Nuclear Forces in the Medium: Insight from the Equation of State

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OUTLINE:

- Can the nuclear complexity emerge from low-energy QCD?
  - How do we predict nuclear structure from fundamental interactions?
  - Can modern theories provide all answers?

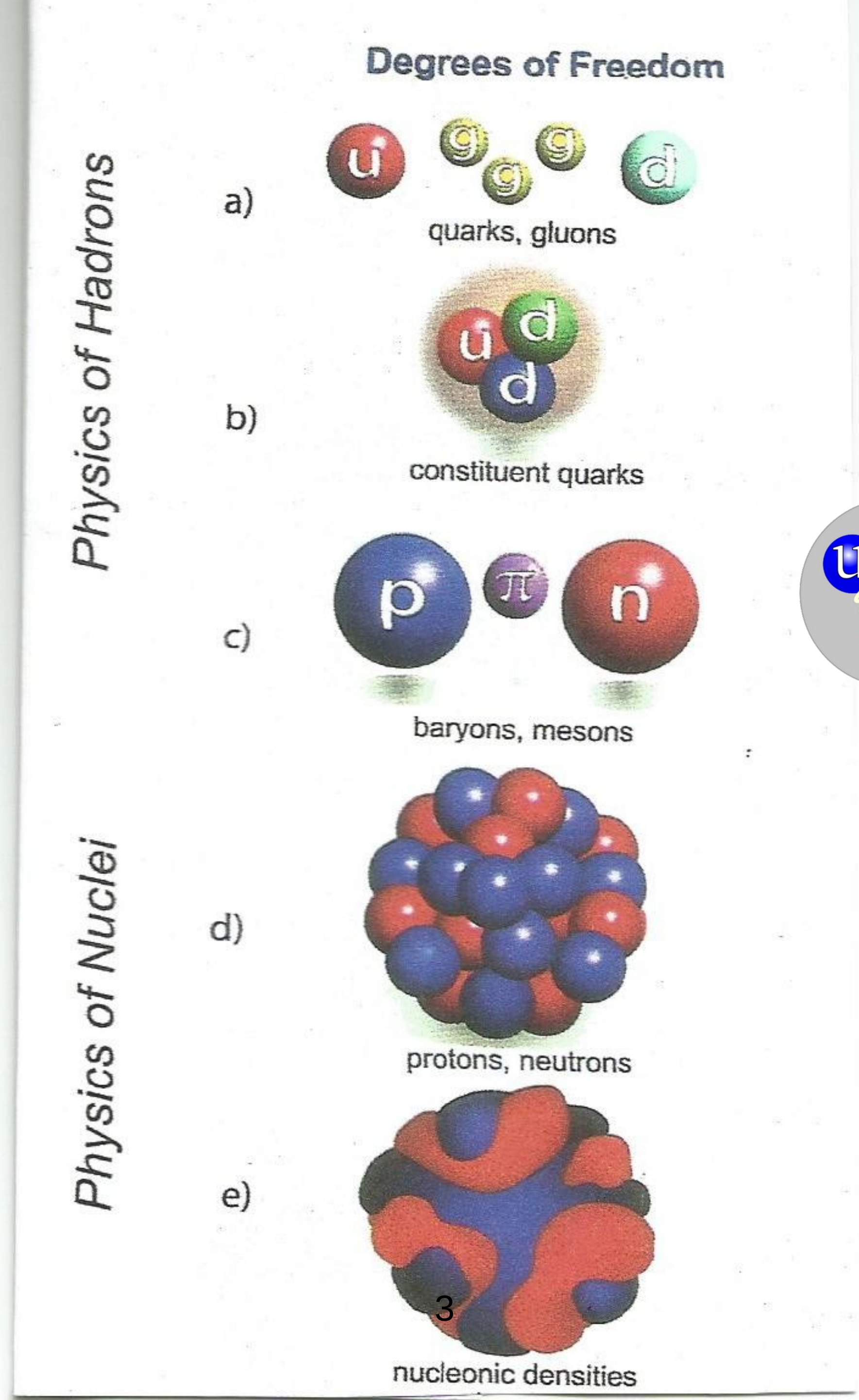
- Recent work with neutron matter and neutron-rich systems

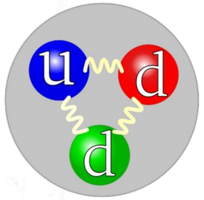
- Work in progress and future plans at the UI nuclear theory group

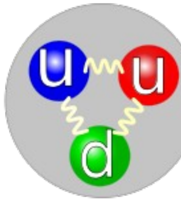
Our (still incomplete) knowledge of the nuclear force is the result of decades of struggle.

Nuclear Forces:
A hierarchy of scales.

Scale determines the appropriate degrees of freedom







The nuclear force: a very brief historical perspective

1960s-70s: The <u>OBE</u> model was developed, followed by more sophisticated <u>meson-exchange</u> models.

1980s: <u>Meson theory</u> became very popular. The goal of deriving the nuclear force from QCD led to the development of <u>quark models</u>.

1980s-1990's: The era of <u>high-precision NN potentials</u> based on meson theory or purely phenomenological (supplemented with phenomenological 3NFs).

<u>Effective Field Theory (EFT) for low-energy QCD</u>: Weinberg 1979, 1990, 1991.

