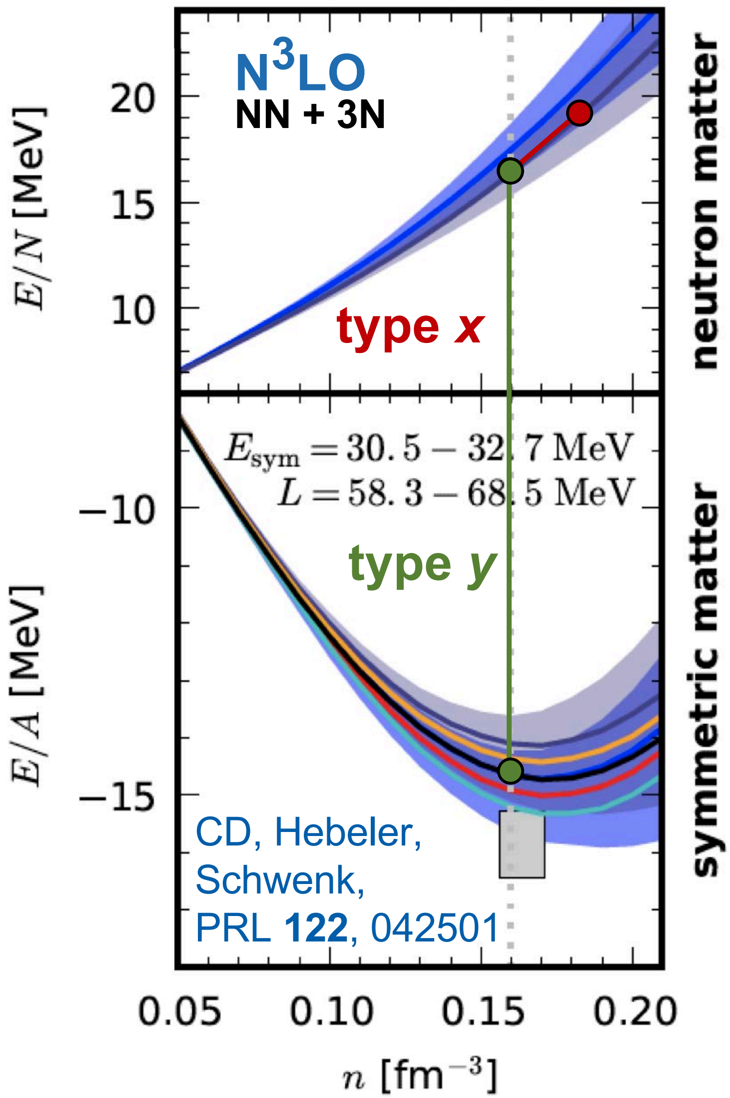

great progress in predicting the **EOS** of infinite matter and the structure of **neutron stars** at densities $\lesssim n_0$

Hebeler, Lattimer *et al.*, APJ **773**, 11
Carbone, Rios *et al.*, PRC **88**, 044302
Hagen, Papenbrock *et al.*, PRC **89**, 014319

needed: *statistically* **robust comparisons** between nuclear **theory** and recent **observational constraints**

Lonardoni, Tews *et al.*, PRR **2**, 022033(R)
Piarulli, Bombaci *et al.*, PRC **101**, 045801
…

But: existing predictions **only** provided **rough estimates** for the with-density-growing **EFT truncation error**, and did *not* account for **correlations**

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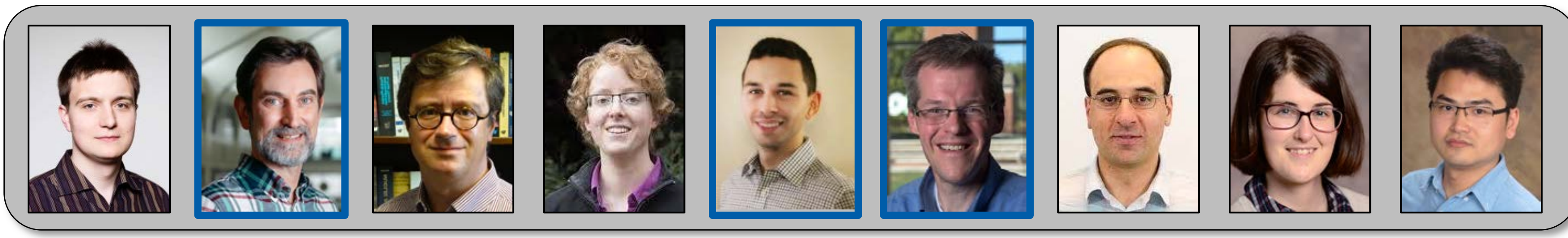
New framework for UQ of EFT calculations

buqeye.github.io



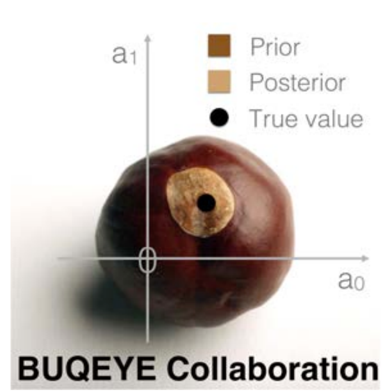
CD, Furnstahl, Melendez, and Phillips

How well do we know the neutron-matter equation of state at the densities inside neutron stars? A Bayesian approach with correlated uncertainties, PRL **125**, 202702

CD, Melendez, Furnstahl, and Phillips

Effective Field Theory Convergence Pattern of Infinite Nuclear Matter, PRC **102**, 054315

See also: Melendez *et al.*, PRC **100**, 044001
Wesolowski *et al.*, JPG **43**, 074001



Bayesian
Uncertainty
Quantification:
Errors for
Your
EFT

UQ framework available at https://buqeye.github.io

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New framework for UQ of EFT calculations

buqeye.github.io

CD, Furnstahl, Melendez, and Phillips

How
equa
stars
unce

Correlated EFT truncation errors are important!

statistically **robust uncertainty estimates**
for key quantities of **neutron stars**

CD,

Effective Field Theory Convergence Pattern of Infinite Nuclear Matter, PRC **102**, 054315

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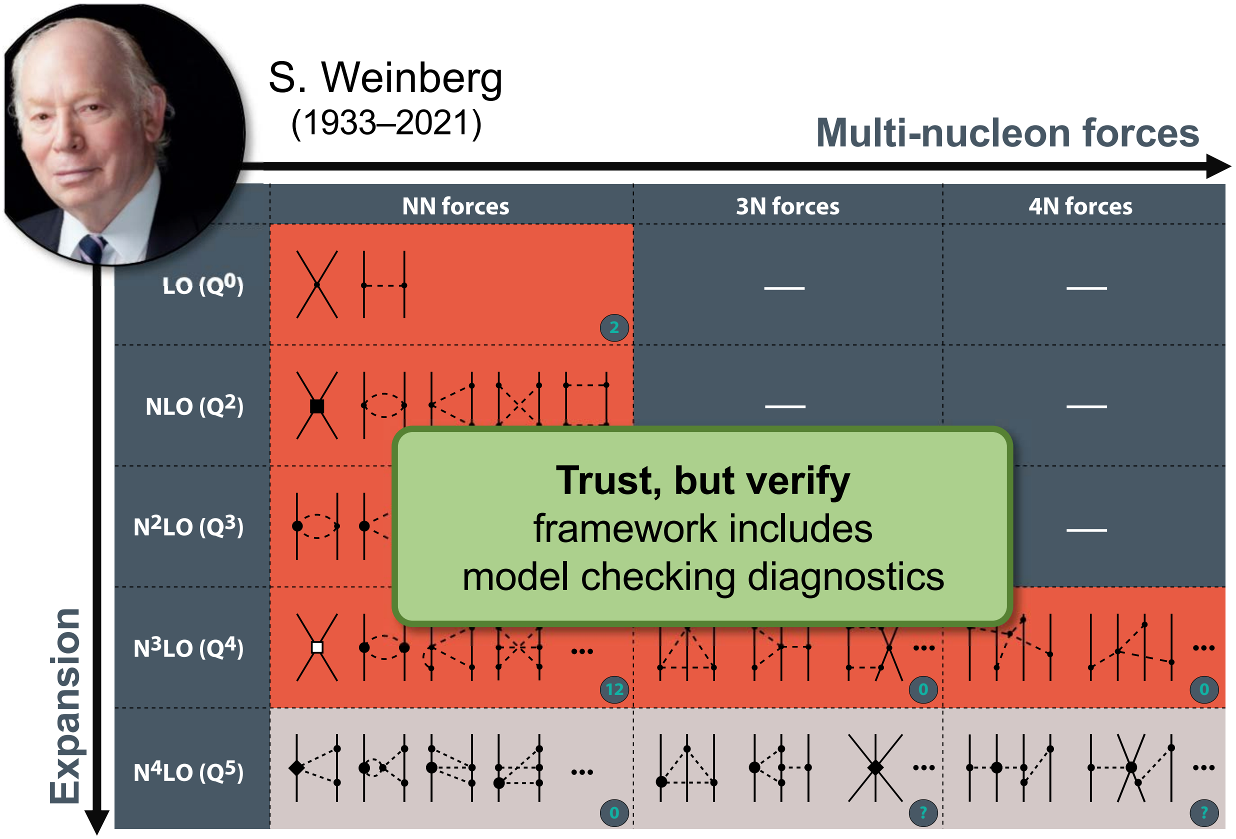


Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Krebs, Machleidt, Meißner, ...

predict observable y_k order by order in EFT

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

c_n are *not* the EFT's LEC

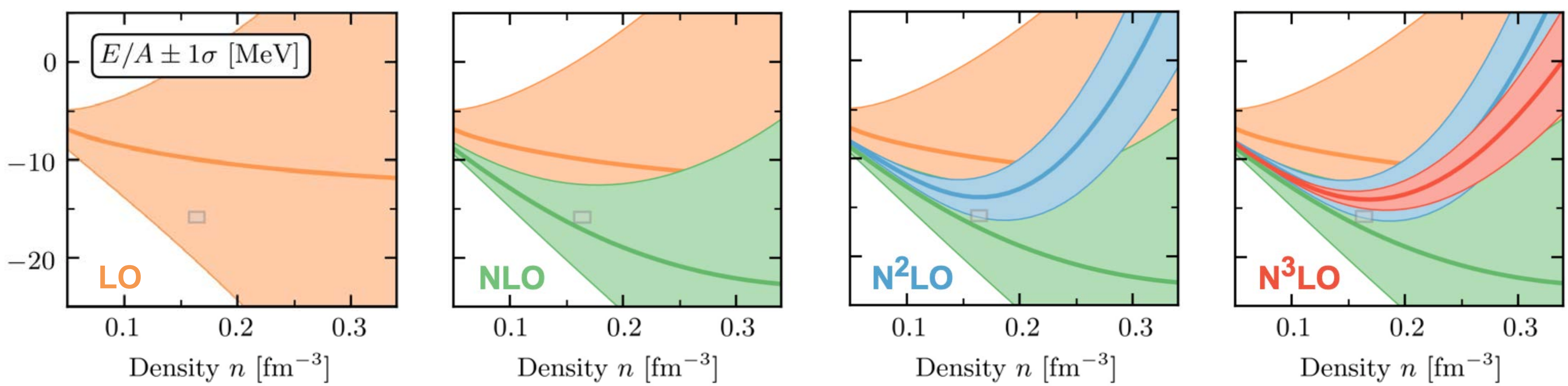
treat all c_n as independent draws from a Gaussian Process

