Recent progress in the nuclear-matter equation of state from chiral EFT

Christian Drischler

Next Frontiers in the Search for Dark Matter | September 27, 2019

astrophysics
neutron stars,
supernovae, …

effective field theory

nuclear physics
structure & reactions
of nuclei

nuclear matter

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The Galileo Galilei Institute
for Theoretical Physics

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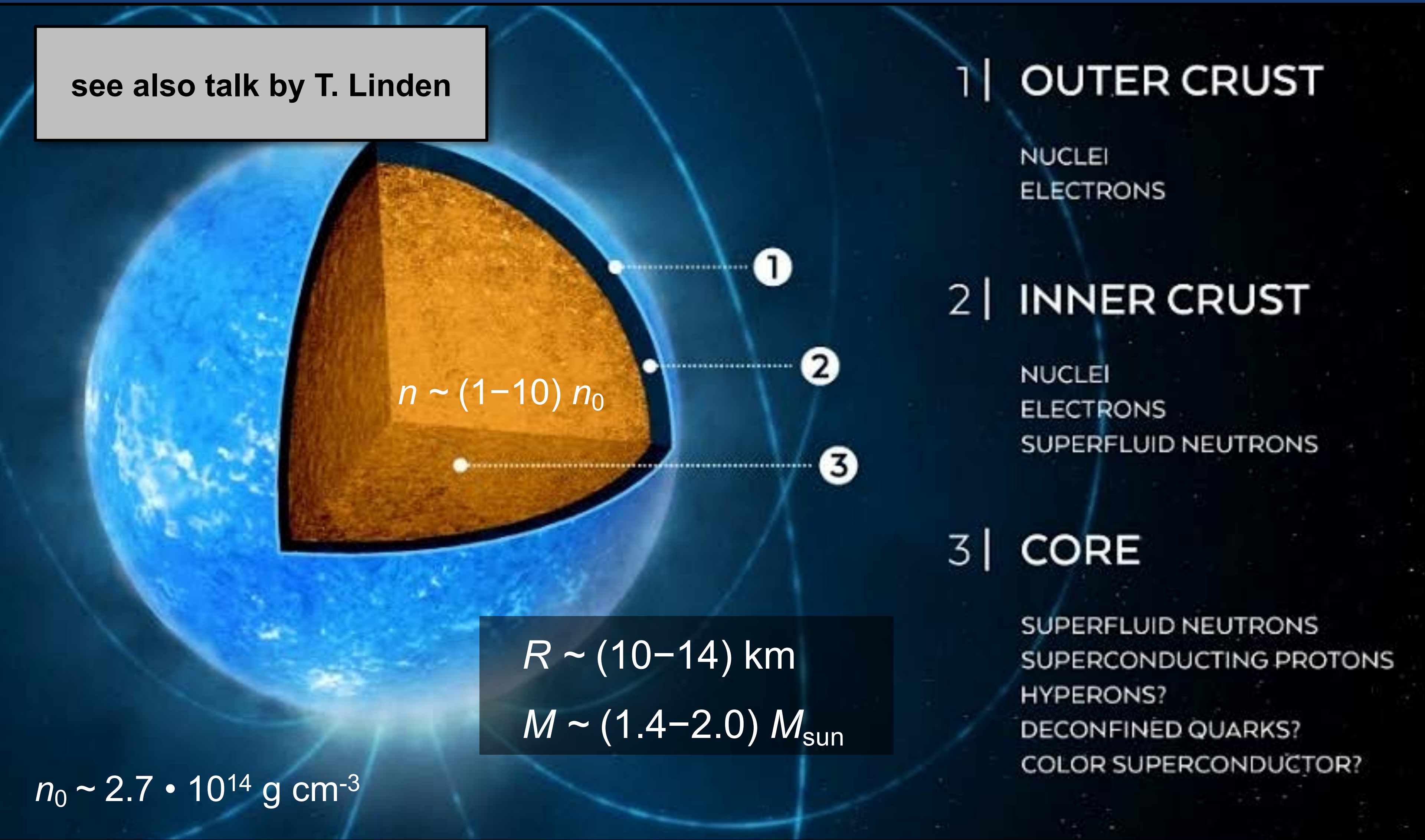
Neutron stars

e.g., Watts *et al.*, Rev. Mod. Phys. **88,** 021001

see also talk by T. Linden



$n \sim (1{-}10)\, n_0$

$R \sim (10{-}14)$ km

$M \sim (1.4{-}2.0)\, M_{sun}$

$n_0 \sim 2.7 \cdot 10^{14}$ g cm^{-3}

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(First) Direct detection of gravitational waves

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ligo.caltech.edu

multi-messenger astronomy

see also talks by D. Racco and D. Croon

+ Virgo
+ GEO600
+ …

Nobel Prize 2017

Binary Neutron-Star Merger

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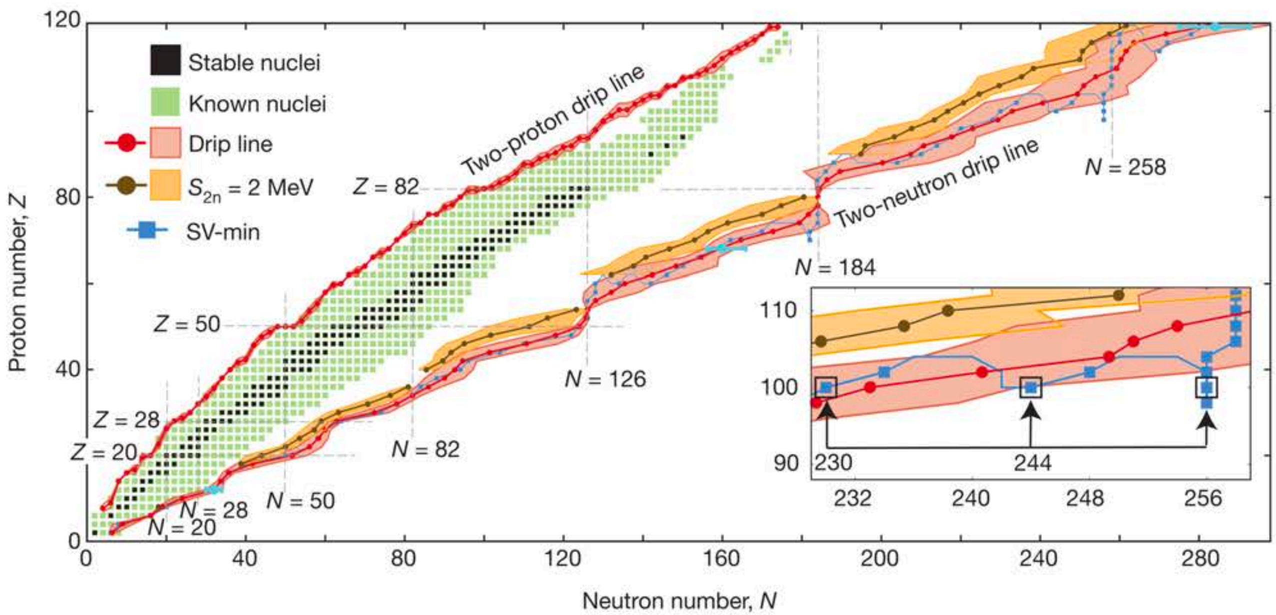
Erler *et al.*, Nature **486**, 509–512

Where do heavy elements come from?

How does the nuclear chart emerge from QCD?