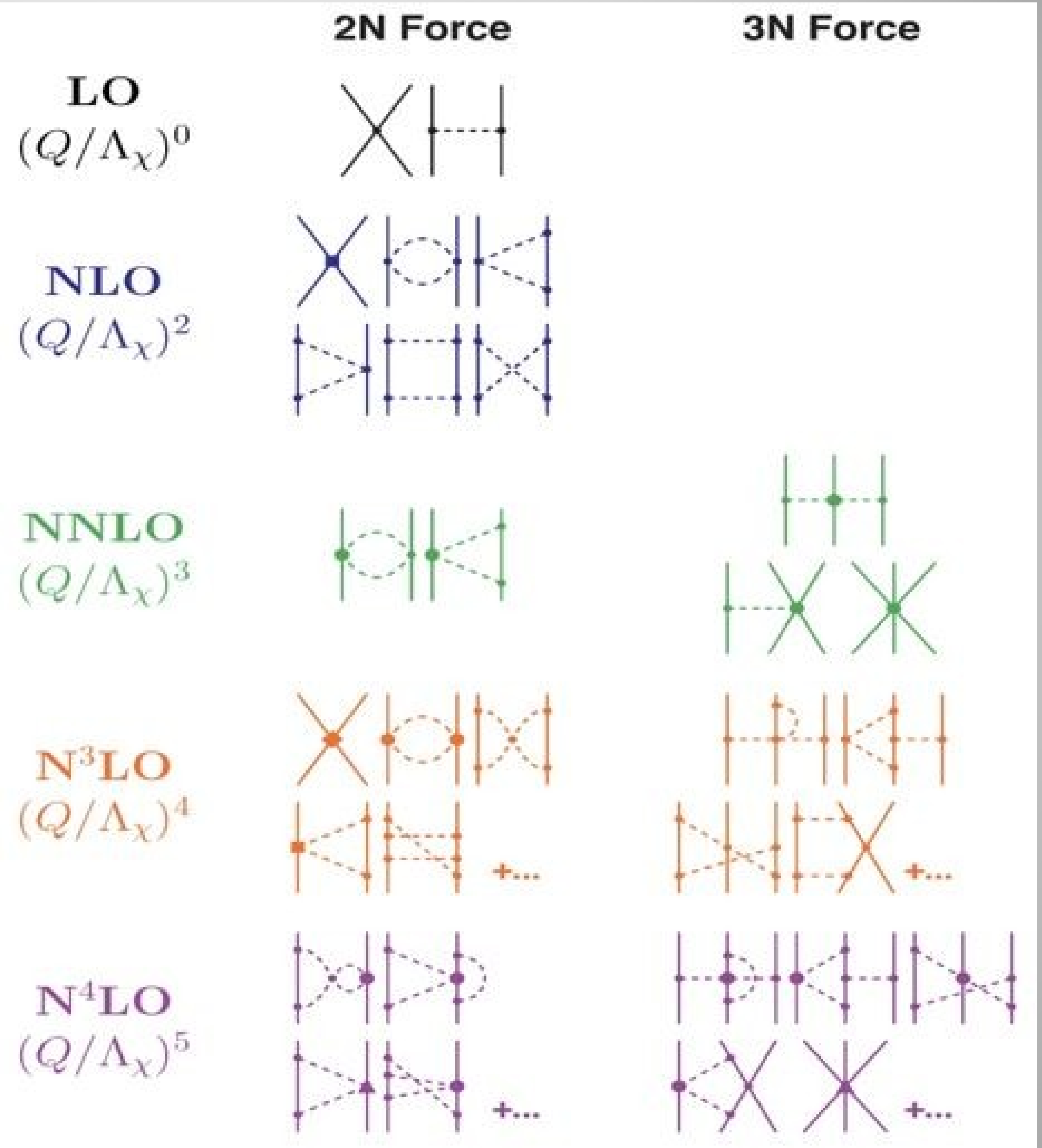
Since more than 2 decades:

For low energies, nuclear chiral EFT has become the most favorable approach to construct nuclear two- and few-body forces in a systematic way.

Based upon the symmetries of low-energy QCD, while using degrees of freedom relevant for low-energy nuclear physics. Predictions can be improved systematically.

Together with an organizational scheme to rank-order the various diagrams (power counting), **nuclear two- and few-body forces can be developed in a controlled hierarchy.**

Hierarchy of nuclear forces in Chi-EFT



….Gaining insight from nuclear matter:

An example……..

EXPLORING THE RELATION BETWEEN SYMMETRIC NUCLEAR MATTER AND NUCLEI WITH CHIRAL FORCES

Symmetric Nuclear matter (SNM):

- An extrapolation from finite nuclei: infinite system with saturation density and energy approximately equal to

$$\rho = 0.16\ fm^{-3} \text{ and } \frac{E}{A} = \text{-16 MeV}$$

- Traditionally seen as a "test bench" for nuclear many-body theories
- What do microscopic approaches predict for such relationship?

Framing the issue:

Chiral 2N and 3N forces (N2LO and N3LO)

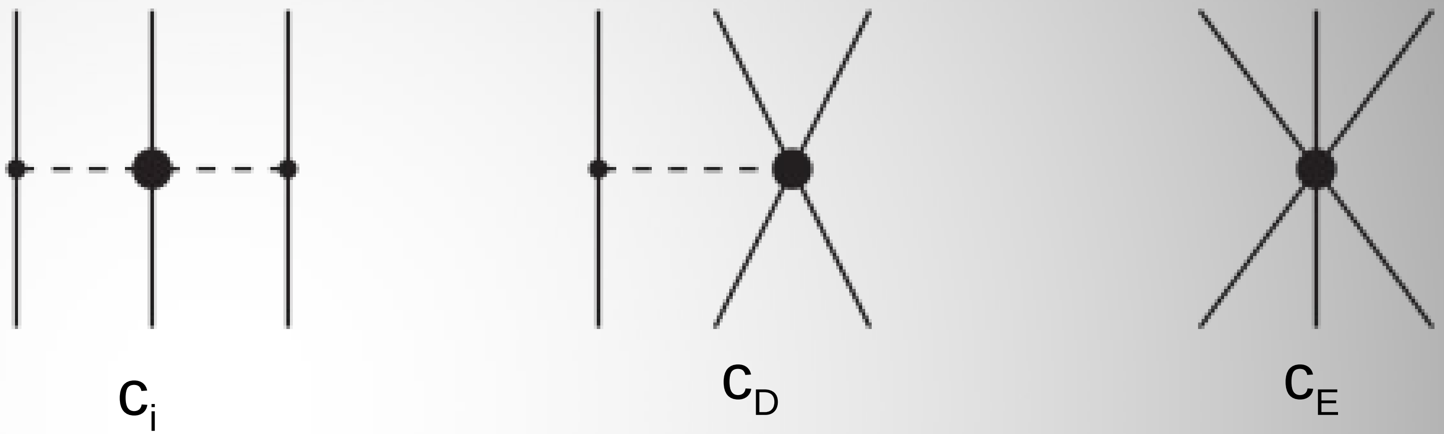
Predict realistic B.E. and radii for a wide range of nuclei, but unable to saturate SNM. (Huether et al., 2019)

If the SNM constraint is included (along with ^{3}H B.E. constraint), medium-mass nuclei are systematically underbound, radii are too large. (Hoppe et al., 2019)

Next, we explore this apparent inconsistency by considering various scenarios.

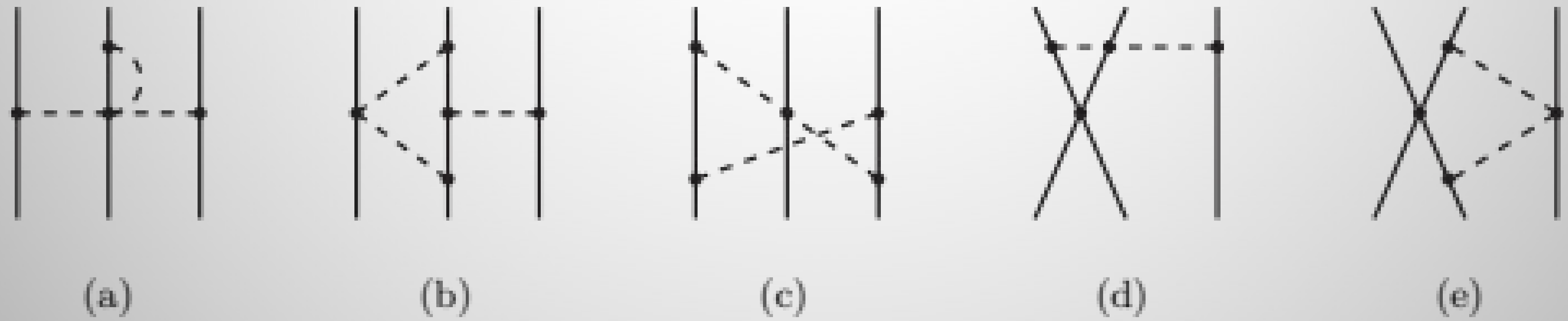
2NF: high-quality NN chiral potentials up to N4LO (Entem, Machleidt, and Nosyk, 2017)

3NF



Diagrams of the leading chiral 3NF

Subleading 3NF: Some typical diagrams:



[1] Fits to ^{3}H B.E. + SNM

[2] Fits to ^{3}H and ^{16}O B.E.