learn GP's hyperparameters & infer EFT truncation error

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

geometric sum

For example: y_k = E/A in SNM at chiral order k



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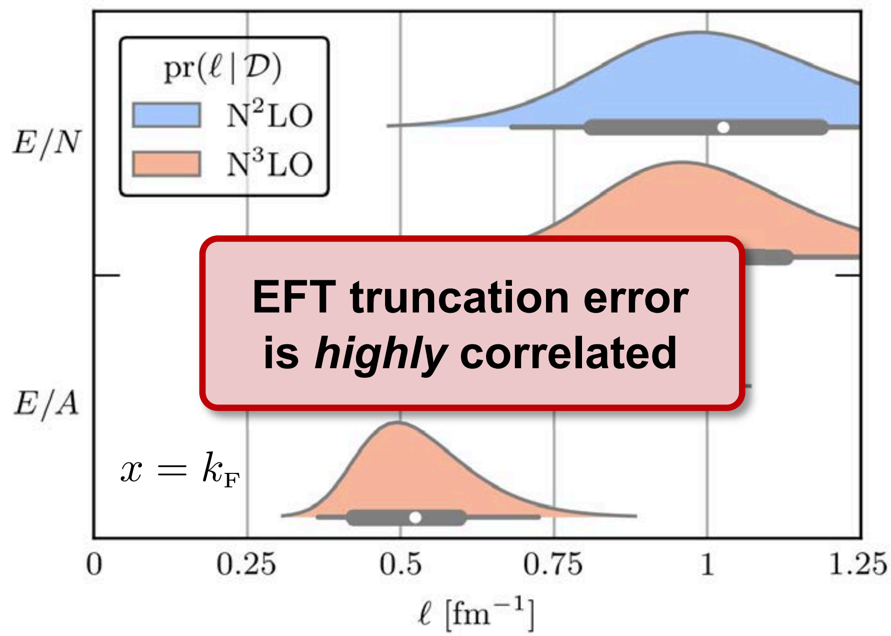
Propagating type-x uncertainties

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

How correlated is nuclear matter ?

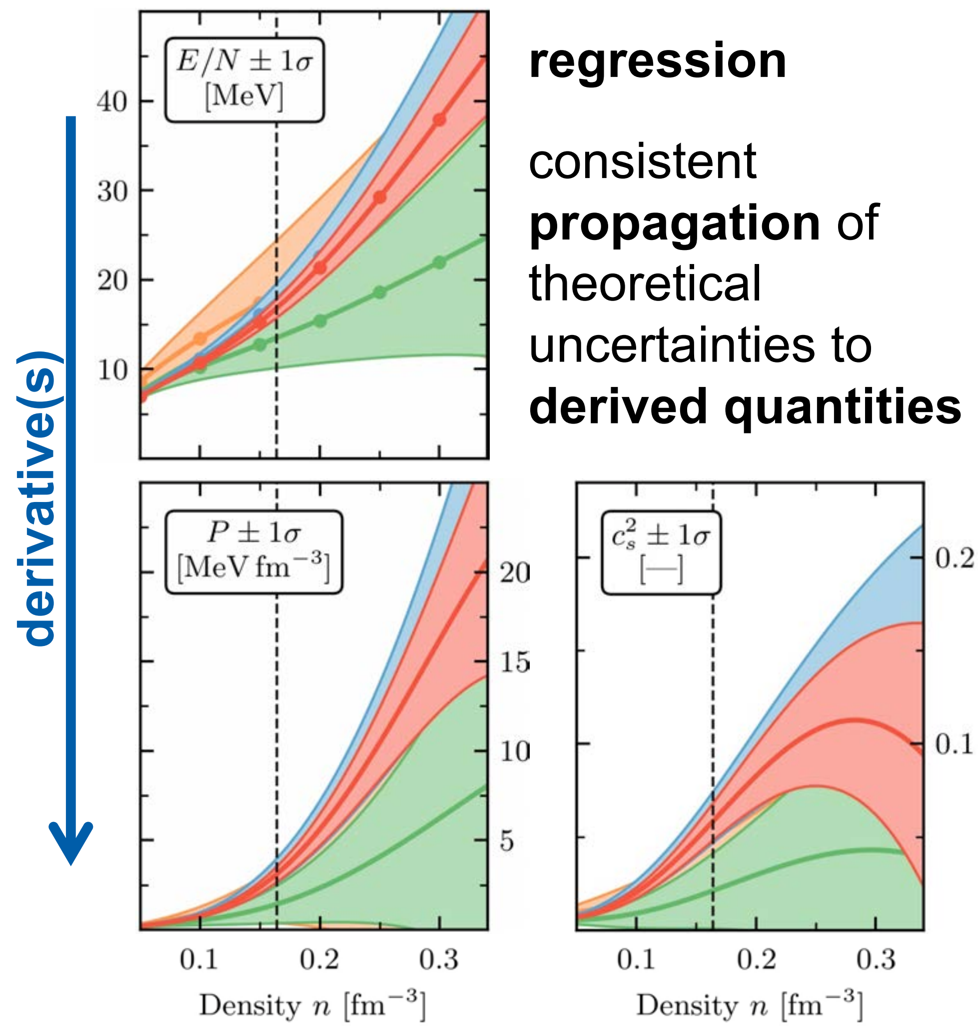
$\mathrm{pr}\,(\ell\,|\,\mathcal{D})$
correlation length



EFT truncation error is *highly* correlated

to be compared with

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



regression

consistent **propagation** of theoretical uncertainties to **derived quantities**

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Bayesian inference

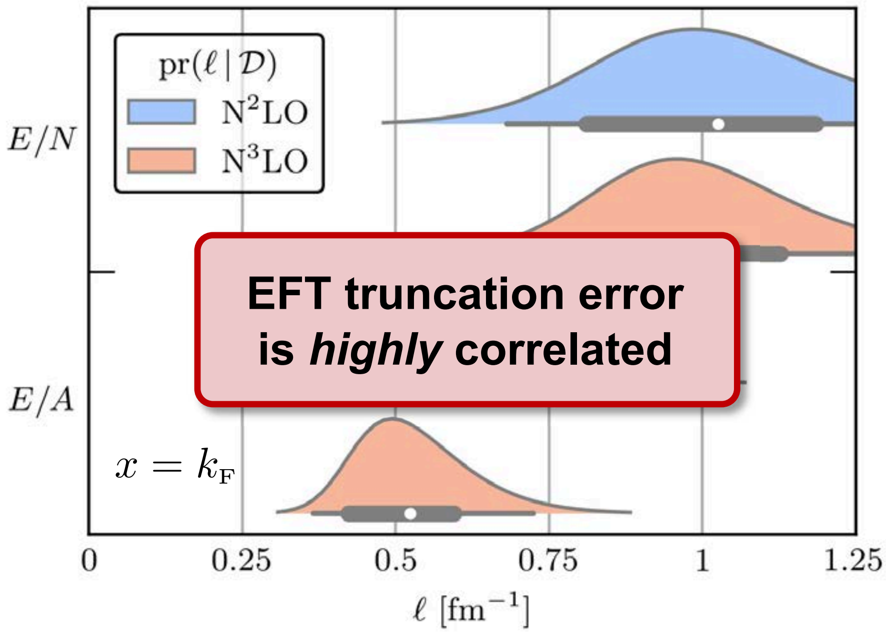
CD, Melendez *et al.*, PRC **102**, 054315

How correlated is nuclear matter ?

$\mathrm{pr}\,(\ell \,|\, \mathcal{D})$
correlation length

Where does the EFT break down ?

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



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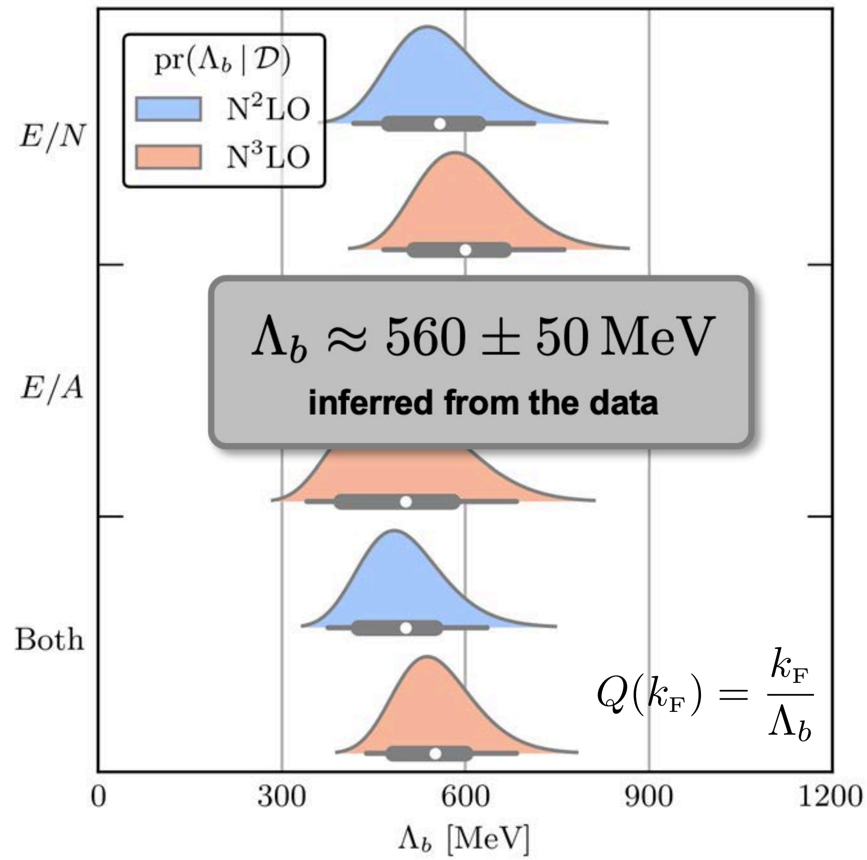

$\Lambda_b \approx 560 \pm 50\,\mathrm{MeV}$
inferred from the data

to be compared with

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

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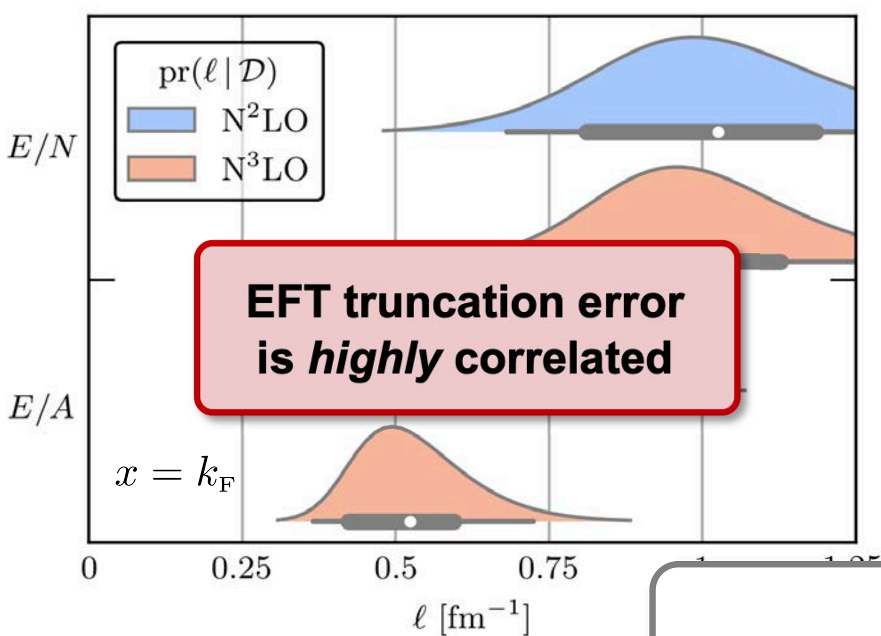