How to predict properties of nuclei?



observables

many-body framework

effective field theory

quantum chromodynamics

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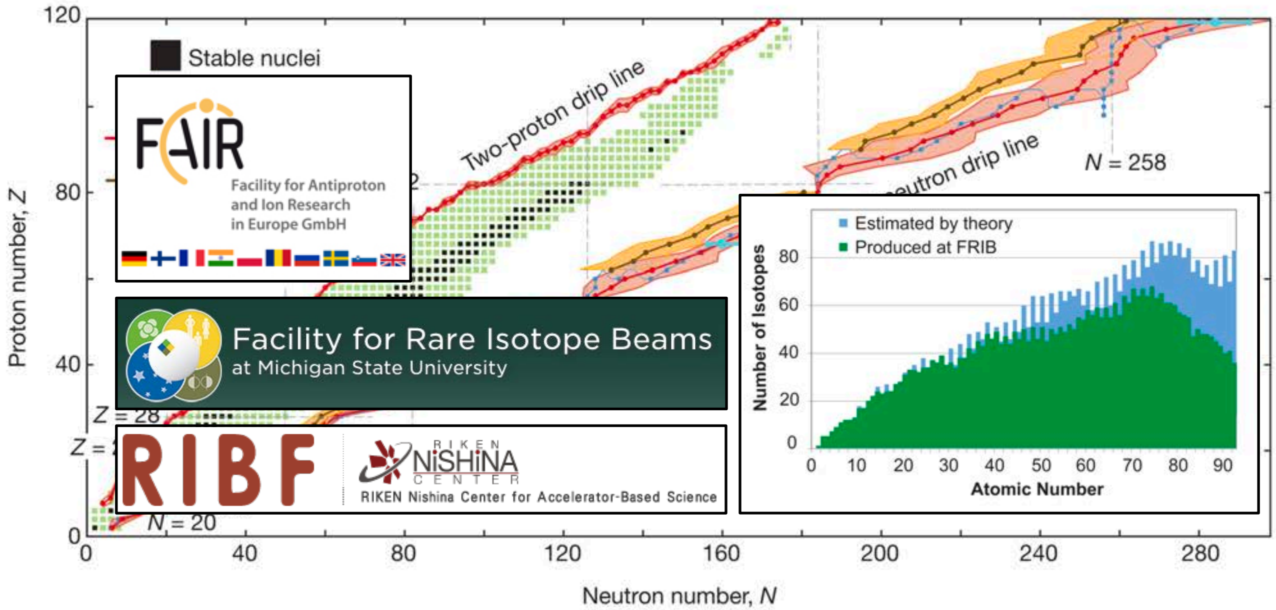

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see also Hebeler *et al.*, ARNPS **65**, 457

equation of state
neutron-star matter | nuclear saturation

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

chiral effective field theory
systematic expansion of nuclear forces
truncation error estimates

CalLat NPLQCD ...

observables

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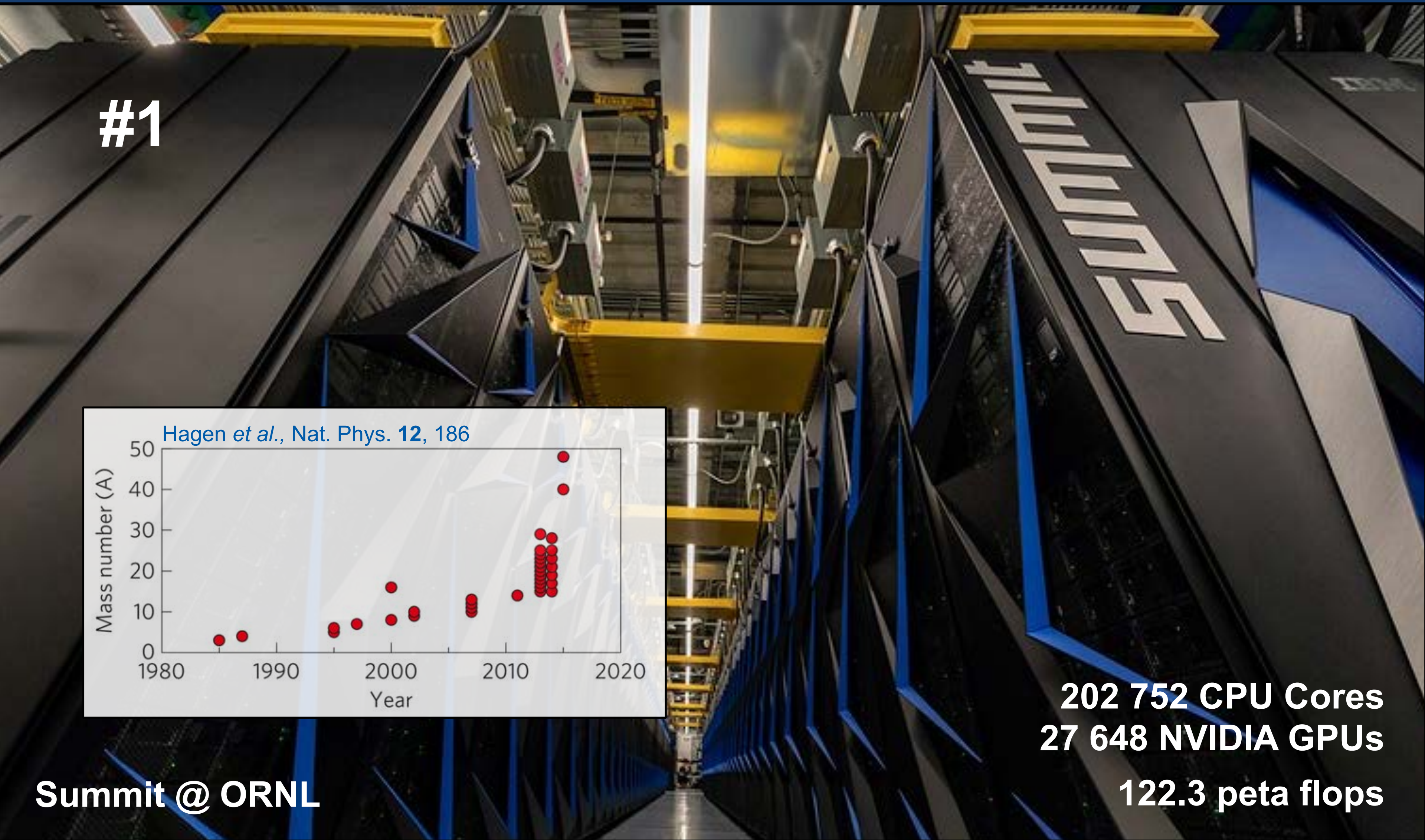
Next-generation supercomputers



#1

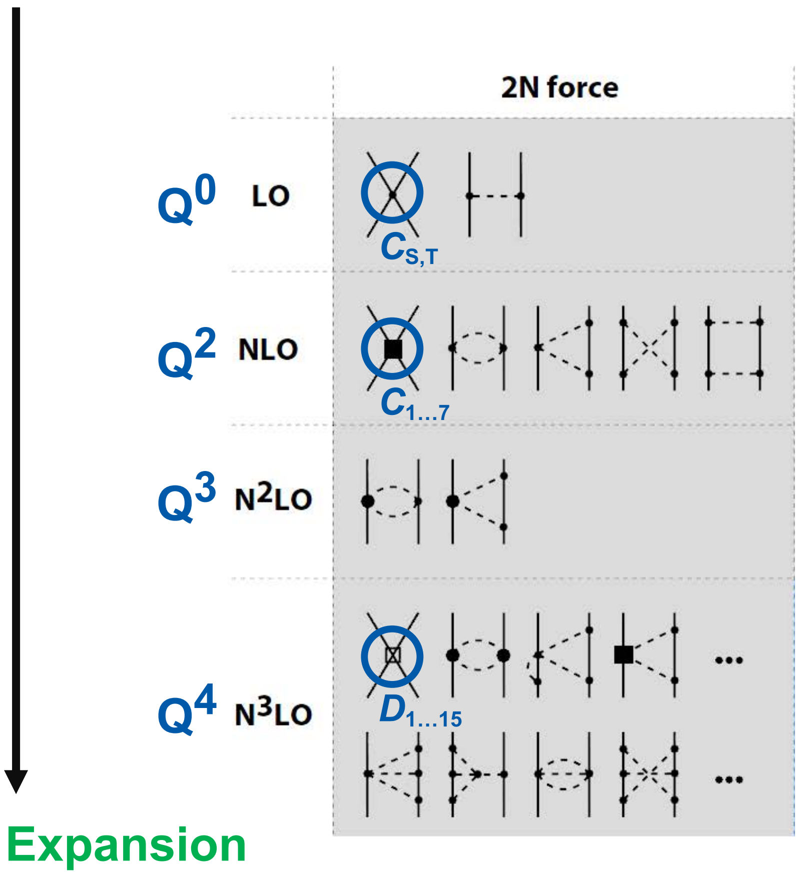
202 752 CPU Cores
27 648 NVIDIA GPUs
122.3 peta flops

Summit @ ORNL

Recent progress in the nuclear-matter equation of state from chiral EFT

Hierarchy of nuclear forces in chiral EFT

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



modern approach to nuclear forces:

- QCD is nonperturbative at the low-energy scales of nuclear physics
- use relevant instead of the fundamental degrees of freedom: *e.g.*, **nucleons** and **pions**
- **pion exchanges** and short-range **contact interactions** (∝ LEC)
- systematic expansion enables improvable **uncertainty estimates**