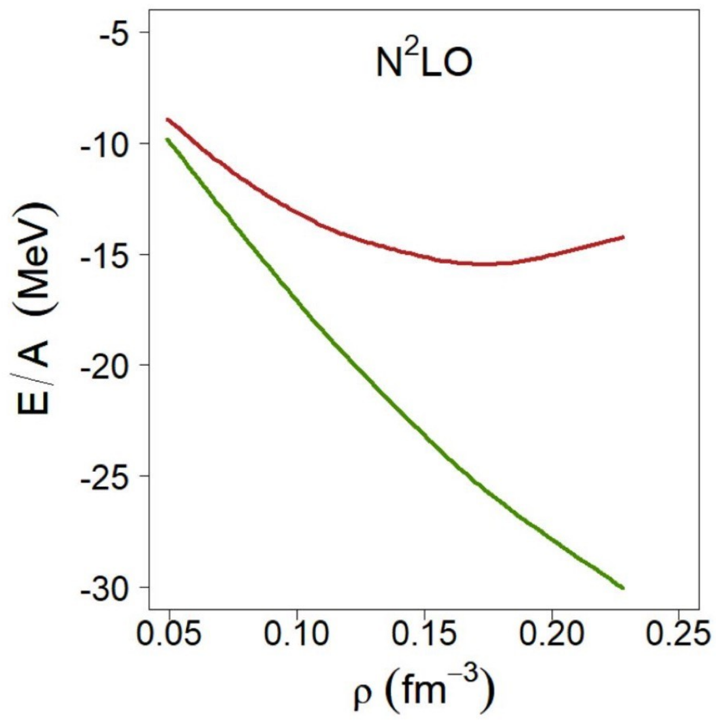
Source	chiral order	Λ (MeV)	c_D	c_E
Ref. [1]	N²LO	450	(a) 2.25 (b) 2.50 (c) 2.75	0.07 0.1 0.13
	N³LO	450	0.0 0.25 0.50	-1.32 -1.28 -1.25
Ref. [2]	N²LO N³LO	450 450	10.0 9.0	0.90 -0.152

[1] Drischler, Hebeler, Schwenk, PRL**122**, 042501 (2019)
[2] Huether *et al.*, PLB **808**, 135651 (2020)

E/A in SNM vs. density.
Red: c_D, c_E from [1];
Green: c_D, c_E from [2]

Both sets of LECs predict the ^{3}H B.E. accurately.

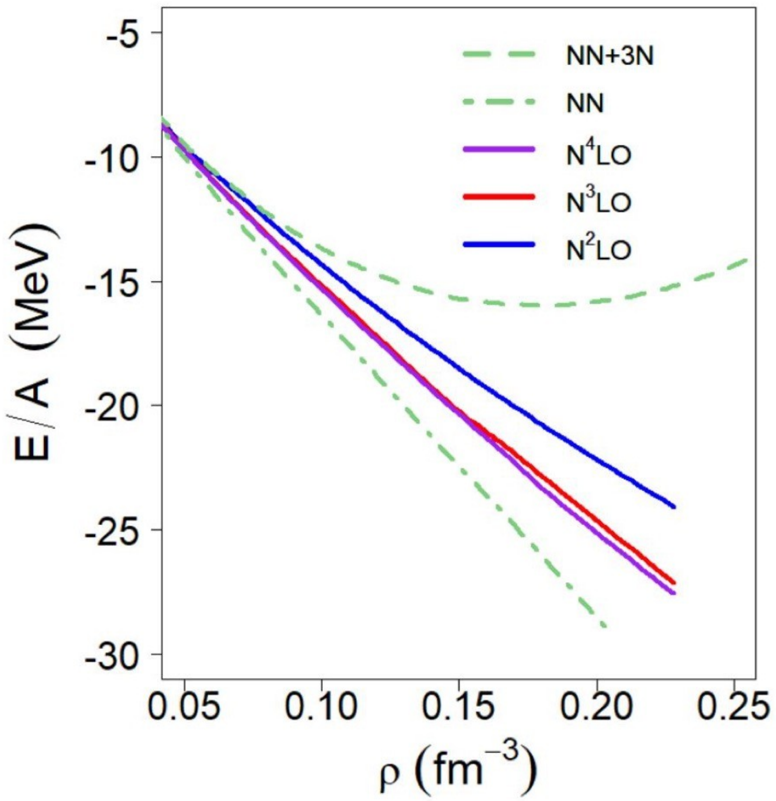
The ^{16}O constraint generates a 3NF that dramatically lowers the EoS at higher densities



[1] Drischler, Hebeler, Schwenk, PRL**122**, 042501 (2019)
[2] Huether *et al.*, PLB808, 135651 (2020)

Ground state energy and charge radii predicted with our EoS (red curve)

Nucleus	Λ (MeV)	(c_D,c_E)	E/A (MeV)	r_{ch} (fm)	E/A (exp.)	r_{ch} (exp.)
^{16}O	450	(a) (b) (c)	-6.83 -6.92 -7.01	2.89 2.88 2.86	-7.98	2.73
^{40}Ca	450	(a) (b) (c)	-7.60 -7.73 -7.86	3.57 3.55 3.53	-8.55	3.49
^{48}Ca	450	(a) (b) (c)	-7.75 -7.88 -8.02	3.63 3.61 3.59	-8.67	3.48
^{208}Pb	450	(a) (b) (c)	-6.87 -7.03 -7.19	5.58 5.54 5.50	-7.87	5.50



[3] Hebeler et al., PRC83, 031301 (2011)

Dash-dot green: Hebeler force [3]
Dashed green: Hebeler force + 3NF

SRG-evolved low-momentum interaction (starting from EM(2003) "1.8/2.0" + 3NF fitted to ^{3}H B.E. and the ^{4}He r_p)

Good description of closed shell nuclei from ^{4}He to ^{78}Ni (Simonis *et al*., 2017)

Can we construct a realistic, bare 2NF, as soft the SRG-evolved from [3]?

Blue, red, purple:
The softest (unpublished) NN potentials of EMN ($\Lambda = 400\ MeV$) from third to fifth order

To summarize the observations:

The value of c_D from fits to ^{16}O (and triton) has the effect of lowering the EoS at all densities.

A 3NF which binds the triton and includes the SNM constraint provides insufficient binding in medium-mass nuclei. The EoS is still on the repulsive side. If the triton constraint is relaxed, the resulting couplings allow for a better description of medium-mass nuclei while substantially overbinding the triton.

This suggests the need for a 2NF-3NF combination that provides sufficient attraction at lower densities while still enabling saturation.

- Large differences exist among the 3NF couplings fitted through different observables.