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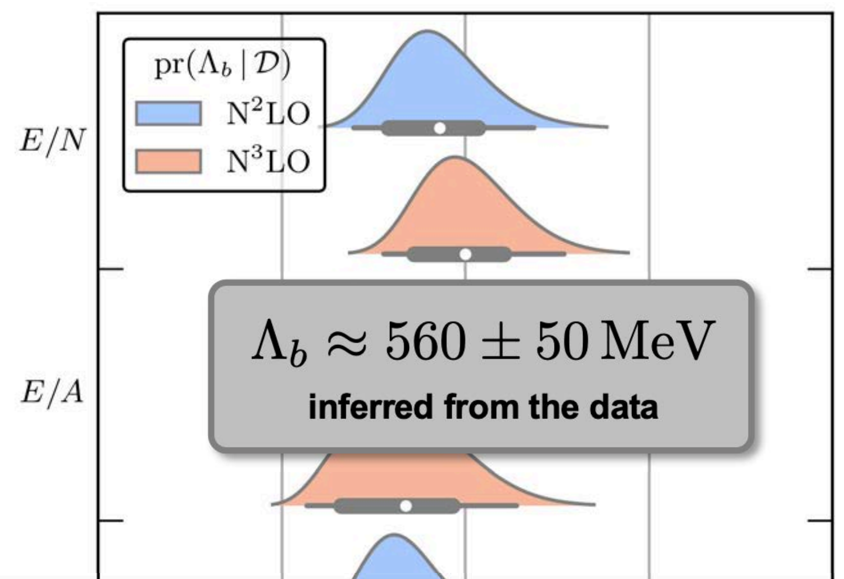

$\Lambda_b \approx 560 \pm 50\,\mathrm{MeV}$
inferred from the data

to be compared with

$$k_\mathrm{F}^\mathrm{max} = \begin{cases} 2.2 \\ 1.7 \end{cases}$$

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

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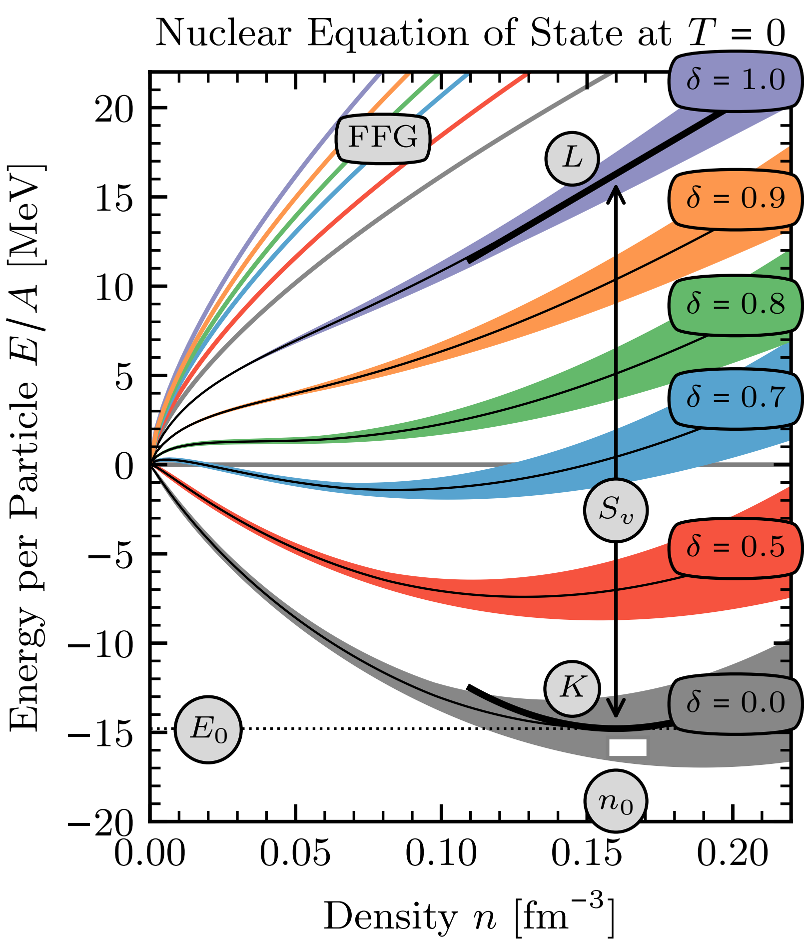
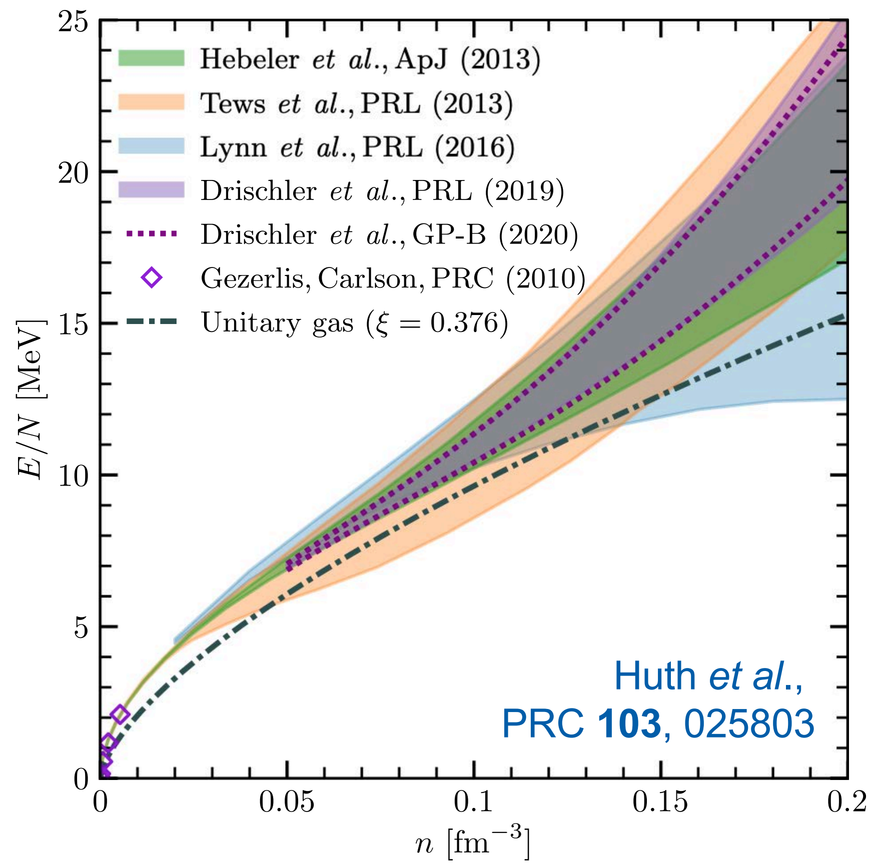
Parameters of the low-density EOS

CD, Holt, and Wellenhofer, ARNPS. **71**, 403





FFG: free Fermi gas; **δ** = $(n_n - n_p)/n$: isospin asymmetry

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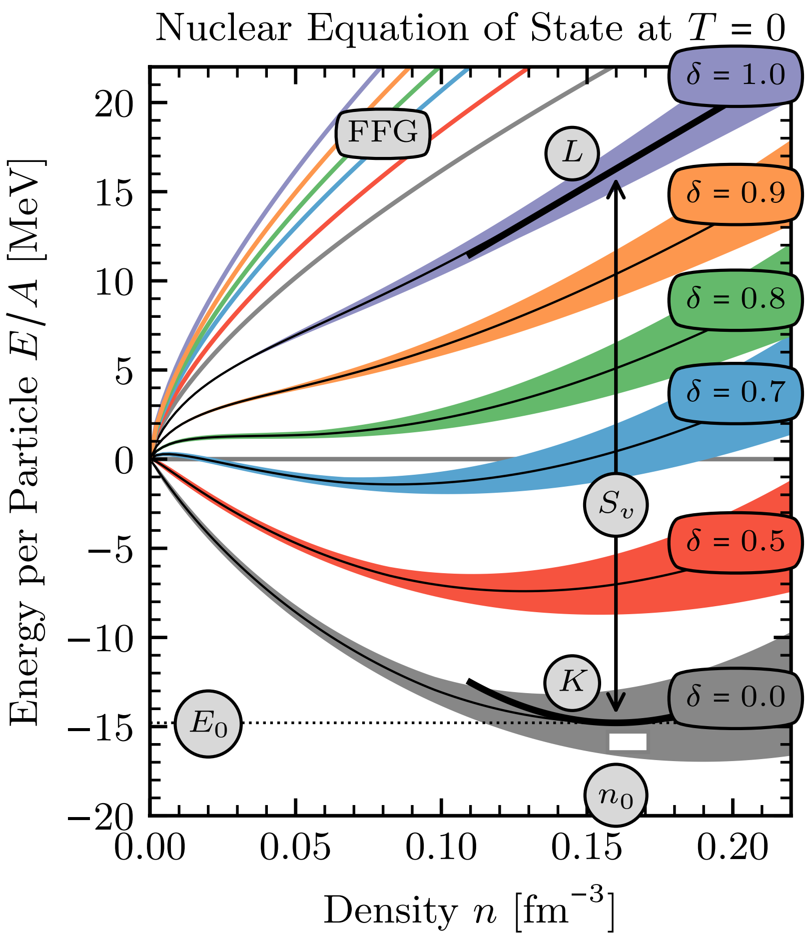

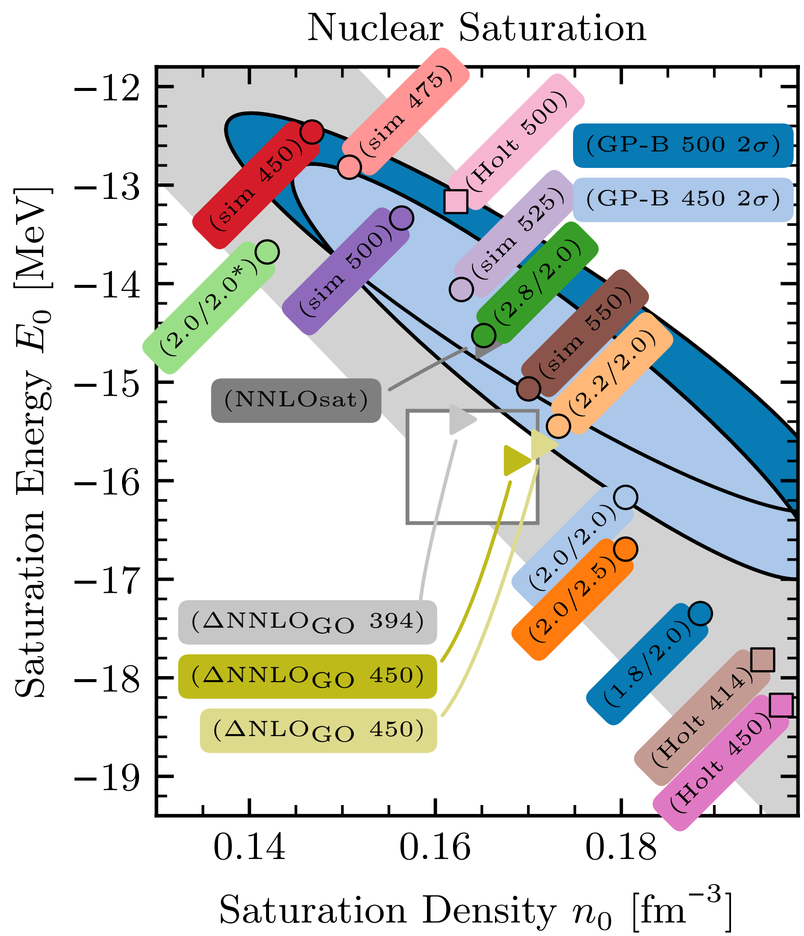

FFG: free Fermi gas; ***δ*** = (n_n – n_p)/n: isospin asymmetry

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

for nuclear saturation, see also Atkinson *et al.*, PRC **102**, 044333; Dewulf *et al*, PRL **90**, 152501