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

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

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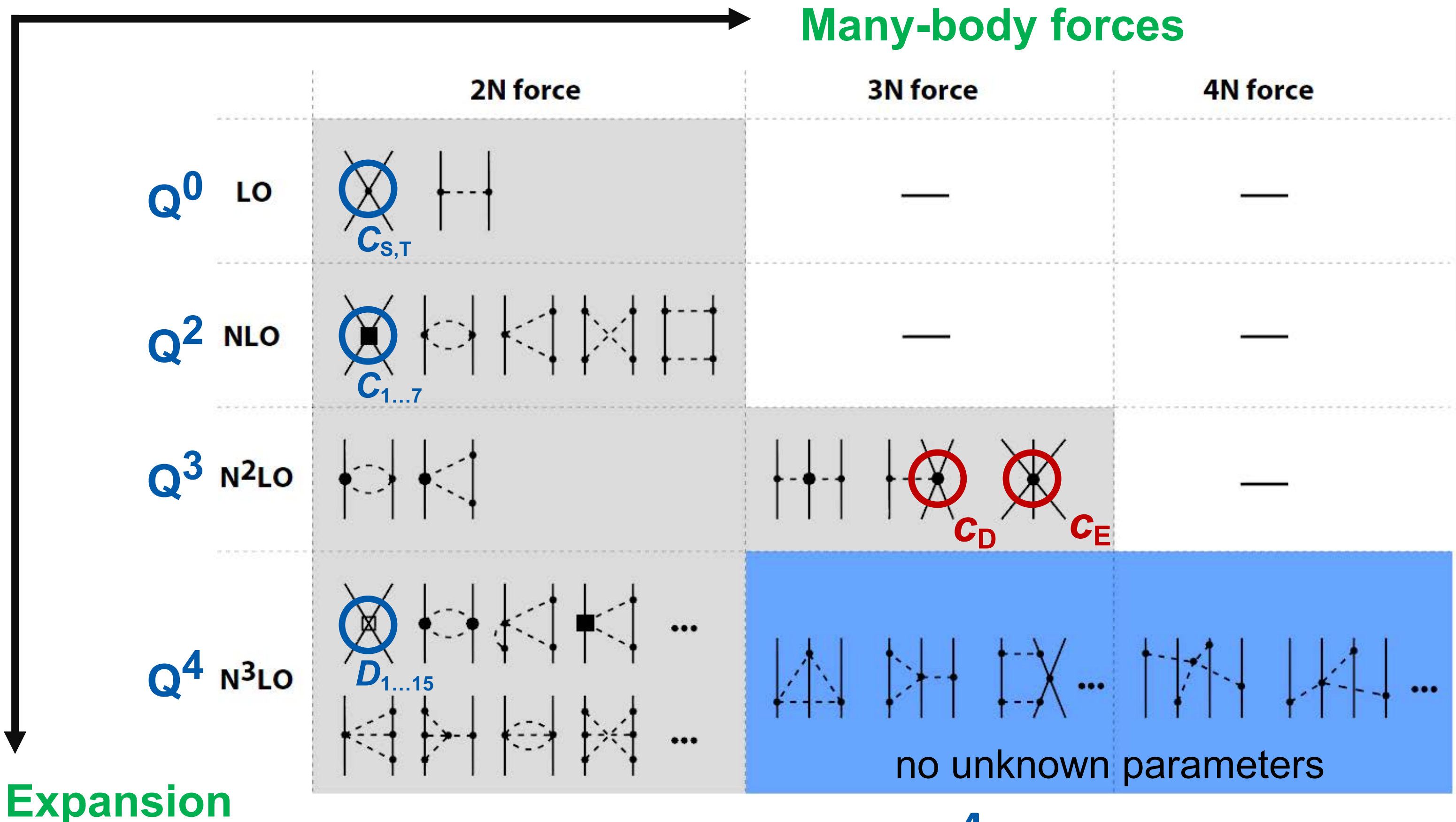

S.Weinberg

... and ongoing work at N^{4}LO and even N^{5}LO...

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

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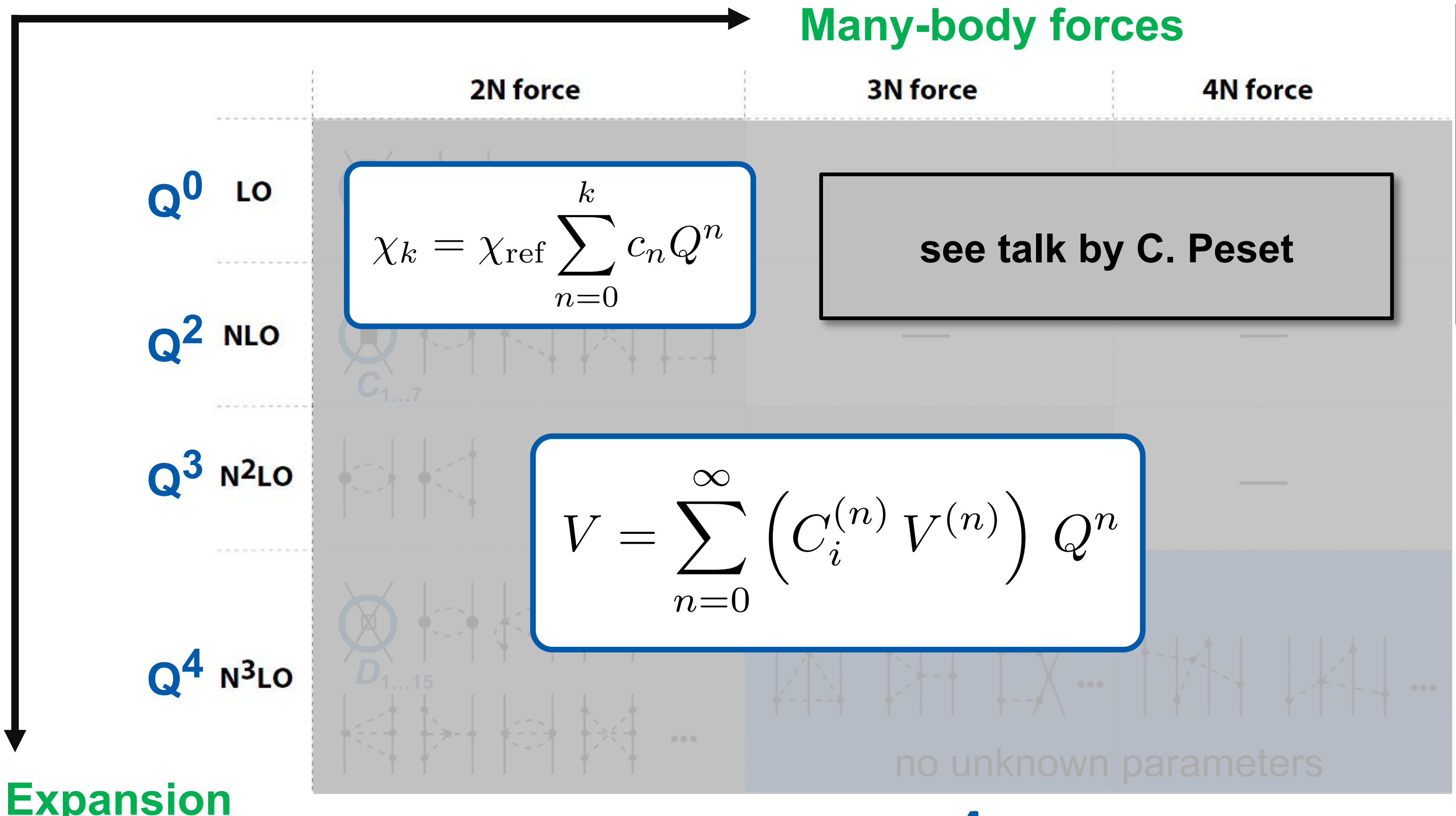