- A simultaneously optimal combination of c_D, c_E for few-nucleon systems, medium-mass nuclei, and nuclear matter, has not been found.

Scenario 1: a “super-soft 2NF combined with a repulsive, strongly density dependent 3NF

Scenario 2: A moderately soft 2NF is combined with a 3NF which is attractive at low density but turns repulsive at and above saturation.

MOVING ON TO OTHER SYSTEMS …

Neutron-rich matter

Energy per particle for isospin asymmetric matter:

Parabolic approximation

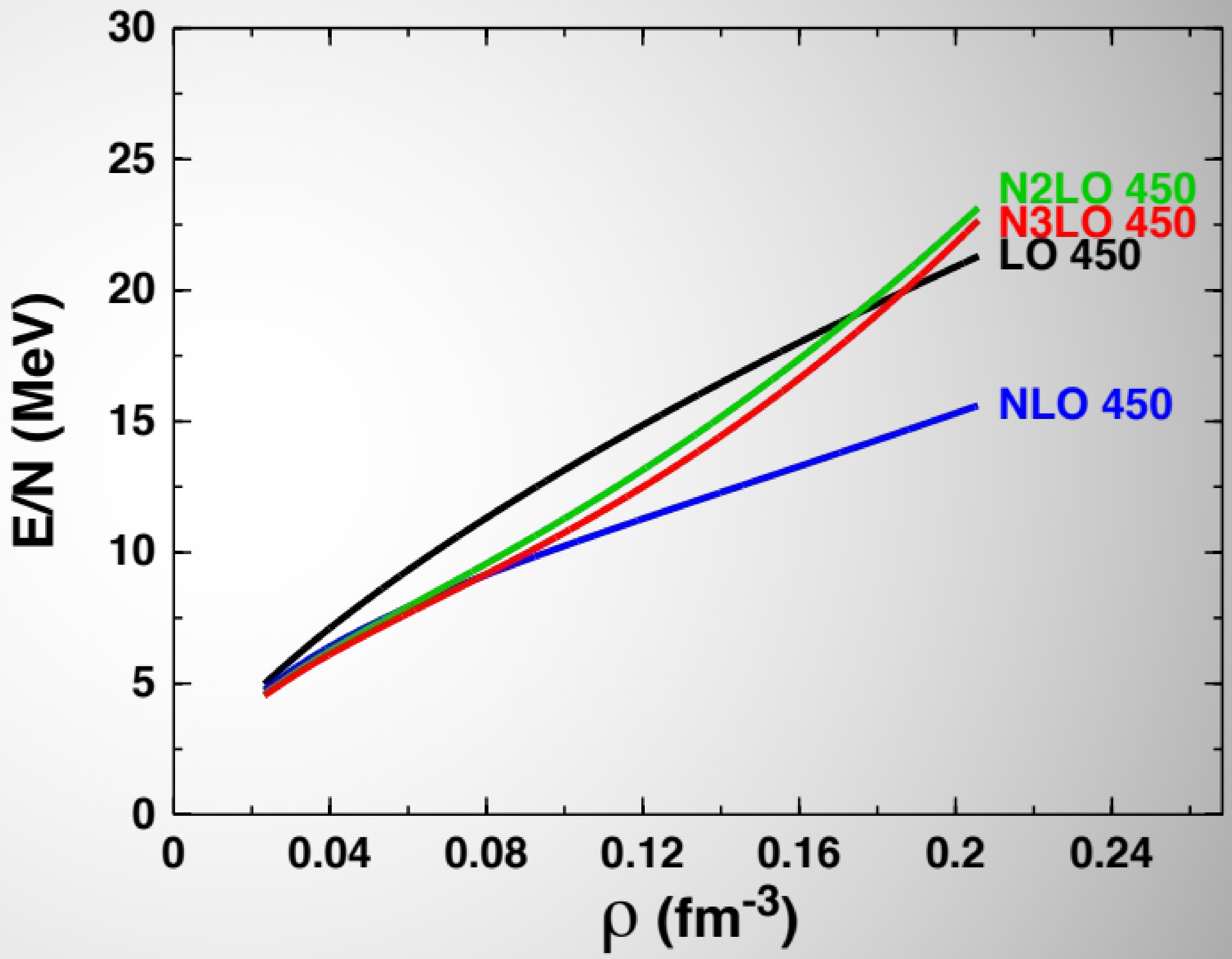
$$e(\rho,\alpha) = e(\rho,0) + e_{sym}\,\alpha^2$$

$$e_{sym}(\rho) = e(\rho,1) - e(\rho,0) \qquad \alpha = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

$$e_{sym}(\rho) = e_{sym}(\rho_0) + L\,\frac{\rho-\rho_0}{3\rho} + \frac{K}{2}\,\frac{(\rho-\rho_0)^2}{(3\rho)^2} + \ldots$$

Pure neutron matter:

Energy per neutron as a function of density at the specified chiral orders.



$J = e_{sym}(\rho_0)$

$e_{nm}(\rho_0) = (16.6 \pm 1.2)\ MeV$

$J = (32.6 \pm 1.5)\ MeV$

$L = (55.7 \pm 9.1)\ MeV$

$P_{nm}(\rho_0) = (2.97 \pm 0.48)\ MeV/fm^3$

From a Bayesian analysis by Drischler et al., 2020:

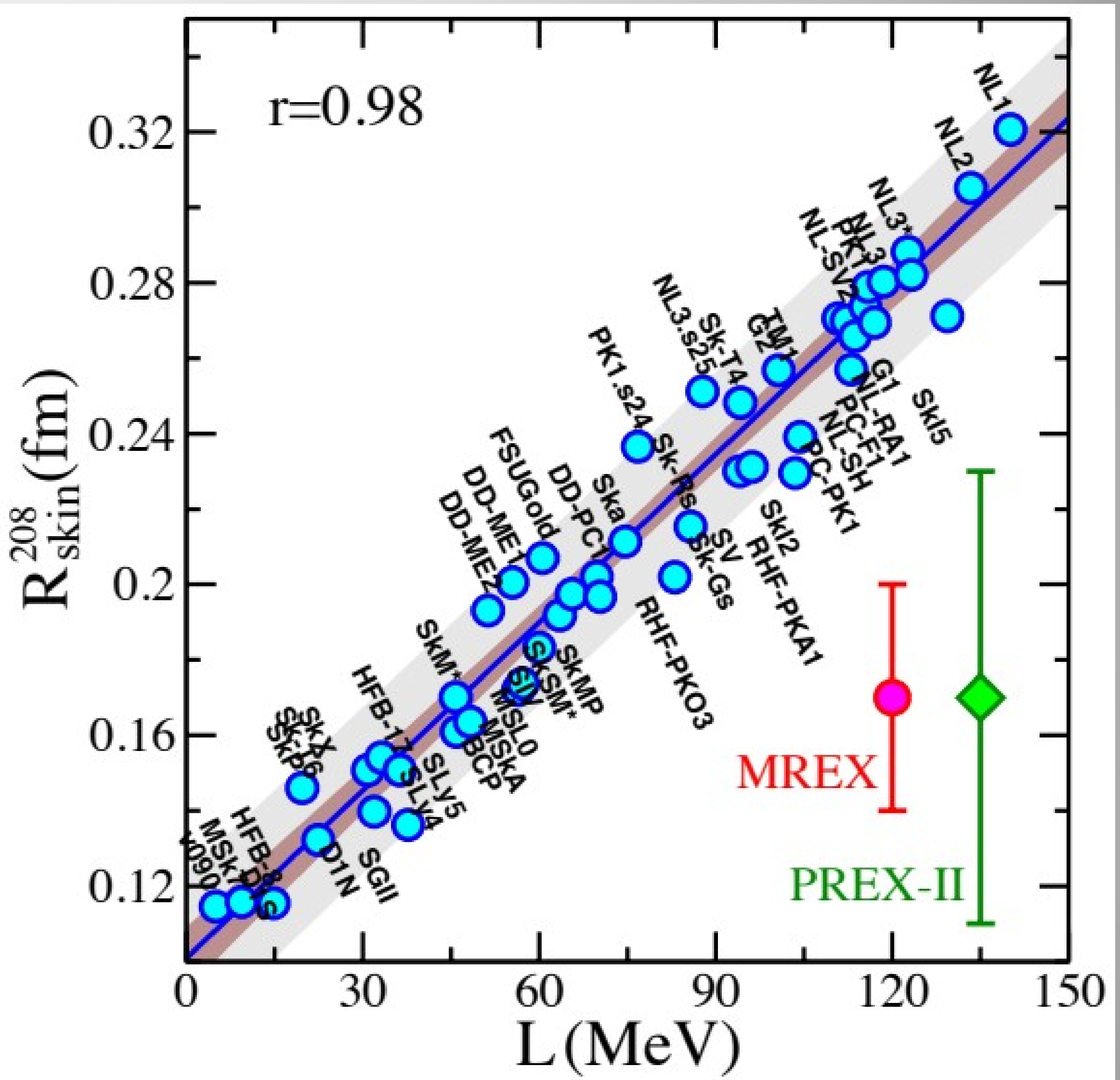
$J = (31.7 \pm 1.1)\ MeV$

$L = (59.8 \pm 4.1)\ MeV$

Neutron skin of 208Pb:

$S = (0.168 \pm 0.010)\ fm$

As to be expected from



PREX II values:

…This result challenges myriad of experimental measurements and theoretical predictions….

arXiv:2101.03193
(Reed, Fattoyev, Horowitz, & Piekarewicz)

Or rather: myriad of experimental measurements and theoretical predictions challenge this result… (F.S.)

!!!

J = 38.09 $\pm 4.73\ MeV$

S = 0.29 $\pm 0.07\ fm$

L = 106 $\pm 37\ MeV$

$$P_{NM}(\rho_0) \approx \frac{1}{3} \mathrm{L}\, \rho_0 = (3.45 - 7.15)\ \mathrm{MeV}\ fm^{-3}$$

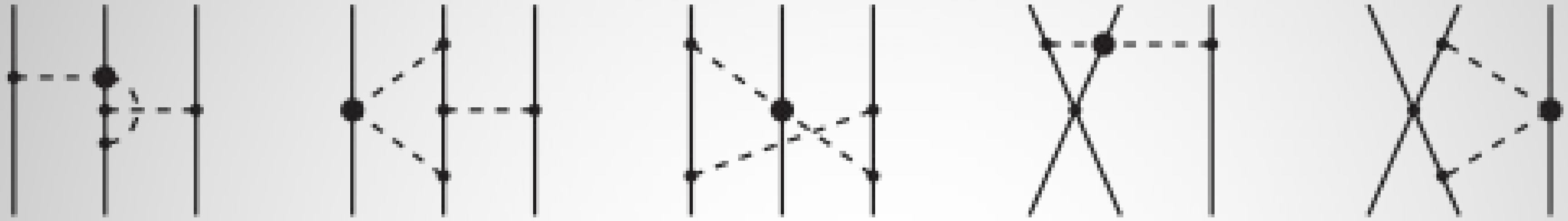
3NF at N3LO: limited degree of flexibility

Some components of the 3NF at N4LO may be necessary

Slower convergence of chiral EFT than expected?

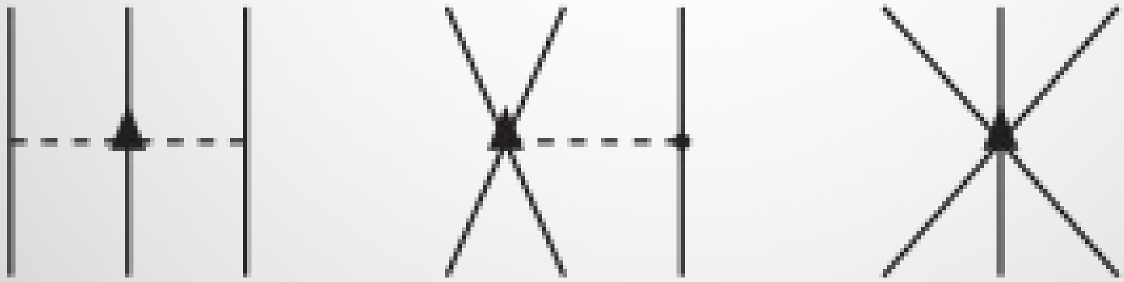
See Girlanda et al. PRC99, 054003 (2019):
Possible solution of the "A_y puzzle" from 3NFs at N4LO?