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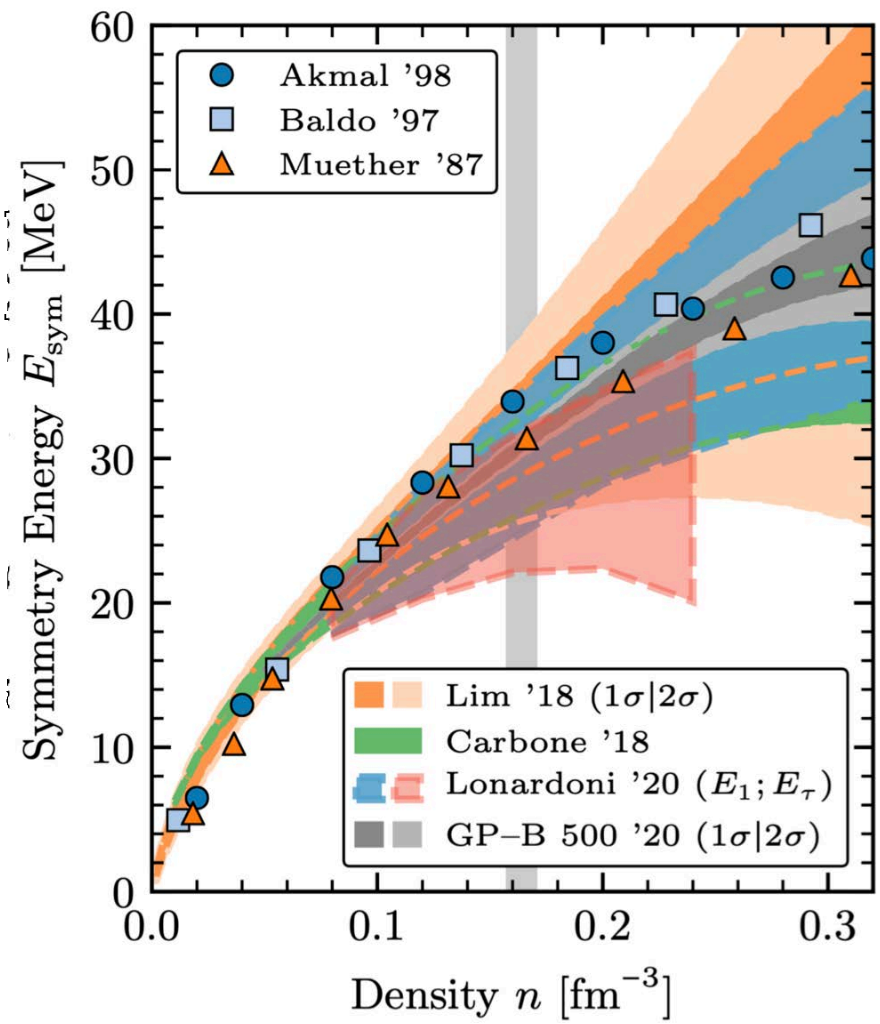
Confronting chiral EFT with empirical constraints

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



$$S_2(n) \approx \frac{E}{N}(n) - \frac{E}{A}(n)$$

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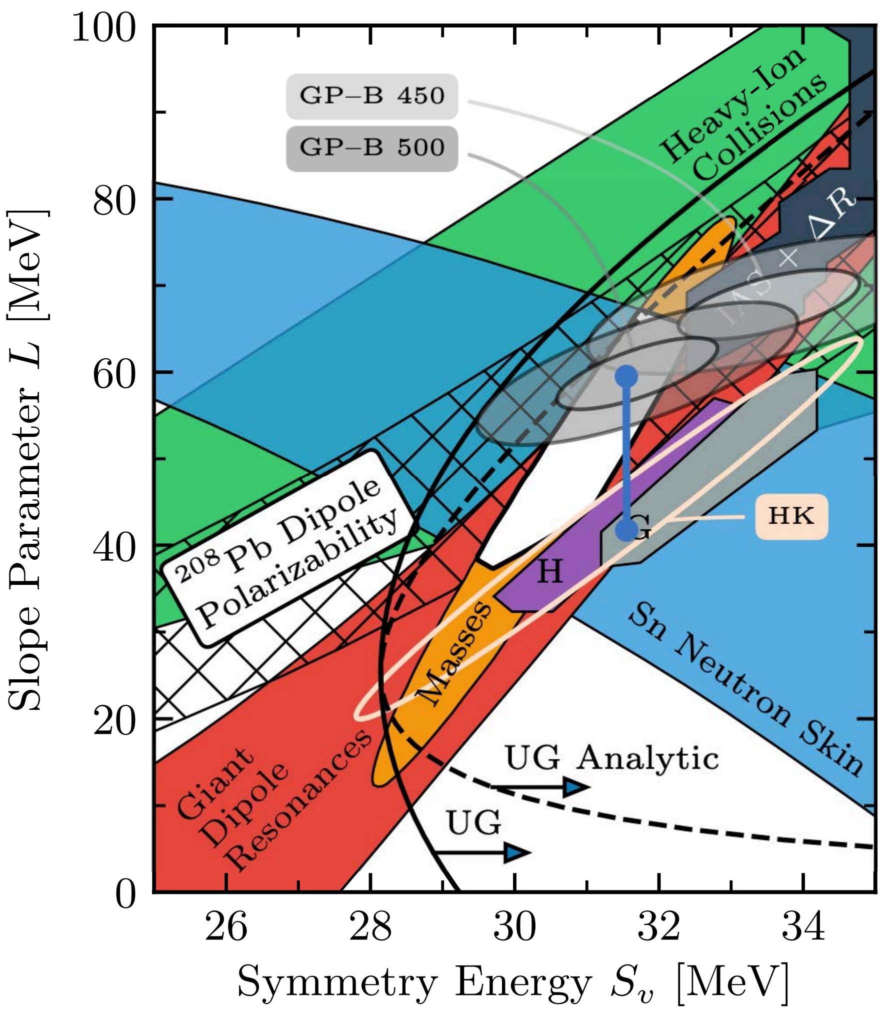
Confronting chiral EFT with empirical constraints

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



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

!

Excellent agreement with experiment

Lattimer and Lim, APJ **771**, 51

$$\mathrm{pr}(S_v, L \,|\, \mathcal{D}) = \int \mathrm{d}n_0\, \mathrm{pr}(S_2, L \,|\, n_0, \mathcal{D})\, \mathrm{pr}(n_0 \,|\, \mathcal{D})$$

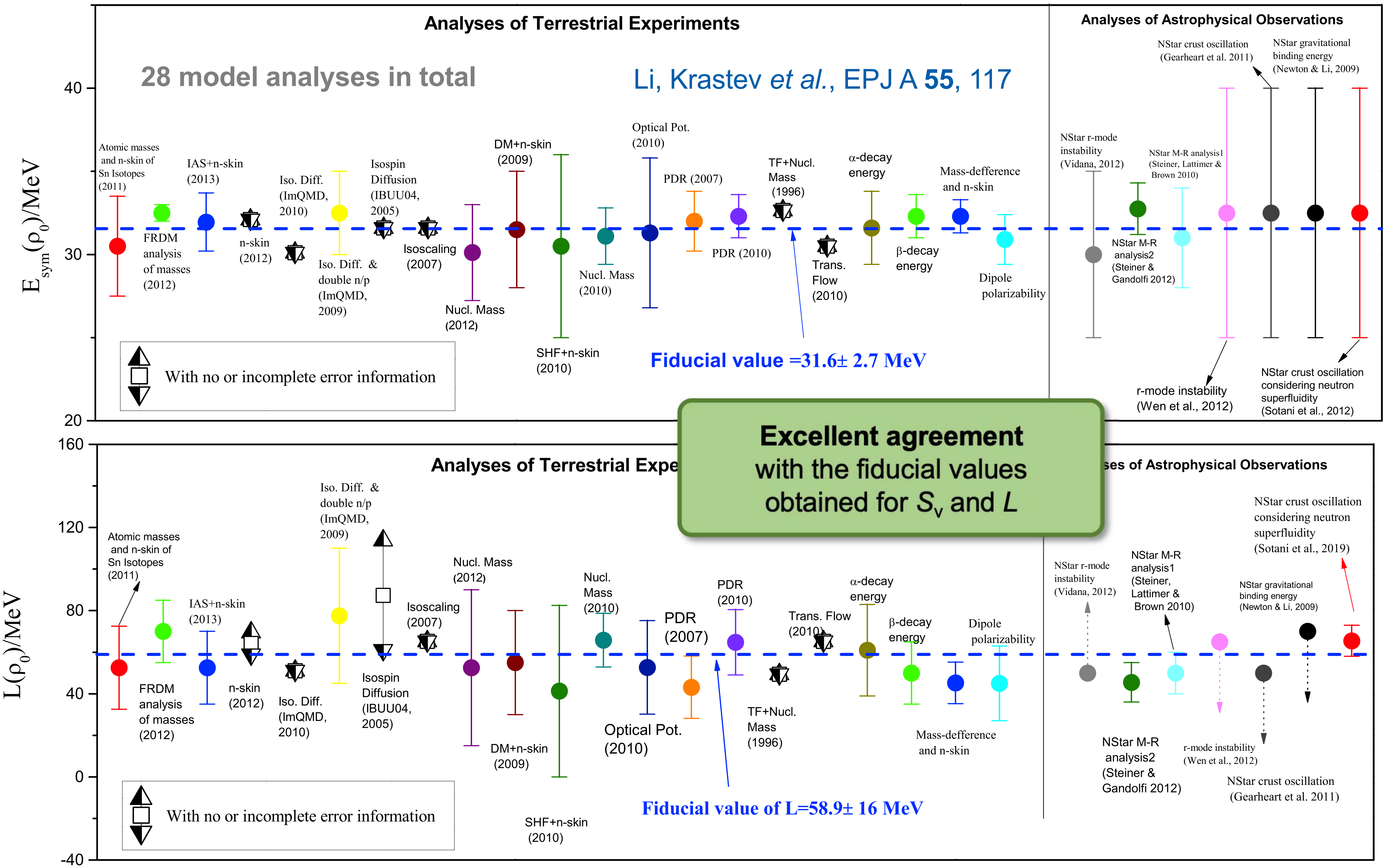
$$\mathrm{pr}(n_0 \,|\, \mathcal{D}) \approx 0.17 \pm 0.01\,\mathrm{fm}^{-3}$$