$$\chi_k = \chi_{\text{ref}} \sum_{n=0}^{k} c_n Q^n$$

$$V = \sum_{n=0}^{\infty} \left(C_i^{(n)} V^{(n)} \right) Q^n$$

S.Weinberg

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Central quantity

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Equation Of State

ground-state energy per particle of a system

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

total density
neutron excess
temperature

consisting of neutron and protons

$$n = n_n + n_p$$

neutron | proton density

$$\beta = \frac{n_n - n_p}{n}$$

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Homogeneous nuclear matter

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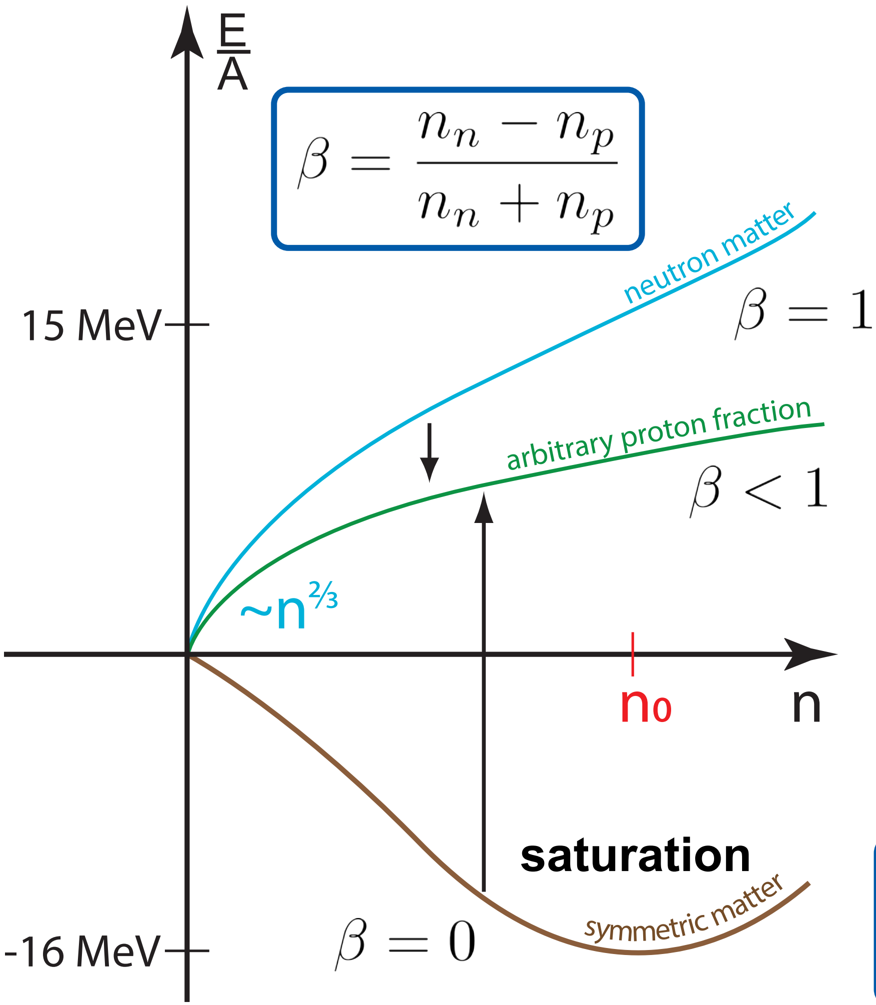

theoretical **testbed** for nuclear forces with important consequences for EOS

- **saturation point** (n_0 ~ 0.16 fm^{-3}, a_v ~ 16 MeV)
- **incompressibility** (K ~ 240 MeV)
- **symmetry energy** (E_{sym} ~ 32 MeV) and its **slope** (L ~ 55 MeV) at n_0

$$11.1\,\mathrm{km} \leqslant R_{1.4\,\mathrm{M}_\odot} \leqslant 12.7\,\mathrm{km}$$

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

$$\frac{E}{A}(\beta, n) = \frac{E}{A}(\beta = 0, n) + \beta^2 E_{\mathrm{sym}}(n)$$

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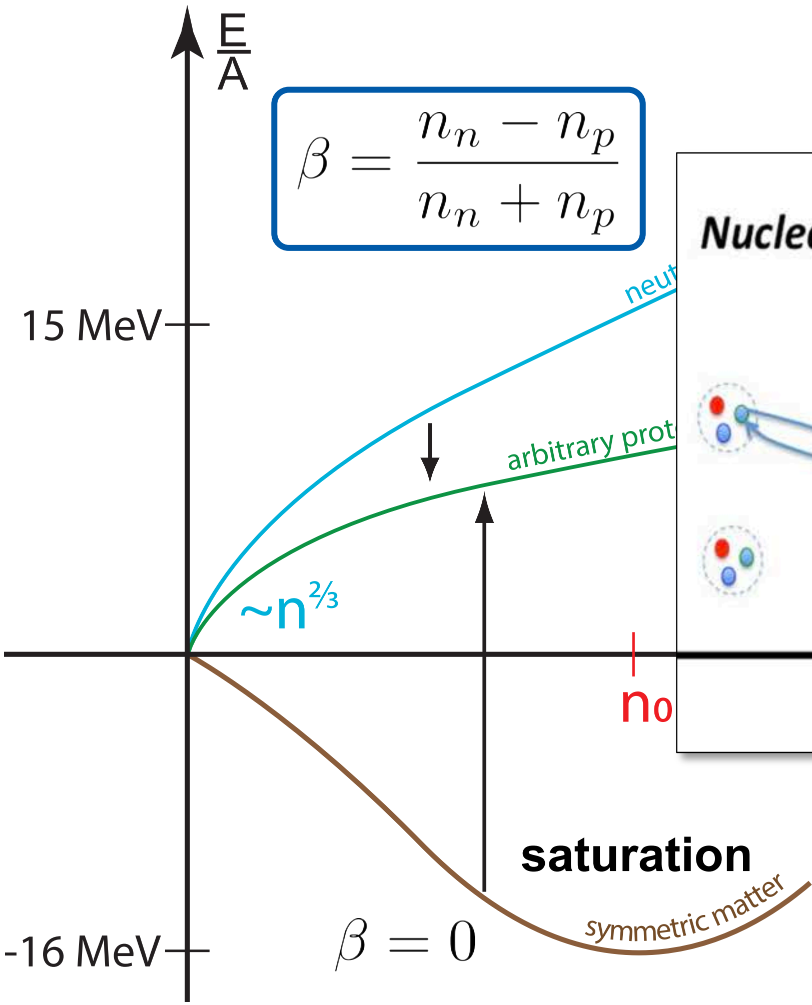
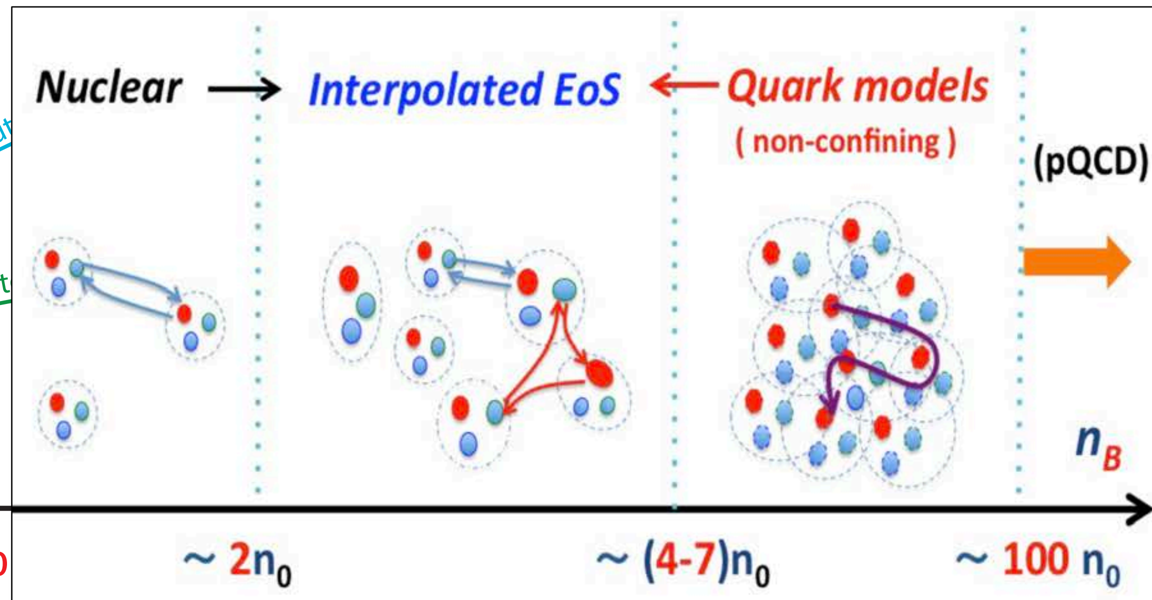