One-loop 3NF diagrams appearing at N4LO



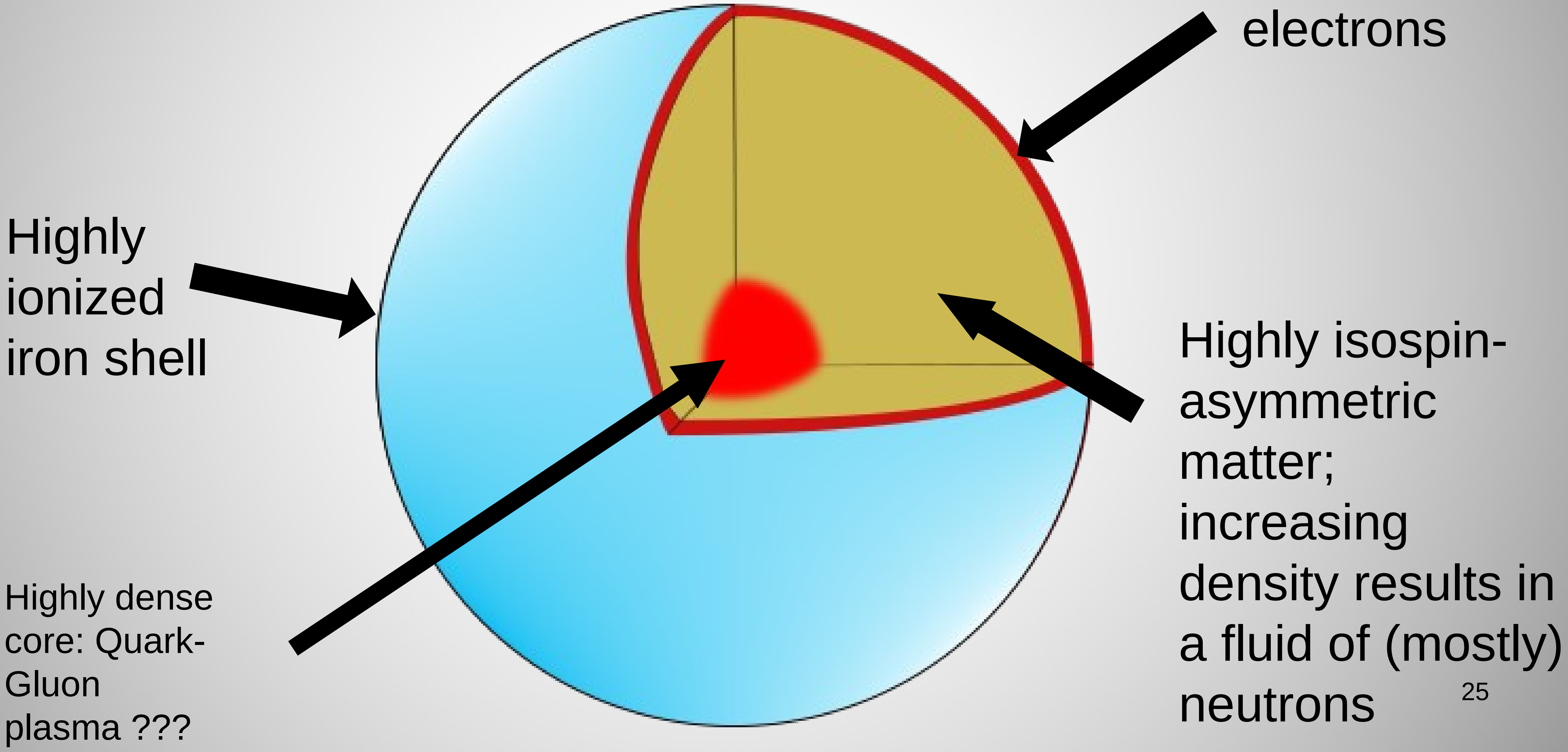
(a) (b) (c) (d) (e)

3NF tree diagrams appearing at N4LO

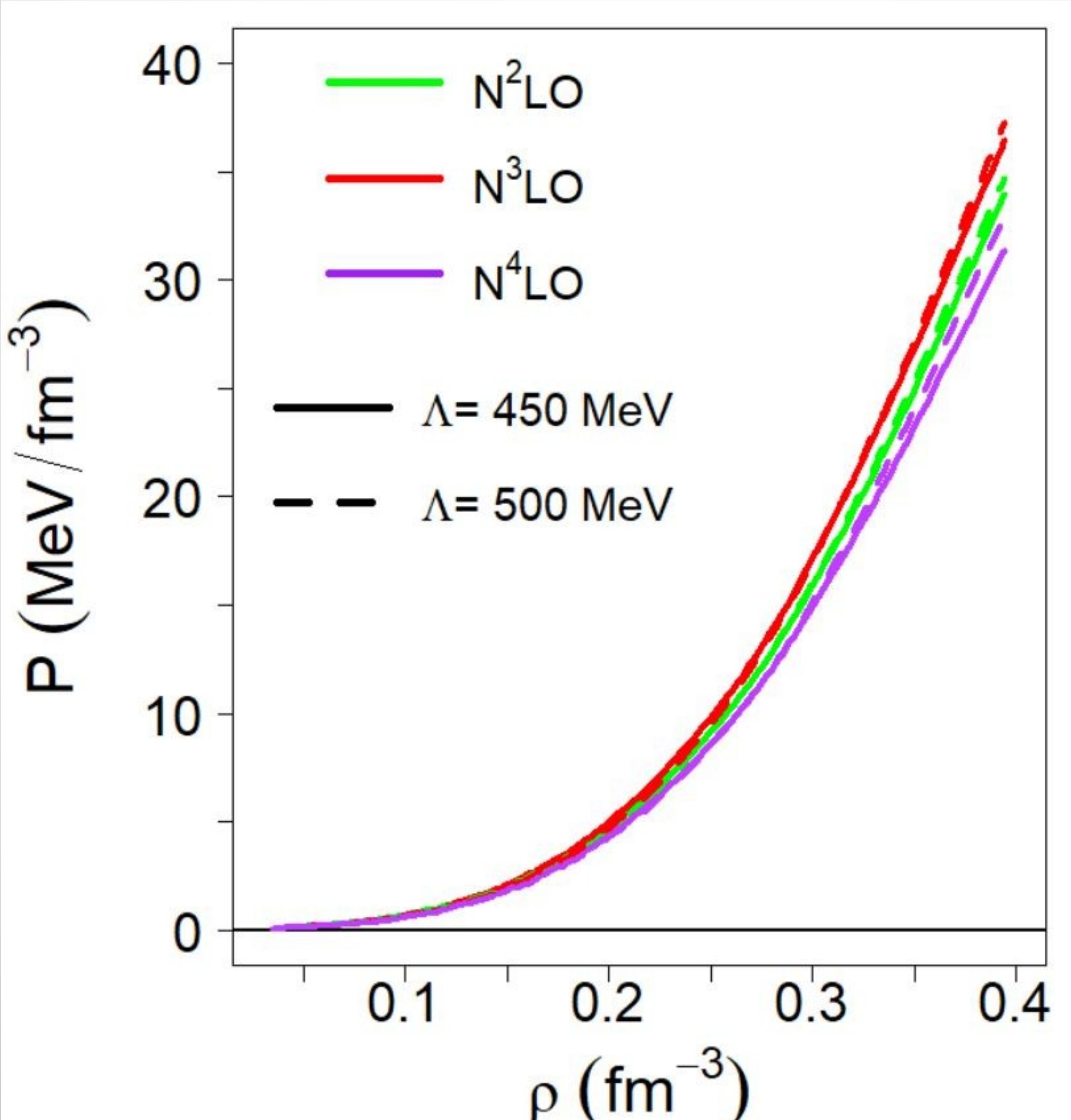


(a) (b) (c)

The EoS and Neutron Stars



Our predictions for the pressure in beta-stable matter as a function of density:



Chiral Effective Field Theory is a low-energy theory. Our chiral EoS is applicable within a limited range of Fermi momenta.