2σ ellipse (light yellow) is completely within the *conjectured* unitary gas limit

predicted range in S_v **agrees** with other **theoretical constraints**; but ~15 MeV stronger density-dependence of $S_2(n_0)$

GP–B (500): two-dimensional Gaussian

$$\begin{bmatrix}\mu_{S_v}\\ \mu_L\end{bmatrix} = \begin{bmatrix}31.7\\ 59.8\end{bmatrix} \qquad \Sigma = \begin{bmatrix}1.11^2 & 3.27\\ 3.27 & 4.12^2\end{bmatrix}$$



Excellent agreement
with the fiducial values
obtained for S_v and L

Compilation of recent terrestrial and astrophysical **constraints on S_v and L**

GP–B (500): two-dimensional Gaussian

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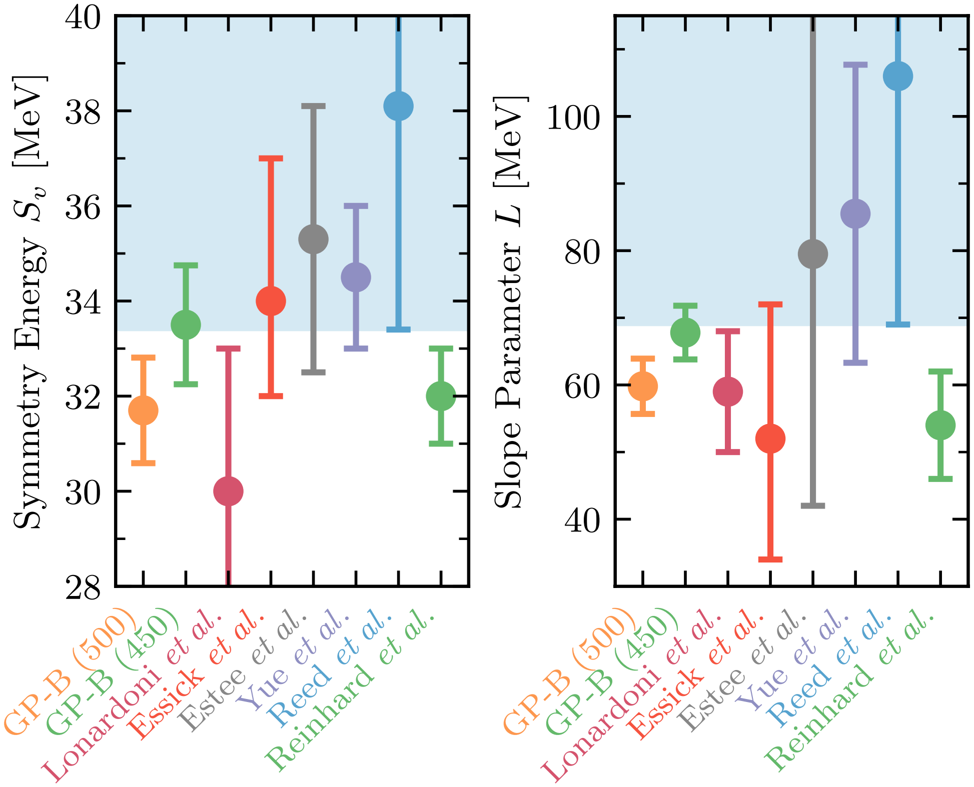
PREX–II vs theory and observation

see also Yue *et al.*, arXiv:2102.05267



Parity violating elastic e scattering

$$R_{\text{skin}}\left({}^{208}\text{Pb}\right) = 0.283 \pm 0.071\,\text{fm}$$

PREX collaboration, PRL **126**, 172502

Exploiting strong correlations (EDFs)

$$S_v = 38.1 \pm 4.7\,\text{MeV}$$
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Reed *et al.*, PRL **126**, 172503

Astron. data + chiral EFT only (incl. GP-B)

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Different EDFs (closest to RCNP & PREX)

$$R\left({}^{208}\text{Pb}\right) = 0.19 \pm 0.02\,\text{fm}$$
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Reinhard, Roca-Maza *et al.*, arXiv:2105.15050

Take away from PREX-II-informed results:

- **uncertainties are still large**
- allows for stiffer EOS at ~n_0, but within the large uncertainties consistent with chiral EFT
- **tension between A_{PV} and α_{D}**

see also: Piekarewicz, PRC **104**, 024329

Equation of State of Dense (Neutron-rich) Matter at Zero Temperature

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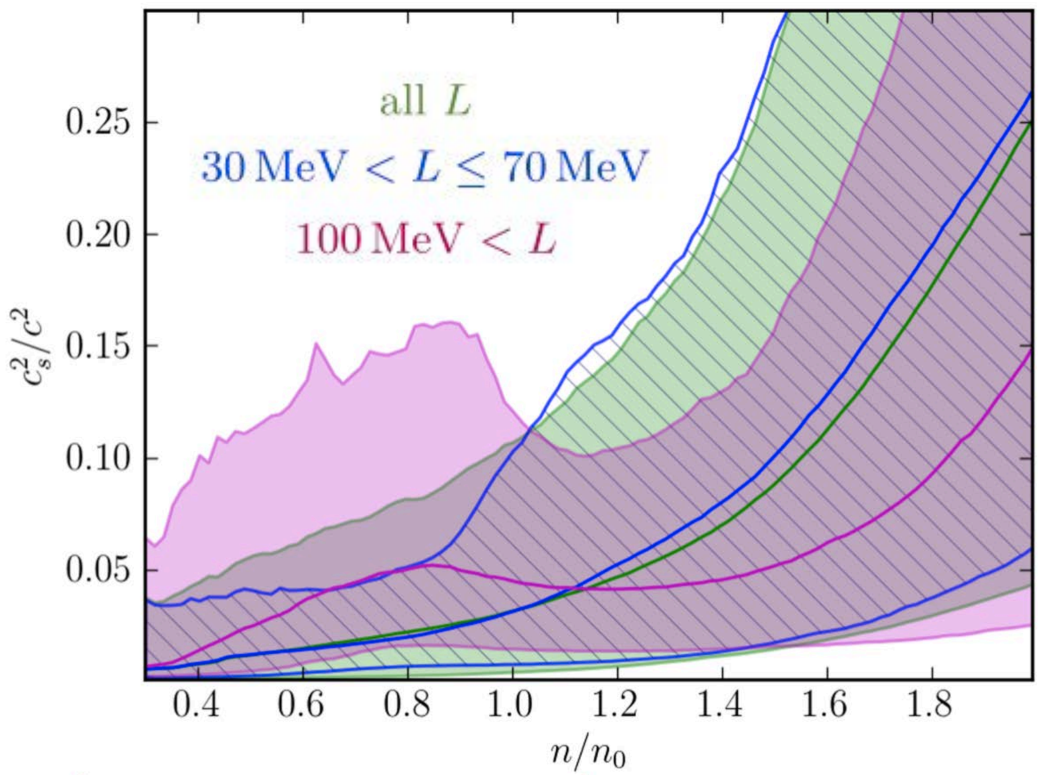

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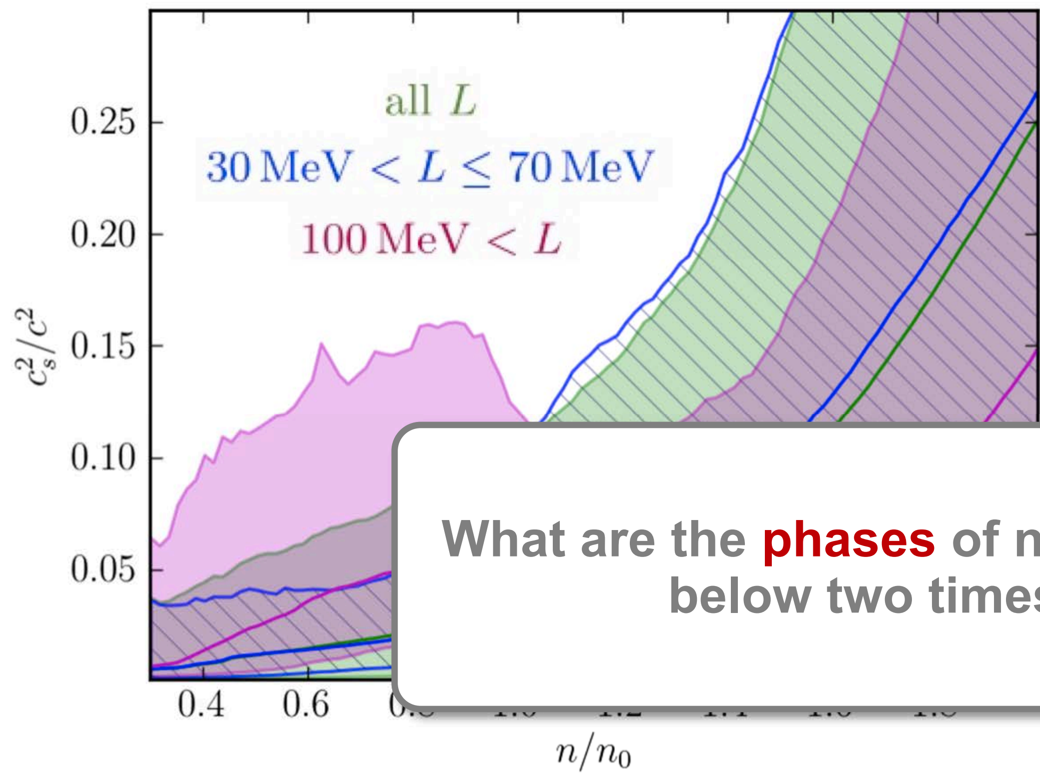

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RL **126**, 172503

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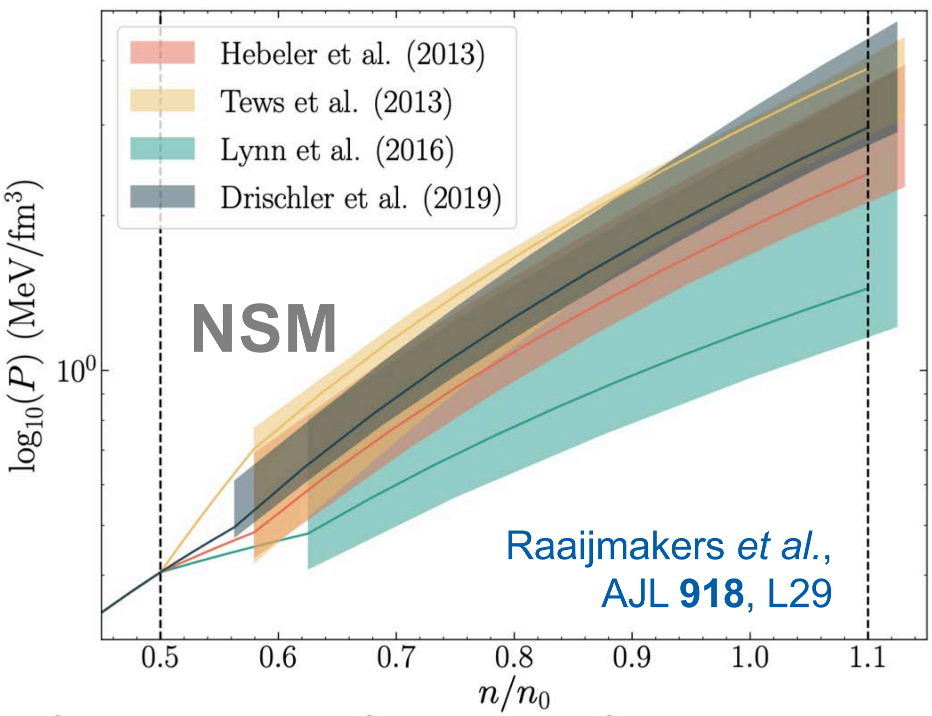
Nonquadratic contributions
to the nuclear symmetry energy