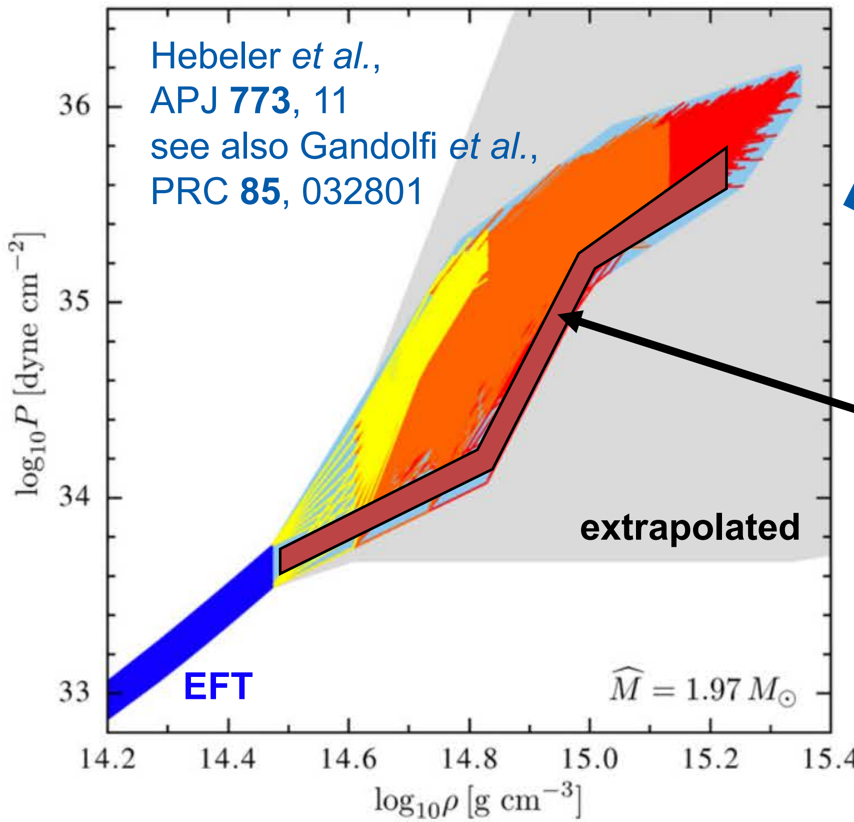
Hagen *et al.*, Nat. Phys. **12**, 186

$$\frac{E}{A}(\beta, n) = \frac{E}{A}(\beta = 0, n) + \beta^2 E_{\rm sym}(n)$$

Recent progress in the nuclear-matter equation of state from chiral EFT

Mass–radius relation

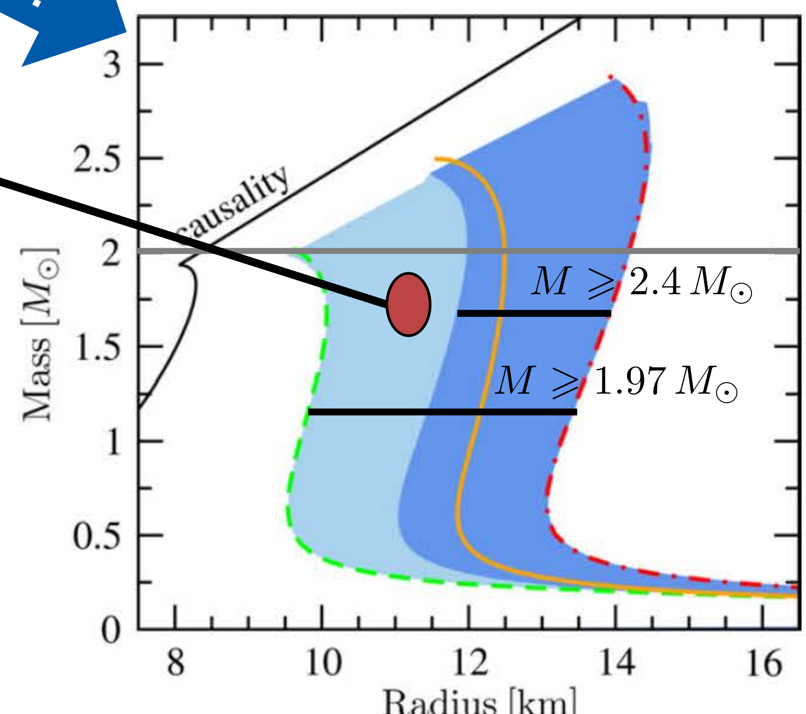
see, *e.g.*, Greif *et al.*, MNRAS **485**, 4



TOV eqs.

constraints from
- \+ causality
- \+ $M_{max} \geq 1.97\ M_{sun}$
- \+ GW170817, …

mass–radius relation



$$R_{1.4\,M_\odot} = 9.7 - 13.9\,\mathrm{km}$$

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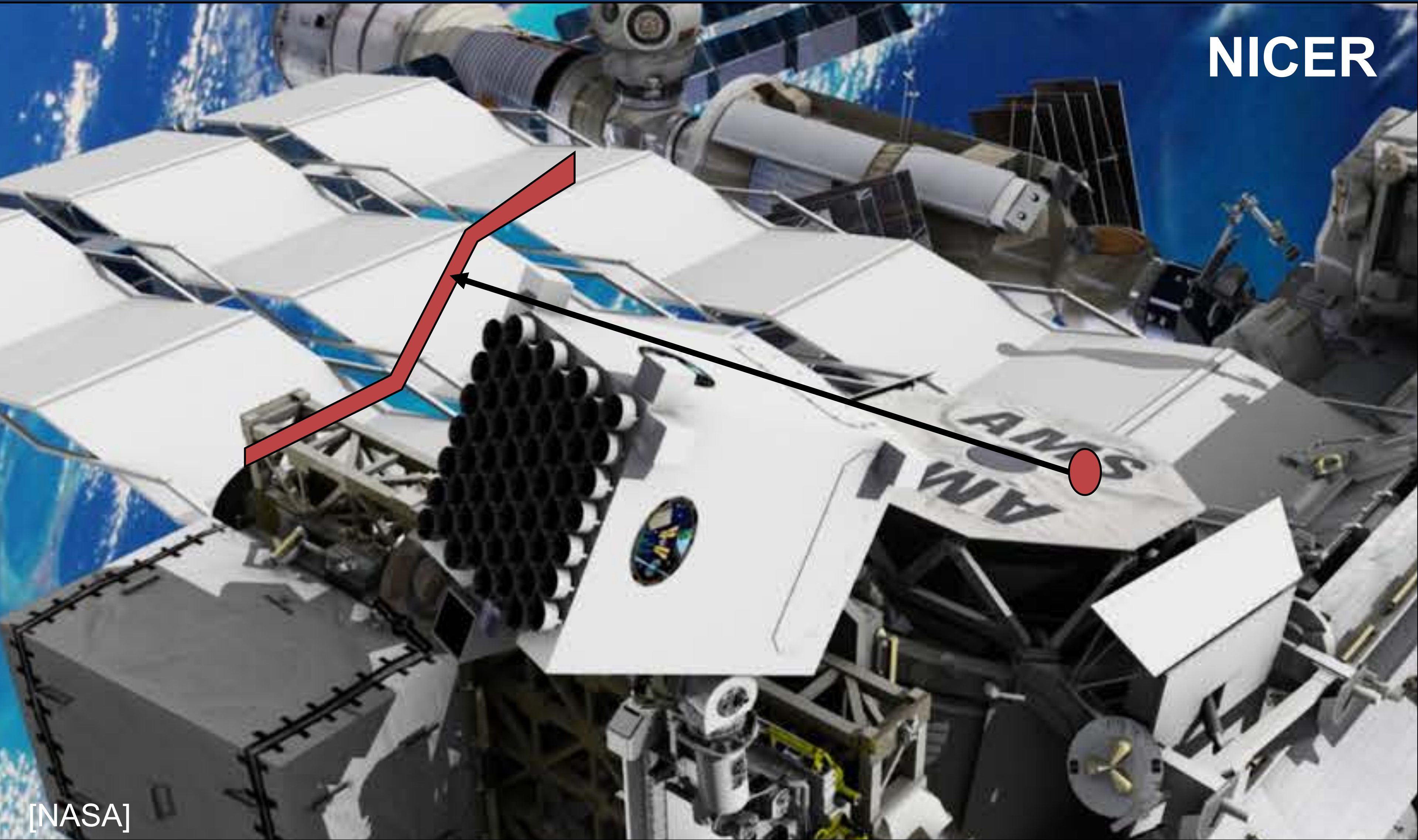