The complete EoS is created by matching three contributions:

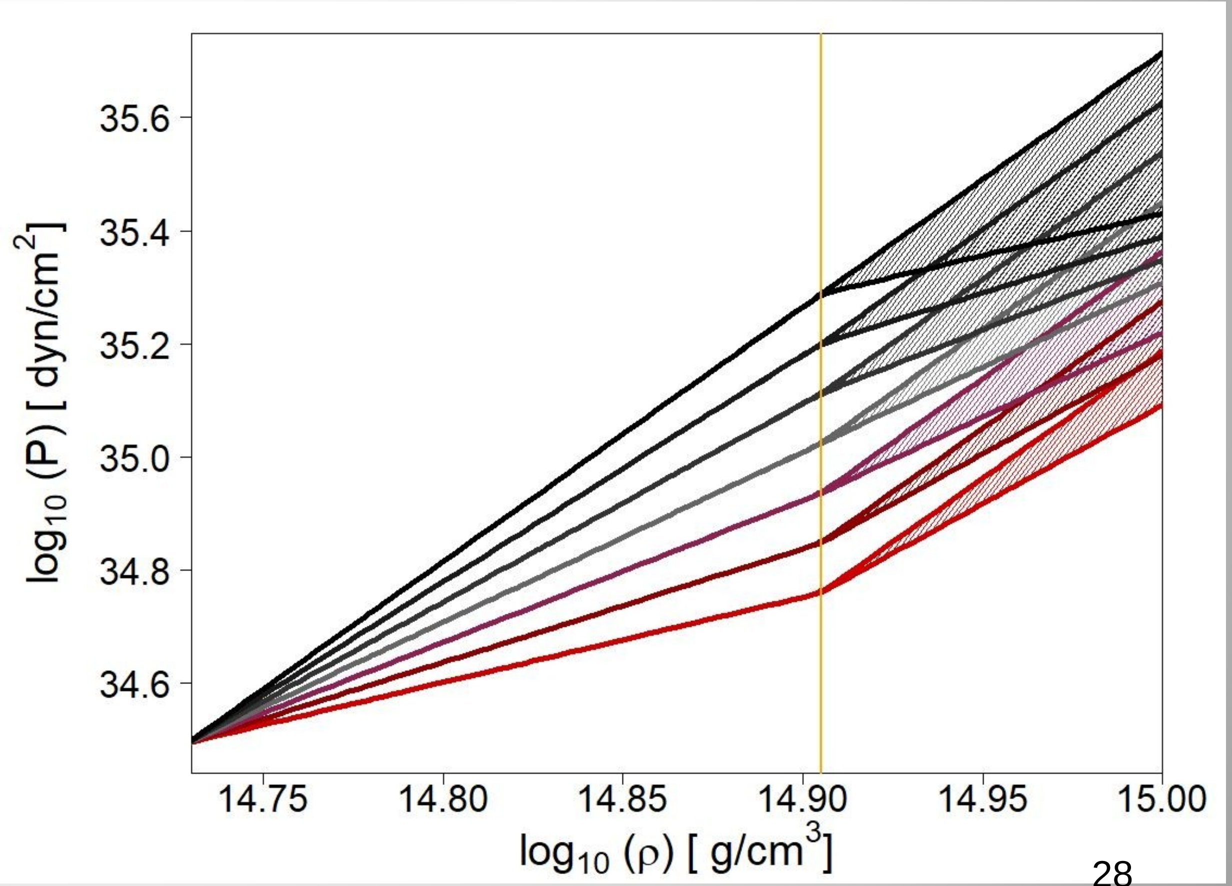
Subnuclear crustal EoS ∪ **Microscopic EoS in beta equilibrium** ∪ **High density polytropic continuation**

High Density Polytropic Continuation

At high densities (above approximately $2\rho_0$) we use (piecewise) polytropes over a broad range of adiabatic indices:

$$P(\rho) = a\,\rho^{\Gamma}$$

In this way, we wish to explore the sensitivity of the radius of the average-mass NS to the corresponding spreading of the pressure.



Neutron star Mass-Radius Relation

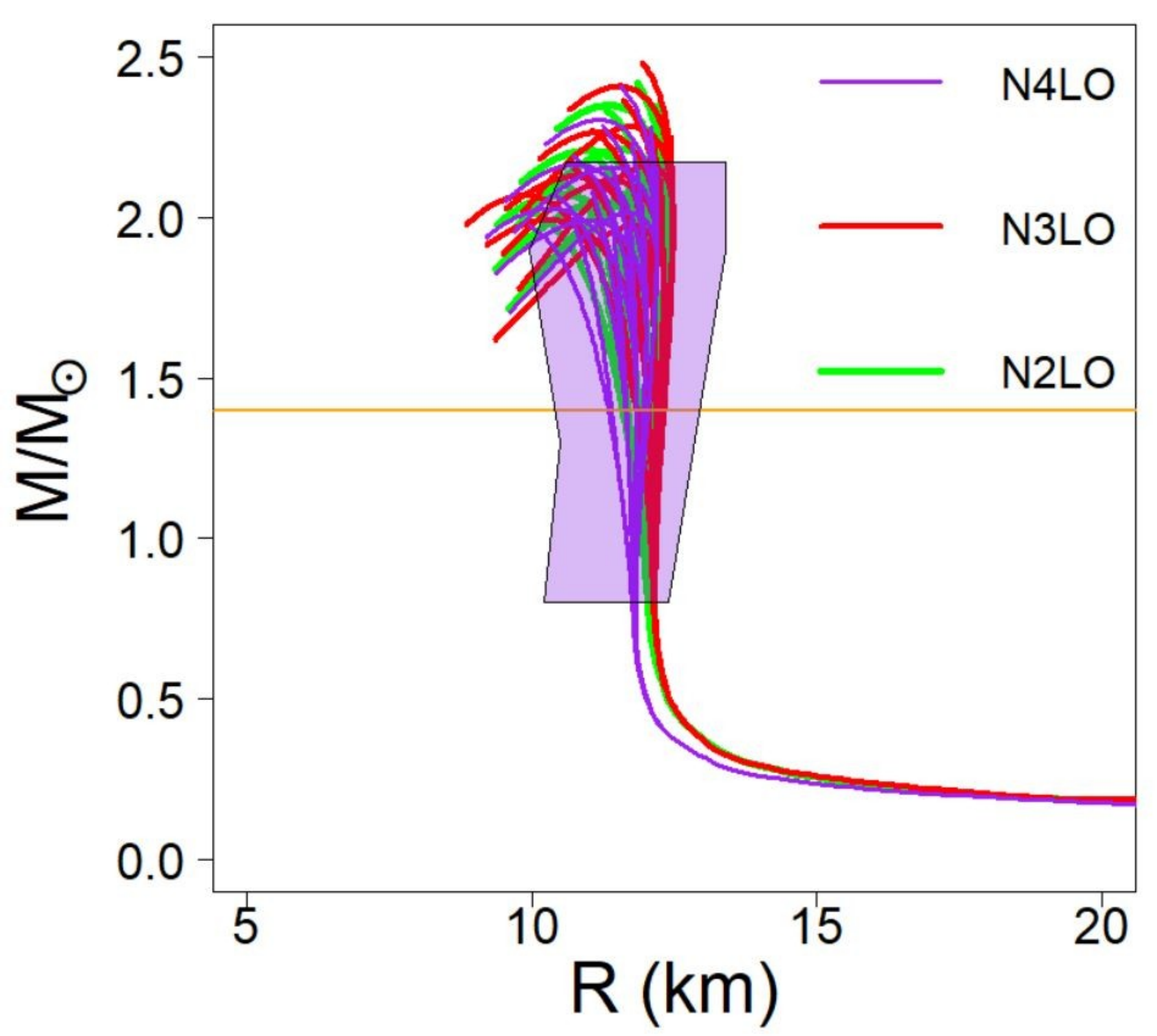
Chirally constrained EoS + polytropic extension → **TOV Equation** → **Mass-radius relation**

Constraints:

Maximum mass at least 1.97 $M_{\odot}$

Causality Constraint: $\frac{dP}{d\mathrm{E}} < 1$

Mass-radius relation at various order of chi-EFT



Estimates for the radius of the canonical-mass neutron star, M = 1.4 solar masses:

Our predictions:

R = (10.8 – 12.8) km

LIGO-Virgo:
(Annala et al., 2018)

R < 13.6 km (S$\leq 0.25\, fm$)

PREX II :

R = (13.33 – 14.26) km

Also, threshold densities for DU consistent with PREX II are very low.