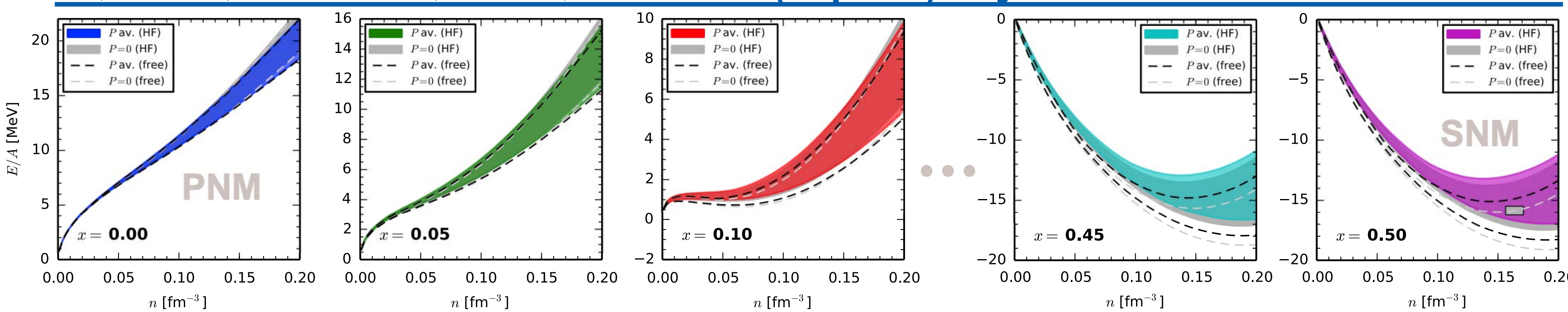
Kaiser, PRC **91**, 065201
Wellenhofer, Holt, and Kaiser, PRC **93**, 055802
Somasundaram, CD, Tews *et al.*, PRC **103**, 045803

$$\frac{E}{A}(n,\delta) = \frac{E}{A}(n,\delta=0) + S_2(n)\delta^2 + \sum_{i>1}\left(A_{2i}(n) \qquad\qquad\right)\delta^{2i}$$



CD, Hebeler, and Schwenk, PRC **93**, 054314

(explicit) asymmetric matter calculations



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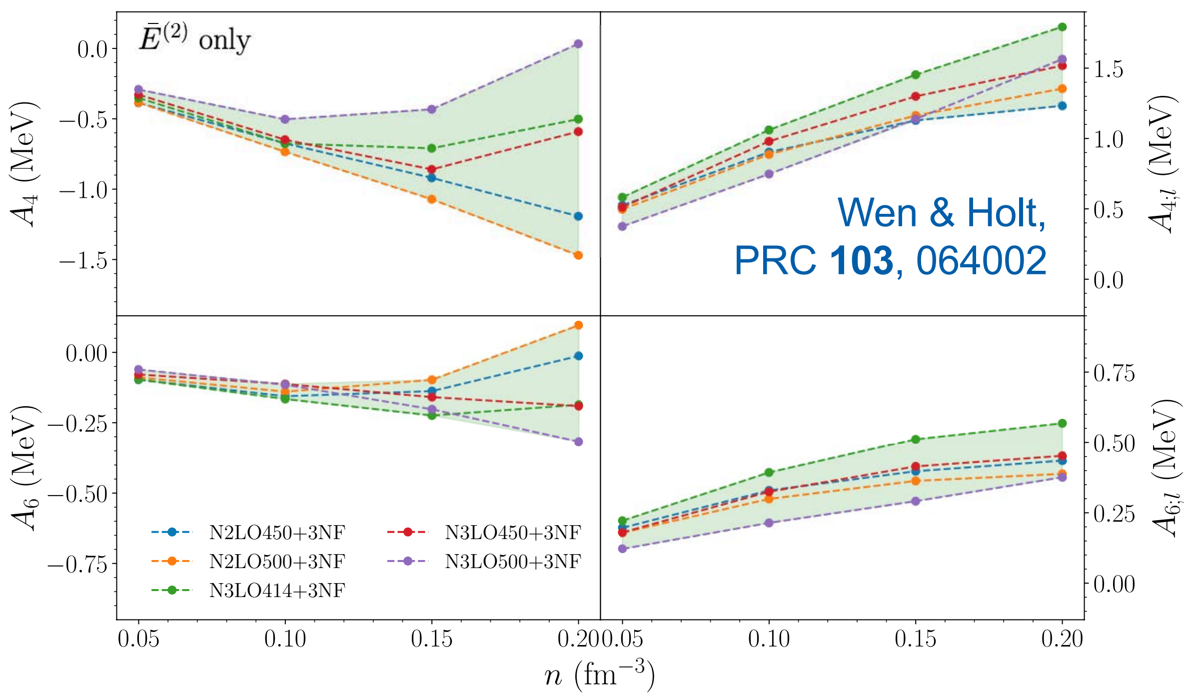


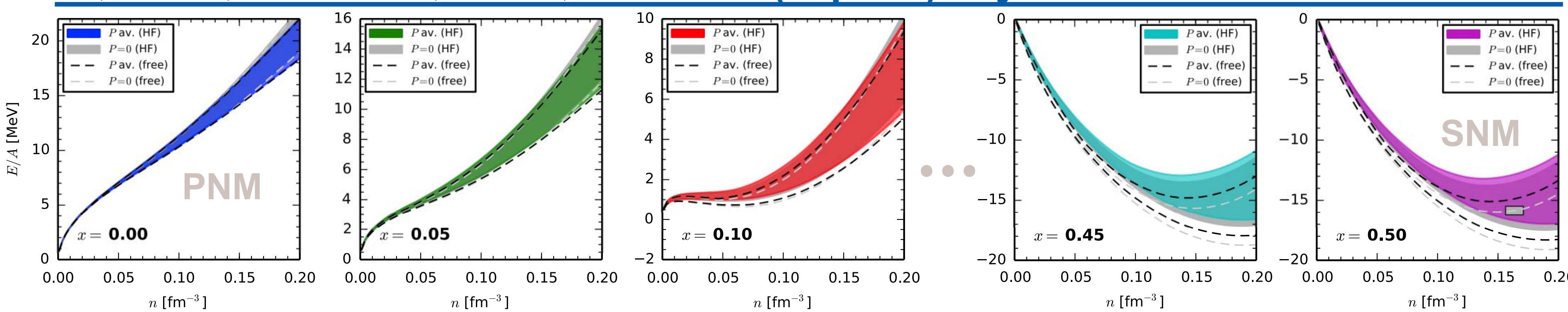
MBPT beyond Hartree-Fock gives rise to (nonanalytic) **logarithmic contributions**

Precision MBPT calculations can **extract** high-order symmetry energy **coefficients**

Overall small contribution from nonquadratic terms
(but can impact β-equilibrium)

CD, Hebeler, and Schwenk, PRC **93**, 054314

(explicit) asymmetric matter calculations



Equation of State of Dense (Neutron-rich) Matter at Zero Temperature

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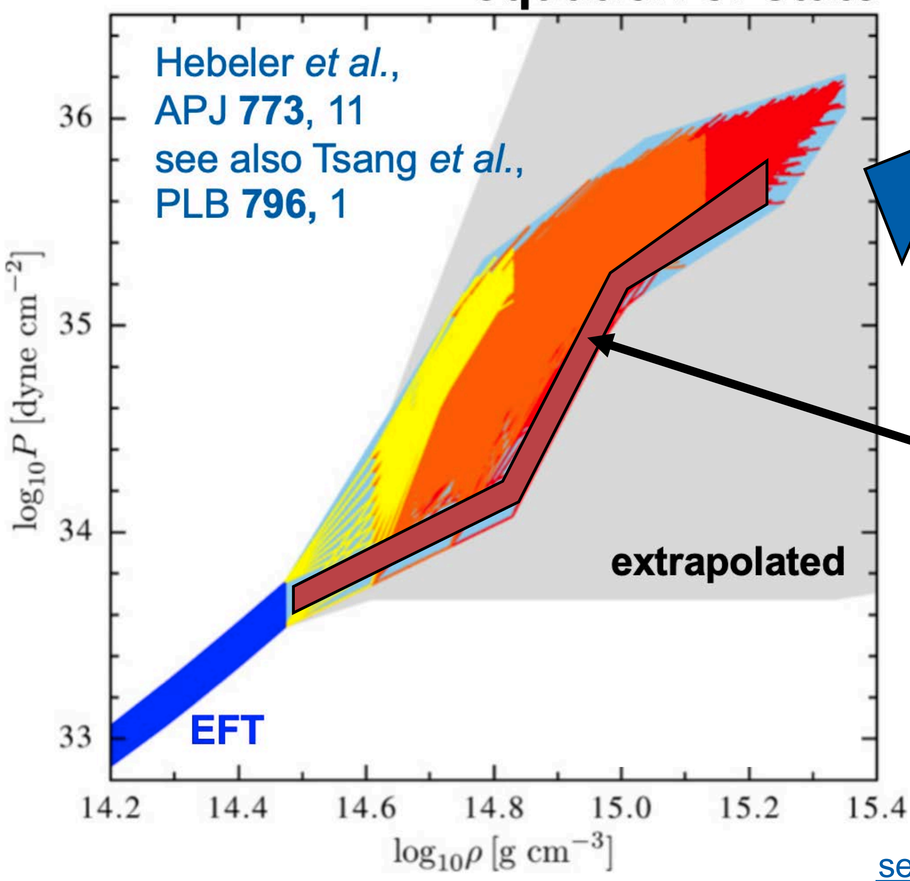
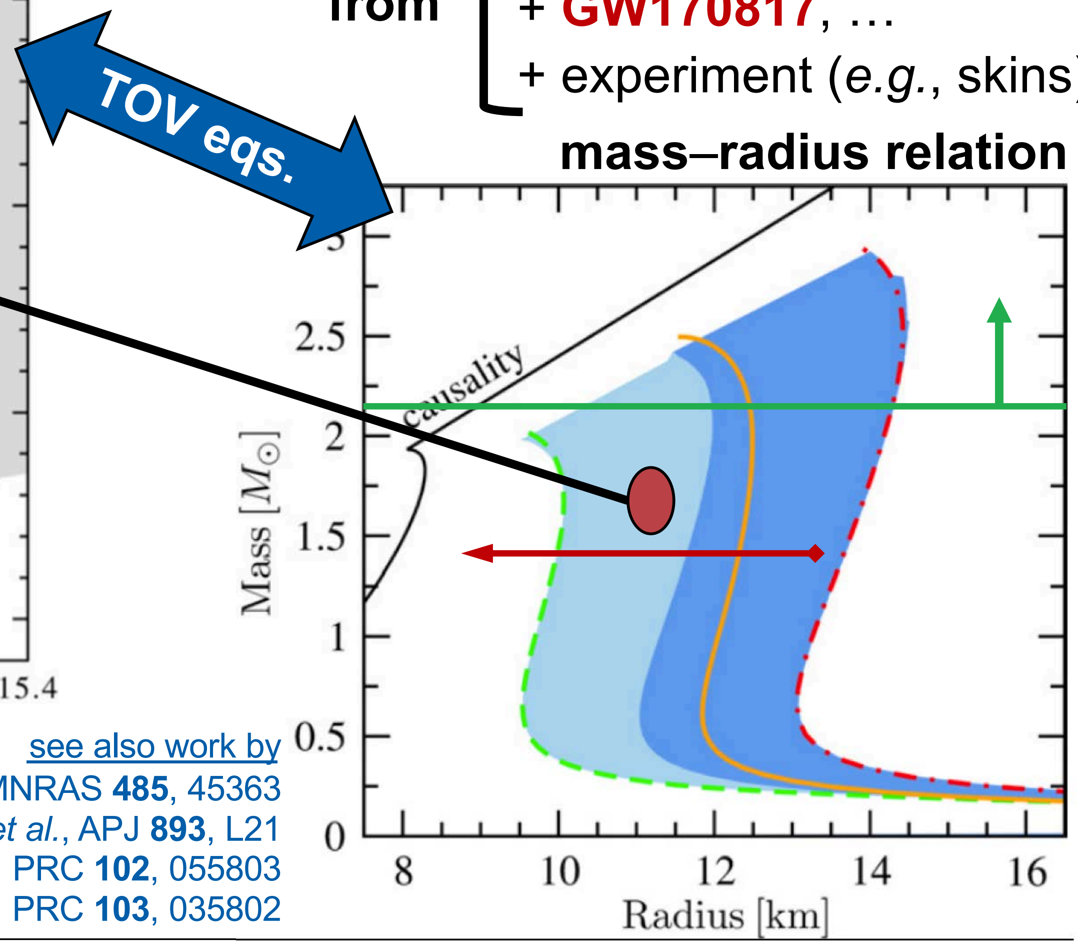
Direct correspondence: *M*–*R* relation and EOS