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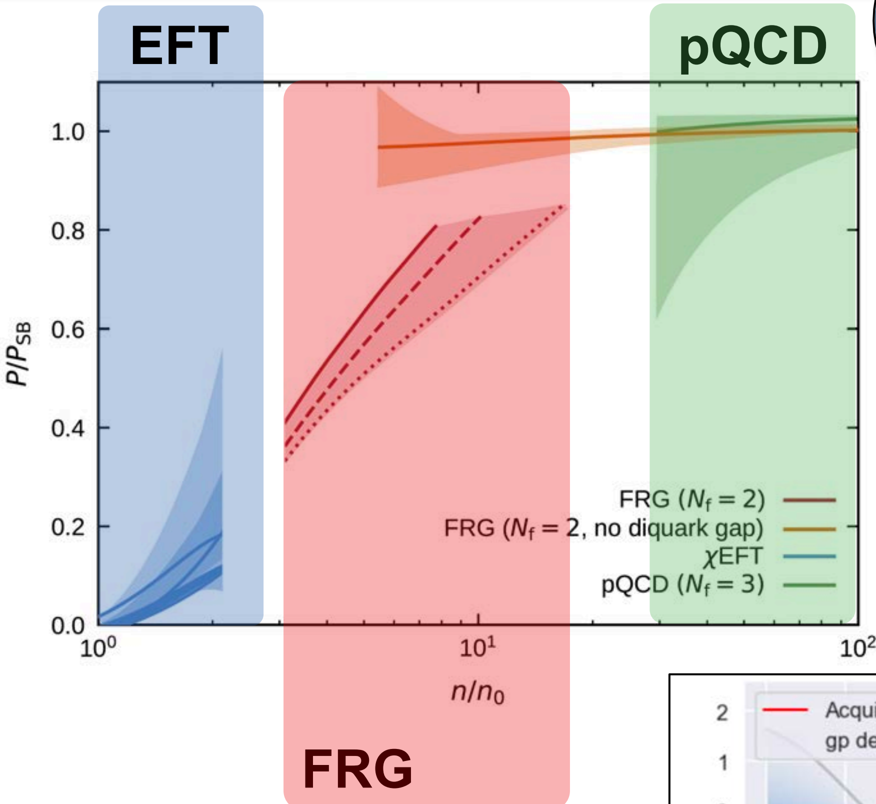
Connecting to QCD



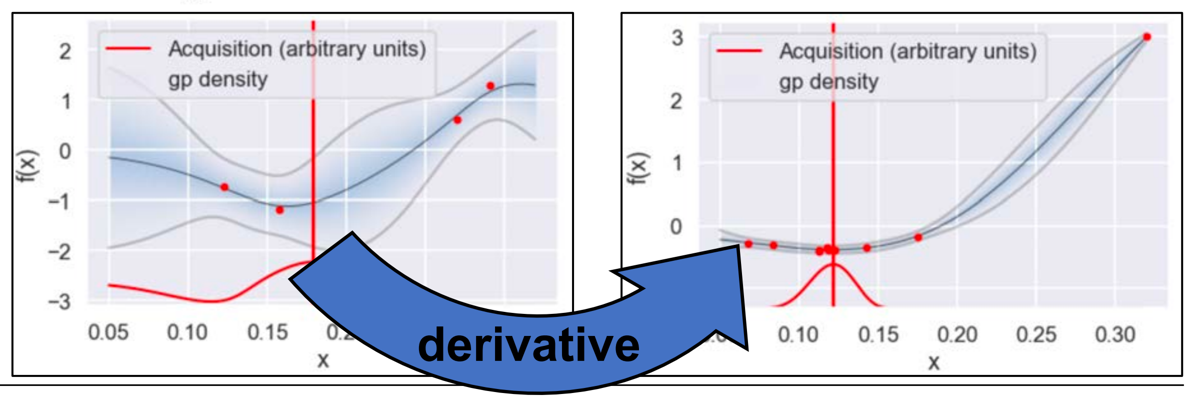
Leonhardt, Pospiech, Schallmo, Braun, CD, Hebeler, Schwenk, arXiv:1907.05814

Pressure

$$P(n,\, \beta) = n^2 \frac{\partial E/A}{\partial n}(n,\, \beta)$$

EFT seems to match first constraints from QCD at intermediate densities

in future, derivatives using GPs instead of finite differencing?



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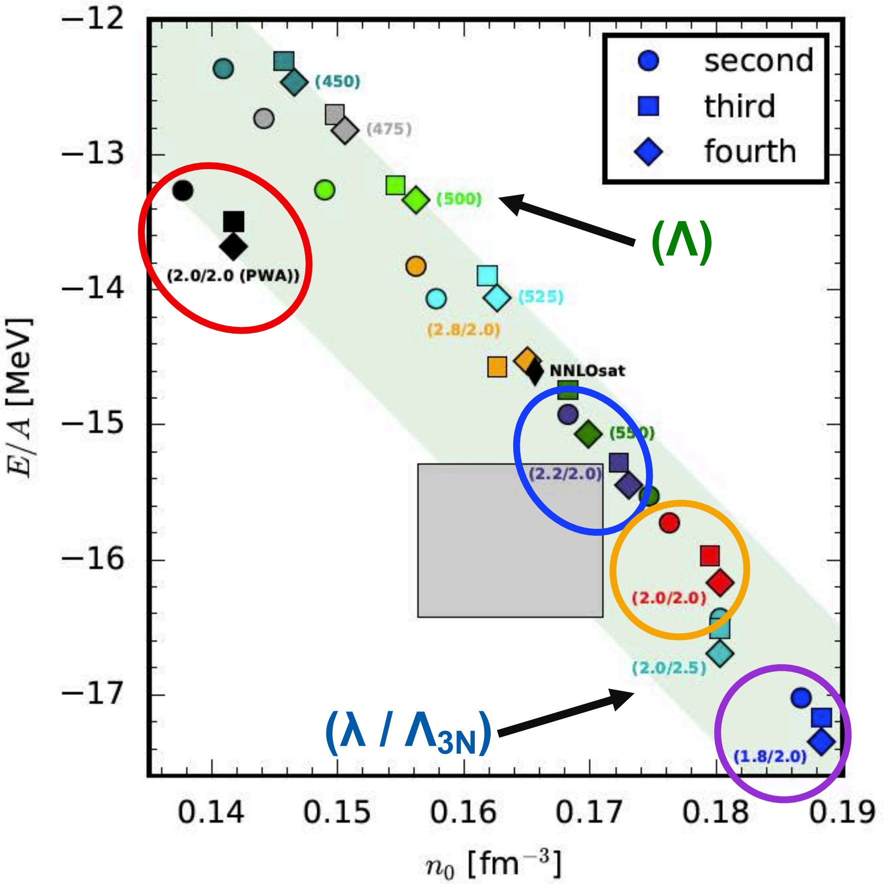
Nuclear saturation

potentials: Hebeler *et al.*, PRC **83**, 031301

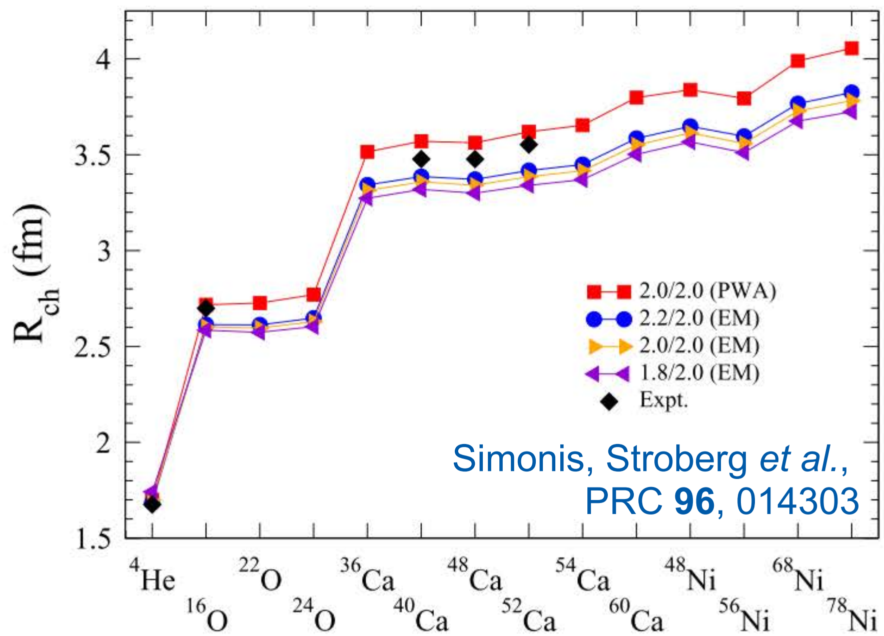
Homogeneous Matter



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

magic **1.8 / 2.0 (EM) agrees well with experimental data!**

Finite Nuclei



Simonis, Stroberg *et al.*, PRC **96**, 014303

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Efficient Monte Carlo framework

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

efficient evaluation of **diagrams**
(single-particle basis)

- **implementing diagrams** has become **straightforward** (also particle-hole or 3N terms)
- using **automatic code generation** based on analytic expressions
- multi-dimensional momentum integrals: VEGAS (openMP, MPI, and CUDA)
- **computational beast:** controlled computation of arbitrary interaction or many-body diagrams

EOS up to high orders

automatic code generation

analytic form of the diagrams

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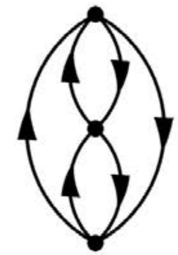
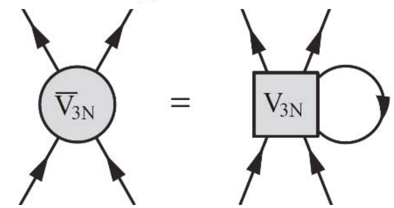
Significant challenges!