….CONCLUSIONS UP TO THIS POINT:

- **After decades of struggle, the 2N force is under control.**

- **Will open questions in nuclear structure be resolved with chiral EFT? Not clear. Although the approach is conceptually pleasing, the proliferation of many-nucleon force contributions with higher orders may be a serious challenge.**

- **As for the neutron matter EoS, we will continue to proceed microscopically and systematically.**

- **Experimental programs (such as at FRIB or Jlab), together with strong theoretical support, are crucial for further progress.**

Work in Progress/Future Plans

- What can we learn from hard electron scattering on nuclei (measured at Jlab)?

  - **Spectral functions and momentum distributions.**
  - **Short range correlations.**
  - **“Measuring” momentum distributions?**

Motivations

Known since a long time:

Nuclear force: short-range repulsion, medium-range attraction.
Therefore, mean-field picture has limitations.

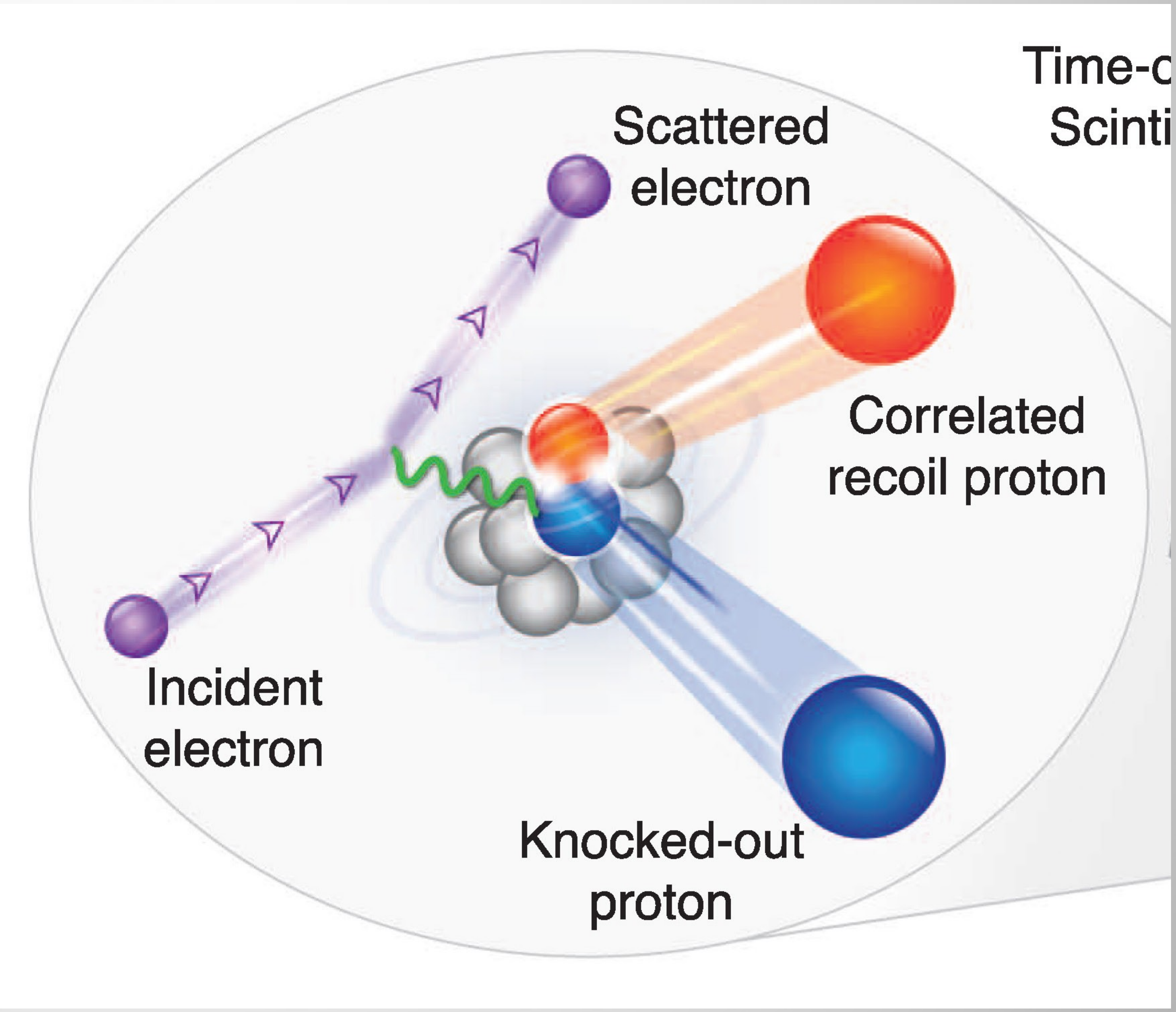
Nuclear wave functions overlap strongly: correlations

Short-range correlations (SRC) = nucleon dynamics at short distances ⟺ Responsible for the high-momentum components in the wave function

The experimental program at Jlab with A(e,e')X (and other) measurements at high momentum-transfer (CLAS Coll., Jefferson Lab Hall A, B, C Coll., etc..) stimulated additional interest

A(e,e')X inclusive
A(e,e'p) exclusive
A(e,e'pN) exclusive

Frankfurt&Strikman (1981),
Egiyan et al. (2003,2006),
Fomin et al. (2012),
Tang et al. (2003),
Piasetzky et al. (2006),
Shneor et al. (2007),
Subedi et al. (2008),
Baghdasaryan et al. (2010)
Hen et al. (2014),
Korover et al. (2014),
Monaghan et al. (2014),
Makek et al. (2016)
R. Cruz-Torres et al. (2019)



Therefore, this is an important and timely issue

(e,e'p) exp. → (Measurements) → Cross section ratios → Analyses → momentum distributions ratios

This step requires approximations which must be considered carefully.

THEORY

Intriguing question:

What does a nucleon "do" in a nucleus?
Can we "see" a high-momentum proton in a nucleus?

1980's:
The <u>bremsstrahlung reaction</u>

$$N + N \rightarrow N + N + \gamma$$

was proposed as a way to determine off-shell aspects of the NN interactions.

1998-2000:
Fearing & Scherer show the
`` *Impossibility of Measuring Off-Shell Amplitudes*"

2020:
F.S. et al.: Should we carefully revisit similar issues as those raised by Fearing *et al.* with regard to constraining the off-shell nature of the NN interaction? (In progress.)

Thank you