equation of state



constraints from
- \+ mass measurements
- \+ radius measurements
- \+ GW170817, …
- \+ experiment (*e.g.*, skins)

mass–radius relation



recent reviews:
Hebeler, Holt *et al.*, ARNPS **65**, 457
Tews, Front. in Phys. **8**,153
CD, Holt, and Wellenhofer, ARNPS **71**, 403

see also work by
Greif *et al.*, MNRAS **485**, 45363
Raaijmakers *et al.*, APJ **893**, L21
Essick *et al.*, PRC **102**, 055803
Xie and Li, PRC **103**, 035802

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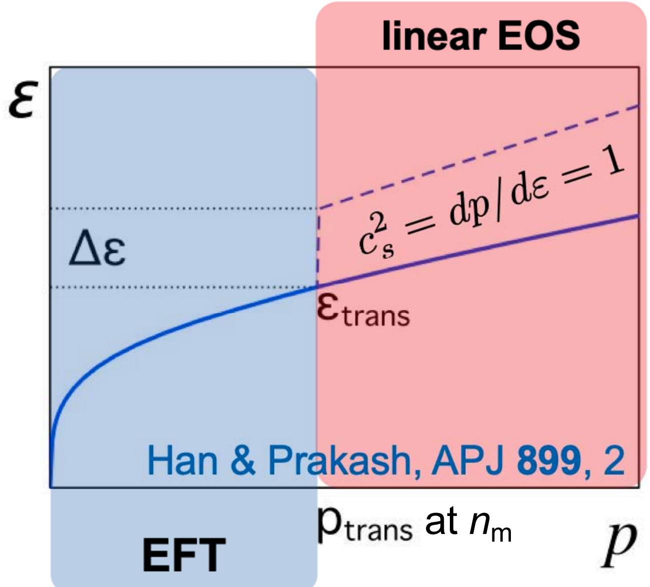
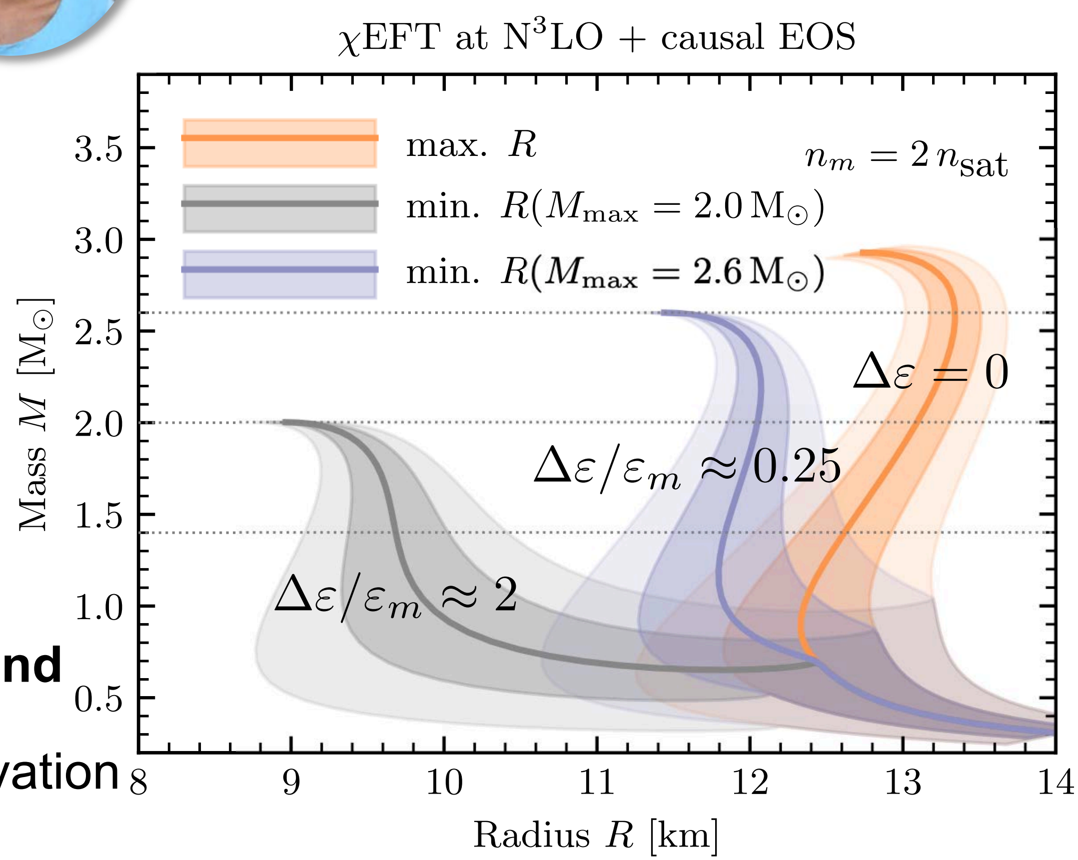
Limiting neutron star radii

CD, Han, Lattimer *et al.*, PRC **103**, 045808



extend EFT EOS at density n_m to a linear EoS with finite discontinuity



see also: Alford *et al.*, JPG: NPP **46**, 114001

$\Delta\varepsilon$ anticorrelates with $M_{\max}$ and R

continuous match sets upper bound

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

Equation of State of Dense (Neutron-rich) Matter at Zero Temperature

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Limiting neutron star radii

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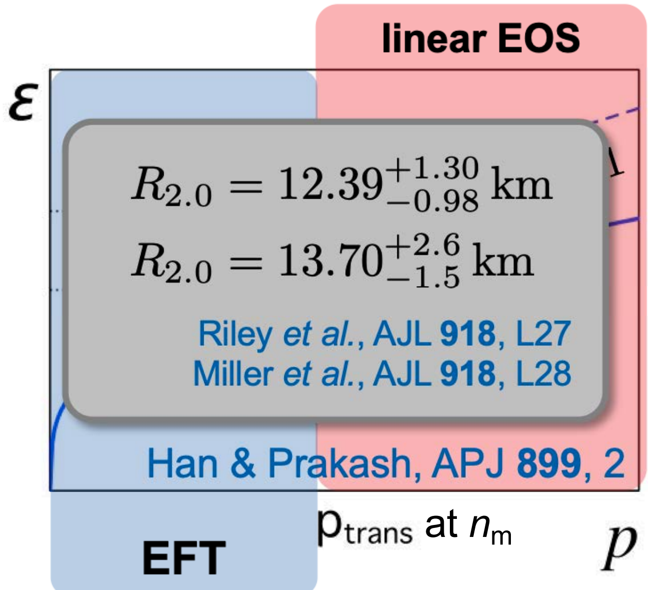


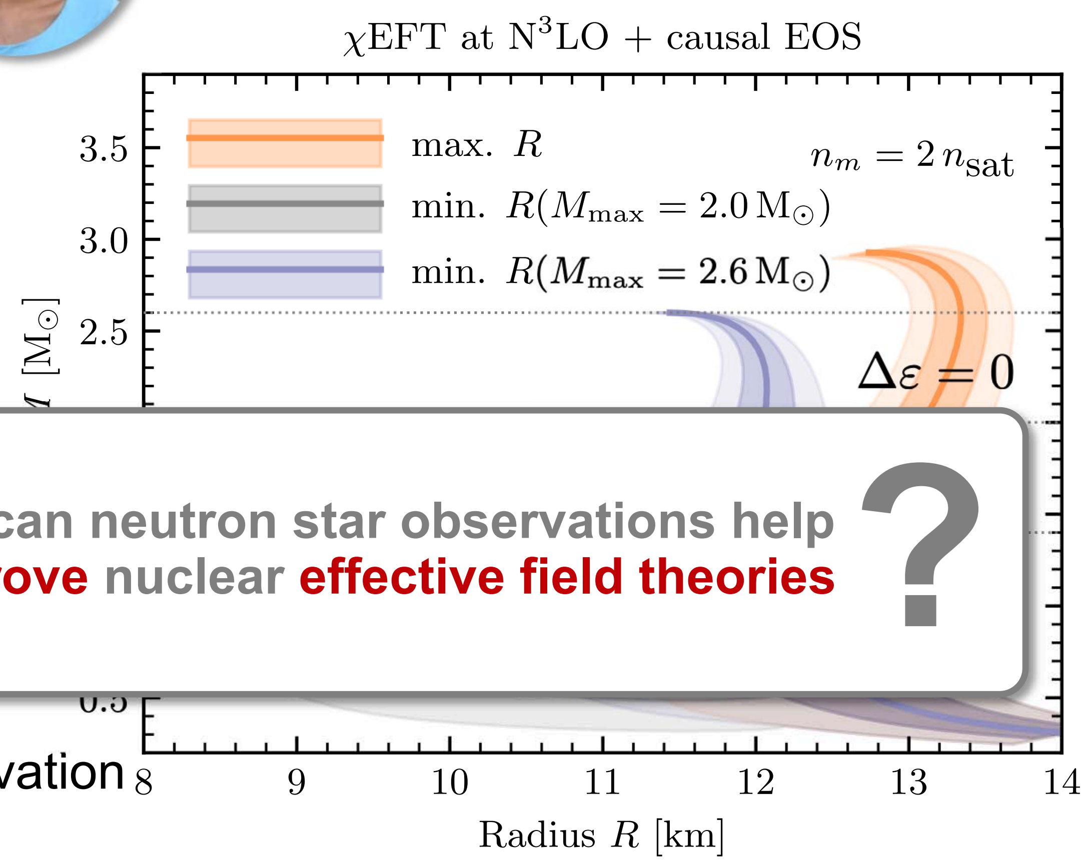
$$R_{2.0} = 12.39^{+1.30}_{-0.98}\ \mathrm{km}$$

$$R_{2.0} = 13.70^{+2.6}_{-1.5}\ \mathrm{km}$$

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

see also: Alford *et al.*, JPG: NPP **46**

extend EFT EOS at density n_{m} to a linear EoS with finite discontinuity



$\Delta\varepsilon$ anticorrelates with M_{ma}

continuous match sets u

How can neutron star observations help **improve** nuclear **effective field theories**?