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

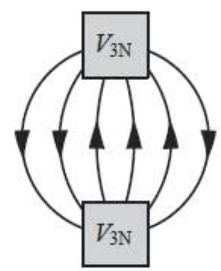


- **Higher orders: particle-hole contributions**
  Coraggio *et al.*, PRC **89**, 044321; Holt, Kaiser, PRC **95**, 034326

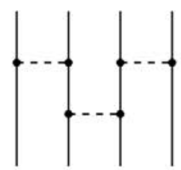


- **Exact normal-ordering**
  Holt *et al.*, PRC **81**, 024002; Hebeler, Schwenk, PRC **82**, 014314

- **Residual 3N diagram included**
  Hagen *et al.*, PRC **89**, 014319; Kaiser, EPJ A **48**, 58



- **Higher many-body forces**
  Hebeler *et al.*, PRC **91**, 044001



» **push state-of-the-art MBPT calculations to higher orders**

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Number of diagrams in MBPT

Stevenson, Int. J. Mod. Phys. C **14**, 1135

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.

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see also Hebeler *et al.*, ARNPS **65**, 457

equation of state
neutron-star matter | nuclear saturation

many-body perturbation theory
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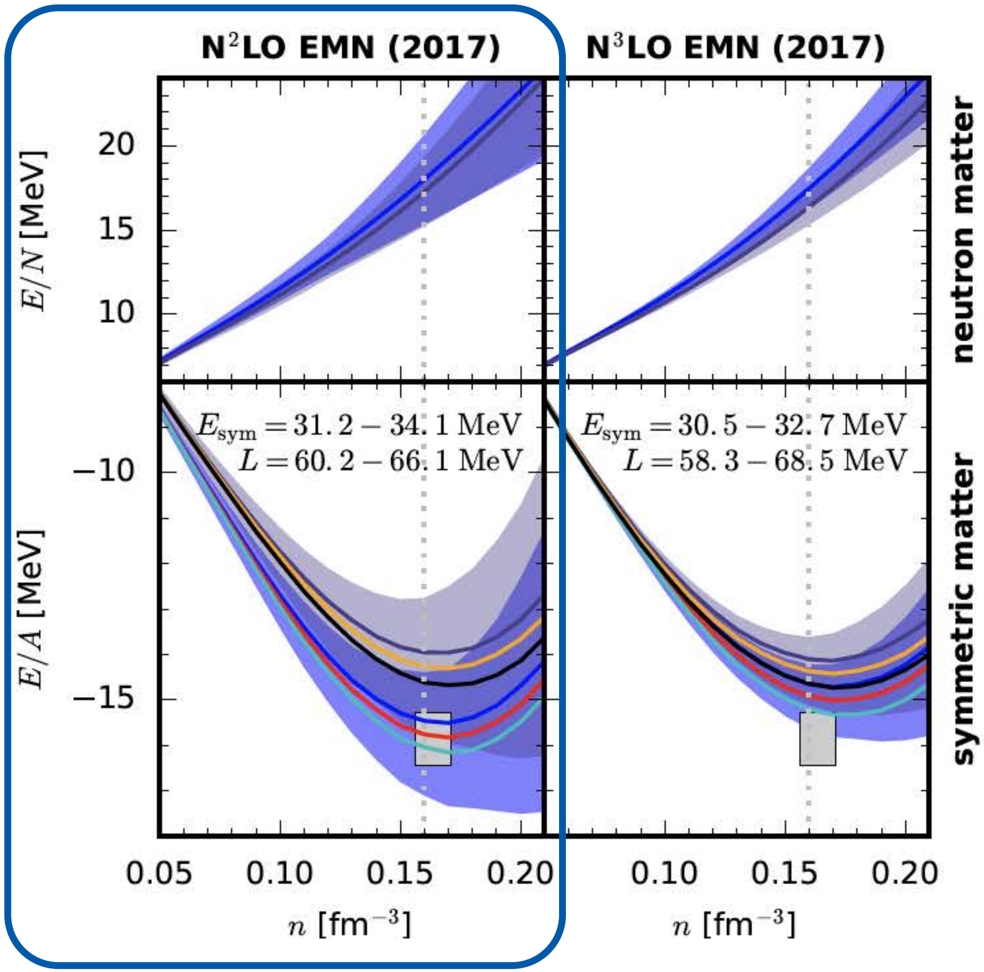
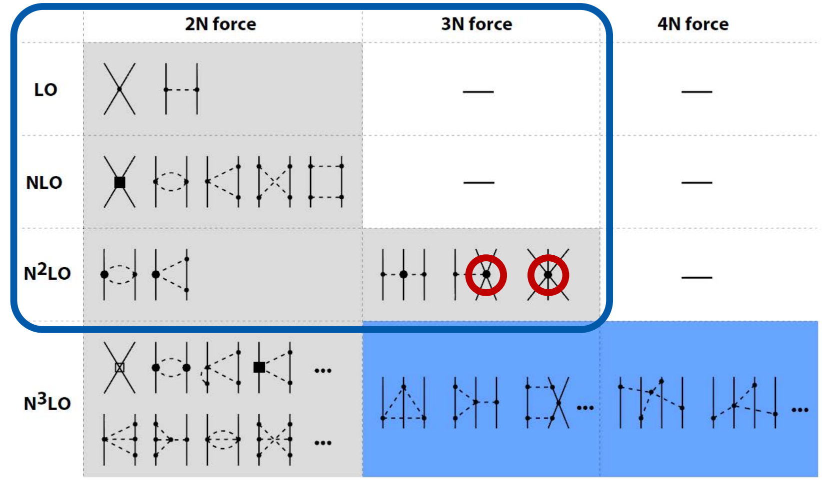
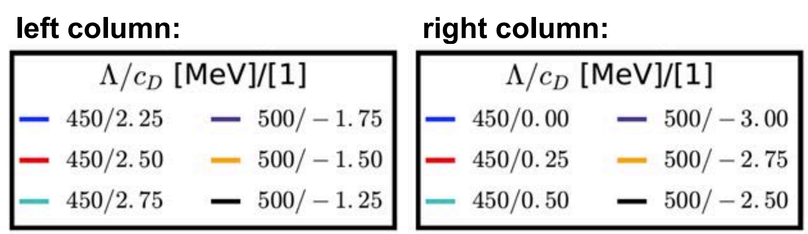
Neutron and nuclear matter at N^3LO

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





reduced uncertainties
due to N^3LO contributions !



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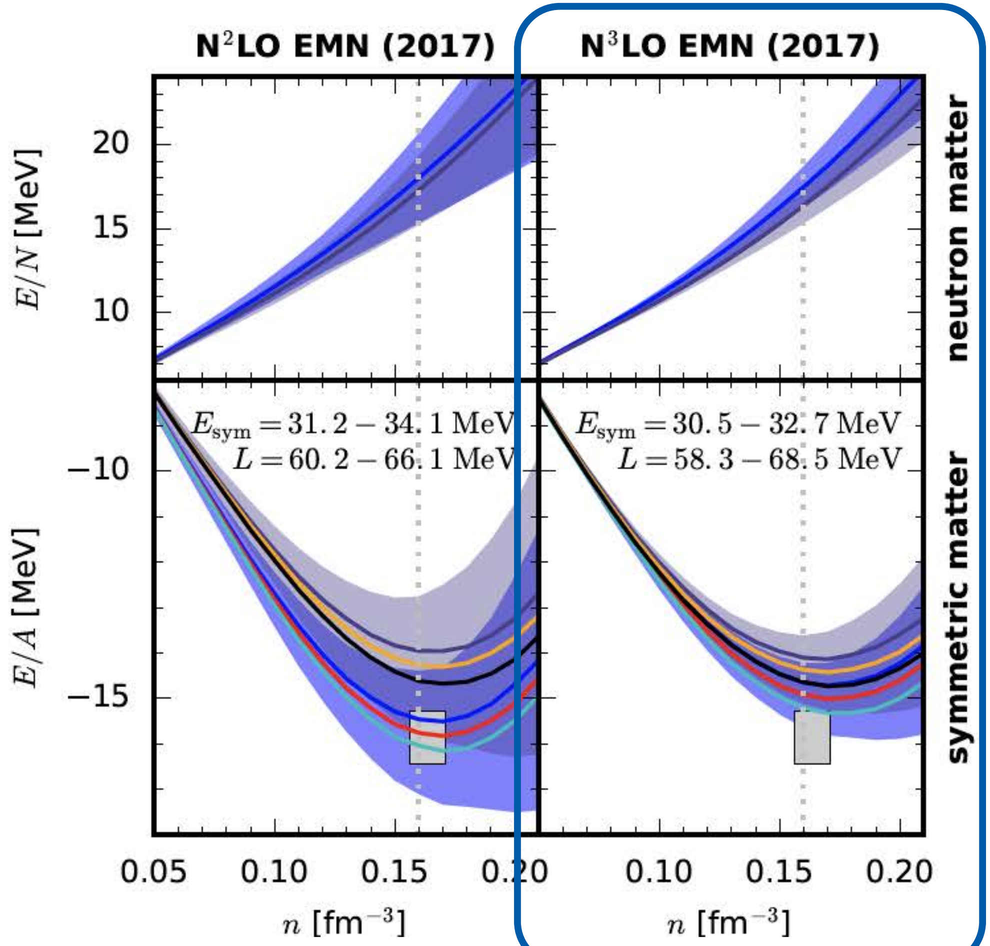
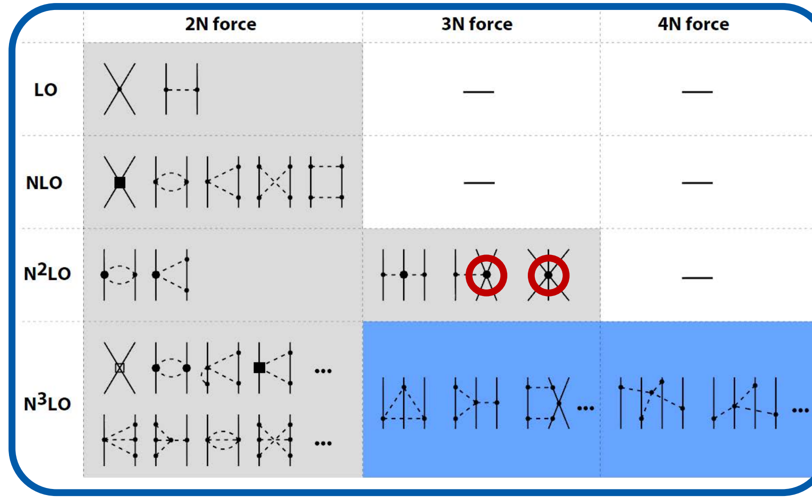
CD, Hebeler, Schwenk, PRL **122**, 042501





reduced uncertainties due to N^{3}LO contributions !

left column:

Λ/c_D [MeV]/[1]	
450/2.25	500/−1.75
450/2.50	500/−1.50
450/2.75	500/−1.25

right column:

Λ/c_D [MeV]/[1]	
450/0.00	500/−3.00
450/0.25	500/−2.75
450/0.50	500/−2.50

Recent progress in the nuclear-matter equation of state from chiral EFT

Truncation error analysis

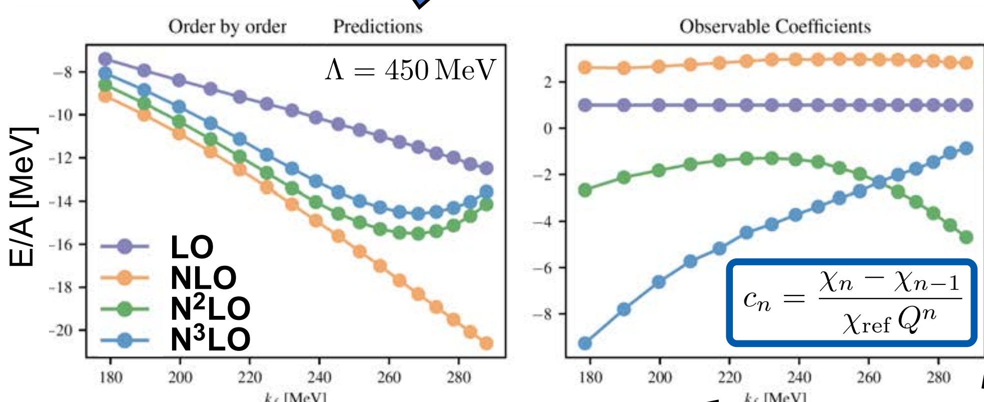
Melendez, Furnstahl, Phillips

start from chiral expansion for observable *X* (= *E* / *A*)

$$\chi_k = \chi_{\text{ref}} \sum_{n=0}^{k} c_n Q^n$$

Evaluate *X* at …

… consecutive orders

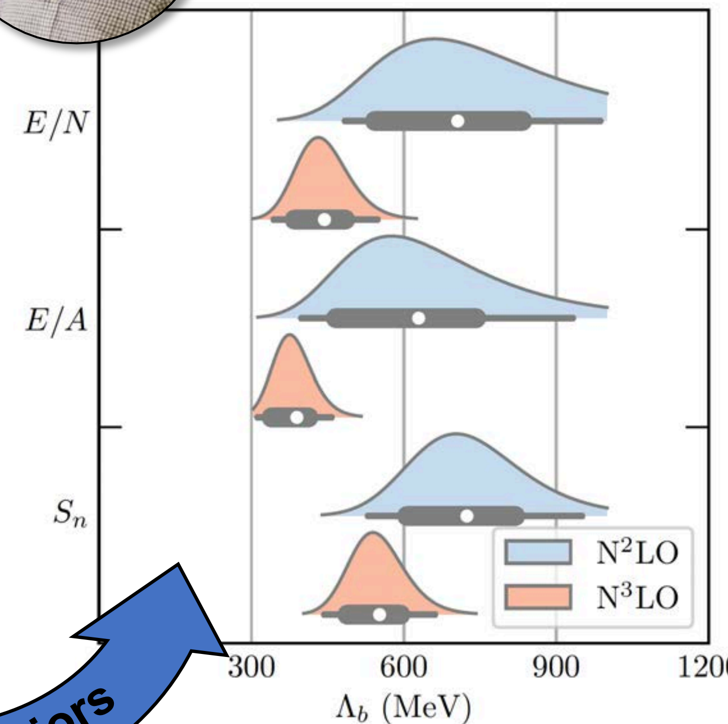


$$c_n = \frac{\chi_n - \chi_{n-1}}{\chi_{\text{ref}} Q^n}$$

check naturalness

GPs

priors



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

Bayesian inference: breakdown scale, higher-order terms

BUQEYE collaboration; Melendez *et al.*, arXiv:1904.10581, Melendez, Wesolowski *et al.*, PRC **96**, 024003, …

Recent progress in the nuclear-matter equation of state from chiral EFT

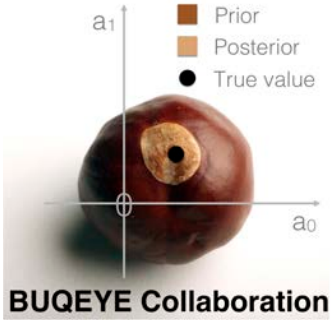
Summary and outlook

1. **Perform zero-T calculations (up to high order)**
   resummation, higher-order single-particle spectra, …
2. **Work out finite-T extension (to third order)**
   finish developments, study thermodynamic properties, …
3. **Construct high-density | temperature EOS**
   observational constraints, interface to astrophysics, …
4. **Quantify theoretical uncertainties**
   Bayesian truncation errors: naturalness, breakdown scale, …

Collaborators:

R. Furnstahl
J. Melendez
D. Phillips

K. Hebeler
K. McElvain
A. Schwenk



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