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

Equation of State of Dense (Neutron-rich) Matter at Zero Temperature

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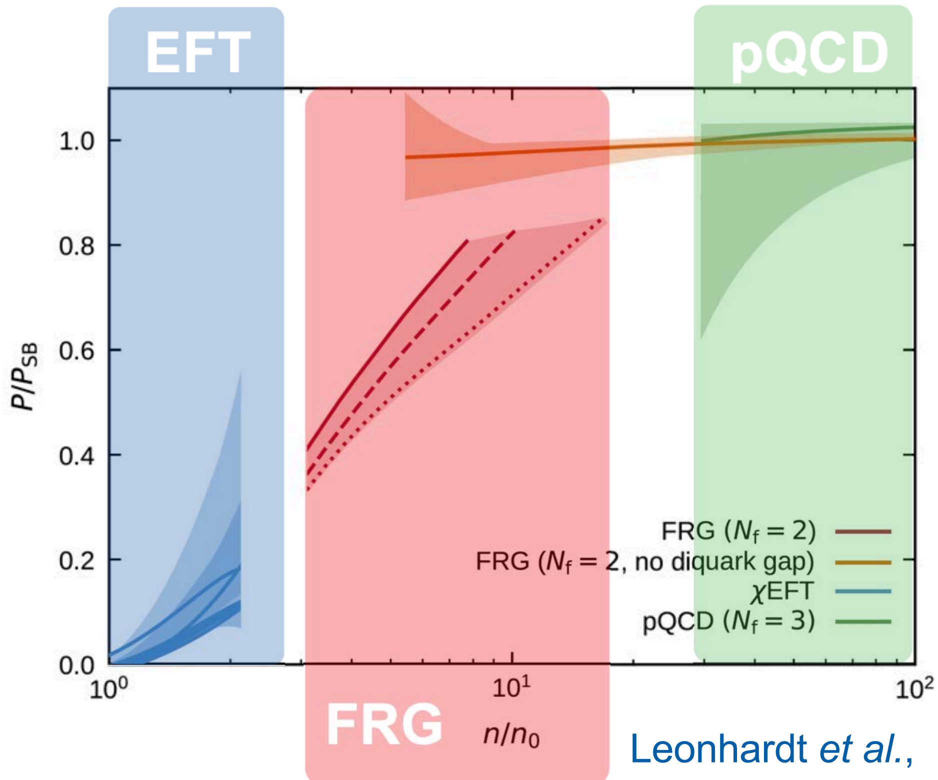
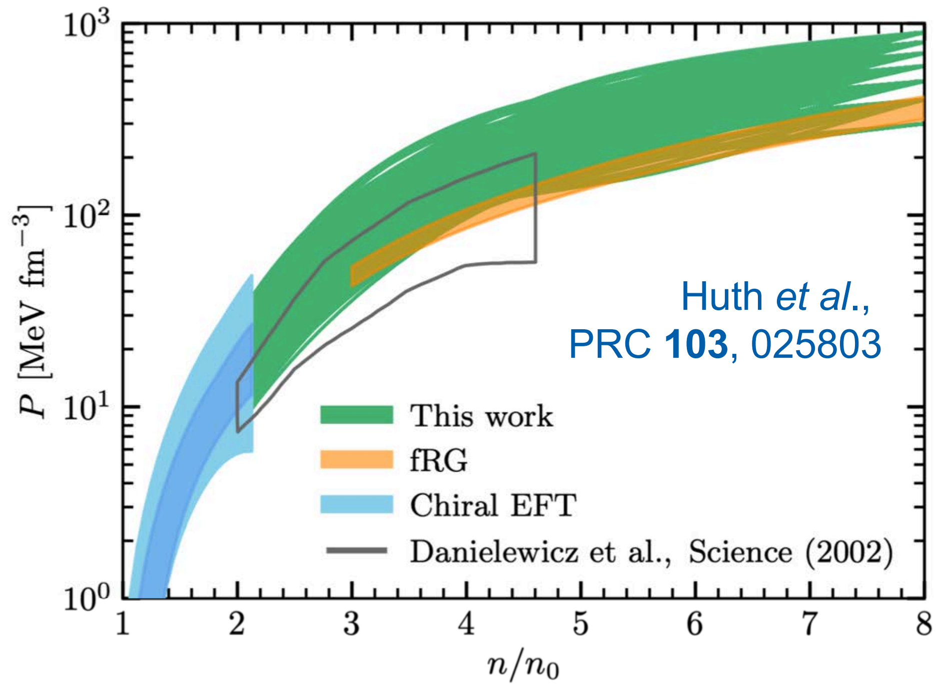
New developments: symmetric nuclear matter



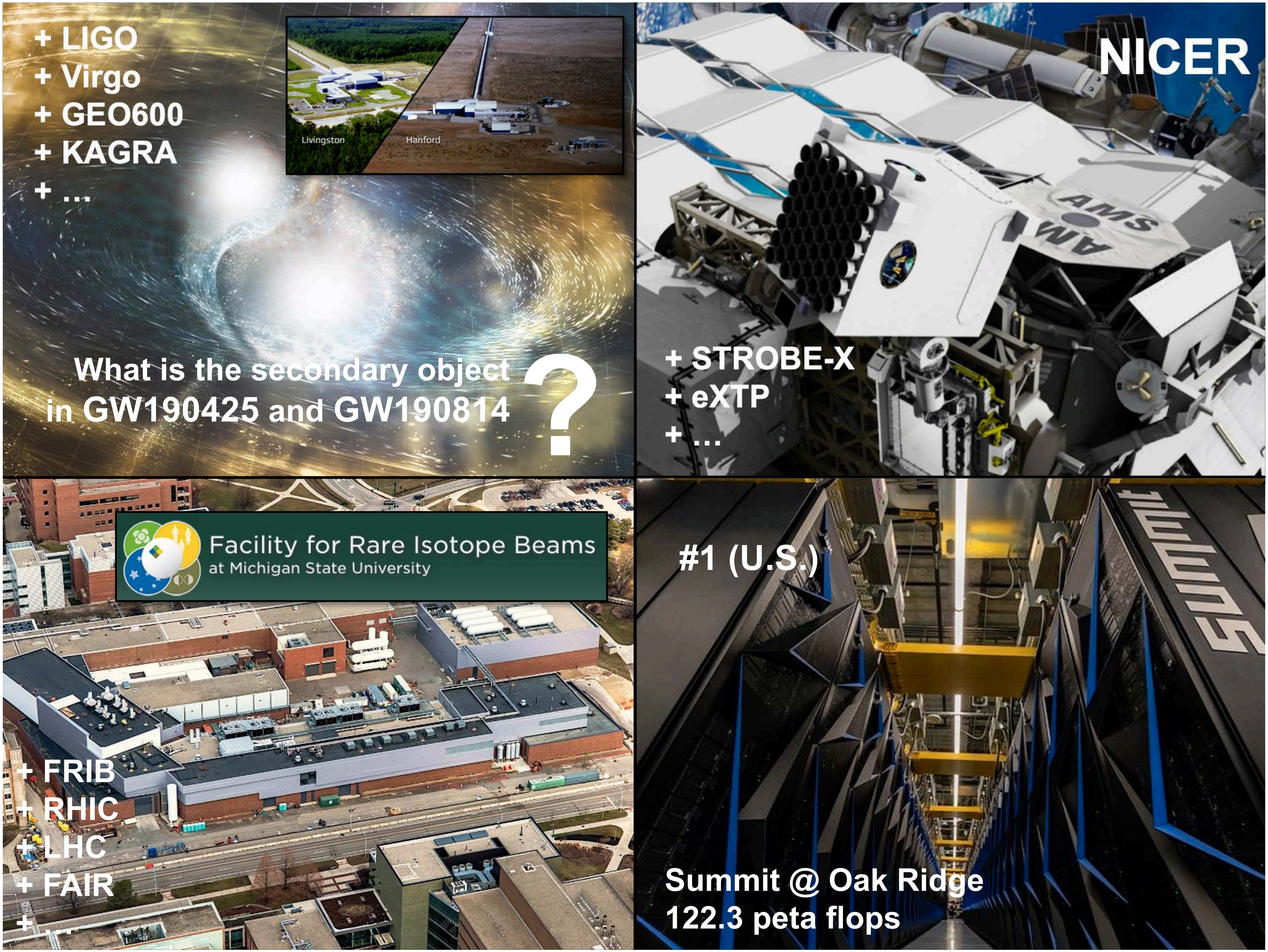
Leonhardt *et al.*, PRL **125**, 142502



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

Functional Renormalization Group: ***complementary*** **constraints at > 3n_0** (beyond the range of chiral EFT) from the QCD action

New insights into the high-density EOS: **remarkable consistency** between the constraints, which suggests that they can be combined via **simple extrapolations**



+ LIGO
+ Virgo
+ GEO600
+ KAGRA
+ ...
Livingston
Hanford
What is the secondary object
in GW190425 and GW190814 ?
NICER
AMS
+ STROBE-X
+ eXTP
+ ...
Facility for Rare Isotope Beams
at Michigan State University
+ FRIB
+ RHIC
+ LHC
+ FAIR
+ ...
#1 (U.S.)
SUMMIT
Summit @ Oak Ridge
122.3 peta flops

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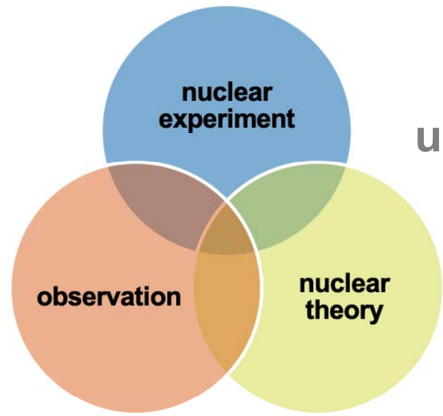
Conclusion

multi-messenger
nuclear precision
FRIB

} era



unique opportunity to **constrain the nuclear EOS**, with great **potential for discoveries**

1 Microscopic EOS constraints | *statistically* robust uncertainties

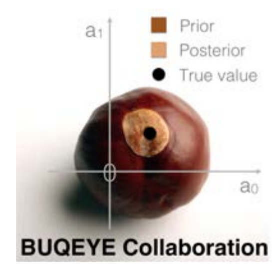
- excellent agreement of predicted S_v–L correlation with experiment
- PNM and SNM show a regular EFT convergence pattern with increasing order
- extracted Λ_b is consistent with NN scattering ● N^2LO coefficient may be an outlier

2 full Bayesian UQ: sample over LECs & hyperparameters

- in future: include consistently uncertainties in the LECs of chiral interactions
- promising: new potentials up to N^2LO by Wesolowski *et al.*, arXiv:2104.04441

thanks to my collaborators:

R. Furnstahl J. Melendez K. McElvain D. Phillips
S. Han J. Lattimer M. Prakash S. Reddy T. Zhao



Equation of State of Dense (Neutron-rich) Matter at Zero Temperature

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Key questions for *ab initio* many-body theory

CD & Holt, PAX-VII Workshop

How can neutron star observations help **improve** nuclear **effective field theories** ?

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

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

…