International Conference Nuclear Theory in the Supercomputing Era – 2018

Daejeon, Republic of Korea, October 29 – November 2, 2018

What is wrong with our current nuclear forces?

R. Machleidt

University of Idaho

OUTLINE

- Introduction
- Current status & current issues in nuclear forces
- How to address the open issues?
- Soft interactions up to N4LO
- Nuclear matter predictions
- Conclusions

PHYSICAL REVIEW C VOLUME 1, NUMBER 4 APRIL 1970

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(Received 25 August 1969)

ONE of the most fundamental and elusive problems in theoretical nuclear physics has been to understand the structure of finite nuclei in terms of the [basic forces between nucleons].

Almost 50 years later:
Still elusive!

Why?

- Microscopic or *ab initio* nuclear structure has two ingredients

1. Quantum many-body theory
2. Nuclear forces

- Many-body methods essentially agree: No problem.

EXAMPLE: PREDICTIONS FOR OXYGEN ISOTOPES USING ALWAYS THE SAME NUCLEAR FORCES, BUT DIFFERENT MANY-BODY METHODS

CC theory/CCEI

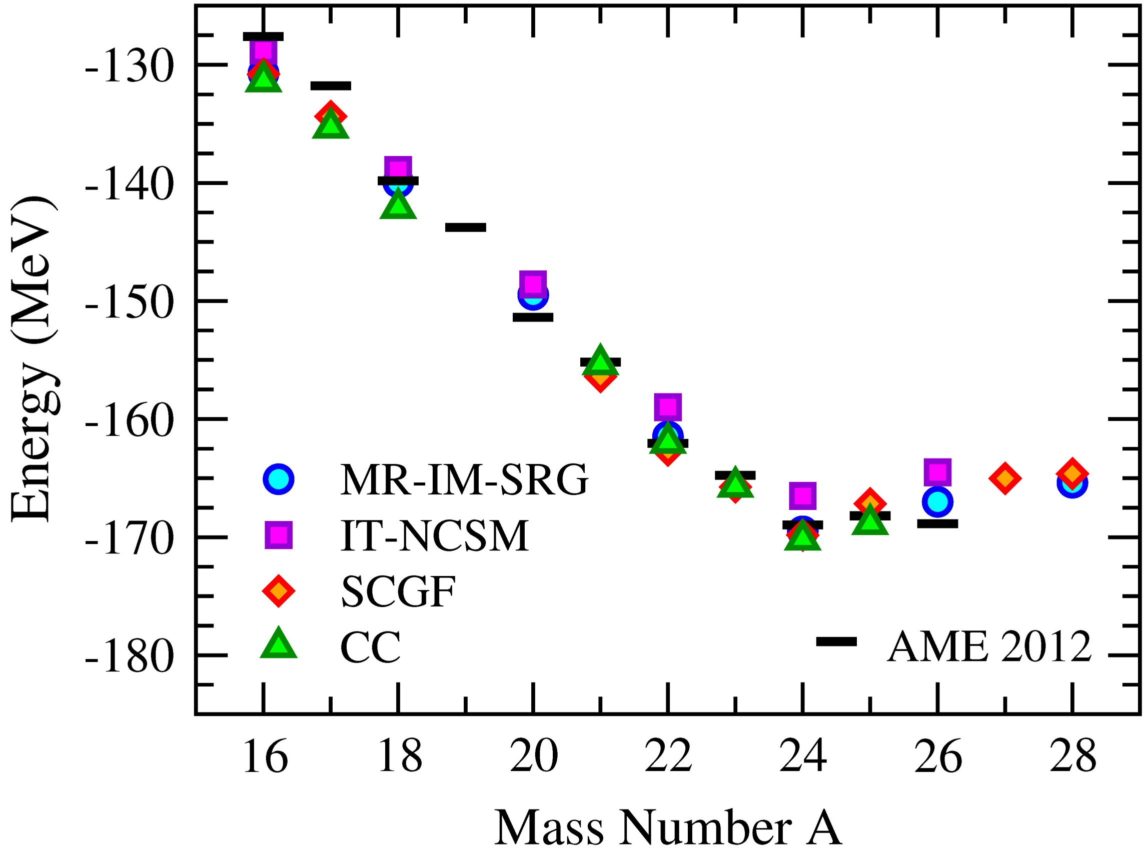
Hagen et al., PRL (2012),
Jansen et al., PRL (2014)

Multi-Reference
In-Medium SRG
and IT-NCSM

Hergert et al., PRL (2013)

Self-Consistent
Green's Functions

Cipollone et al., PRL (2013)



Very small uncertainties!

Why?

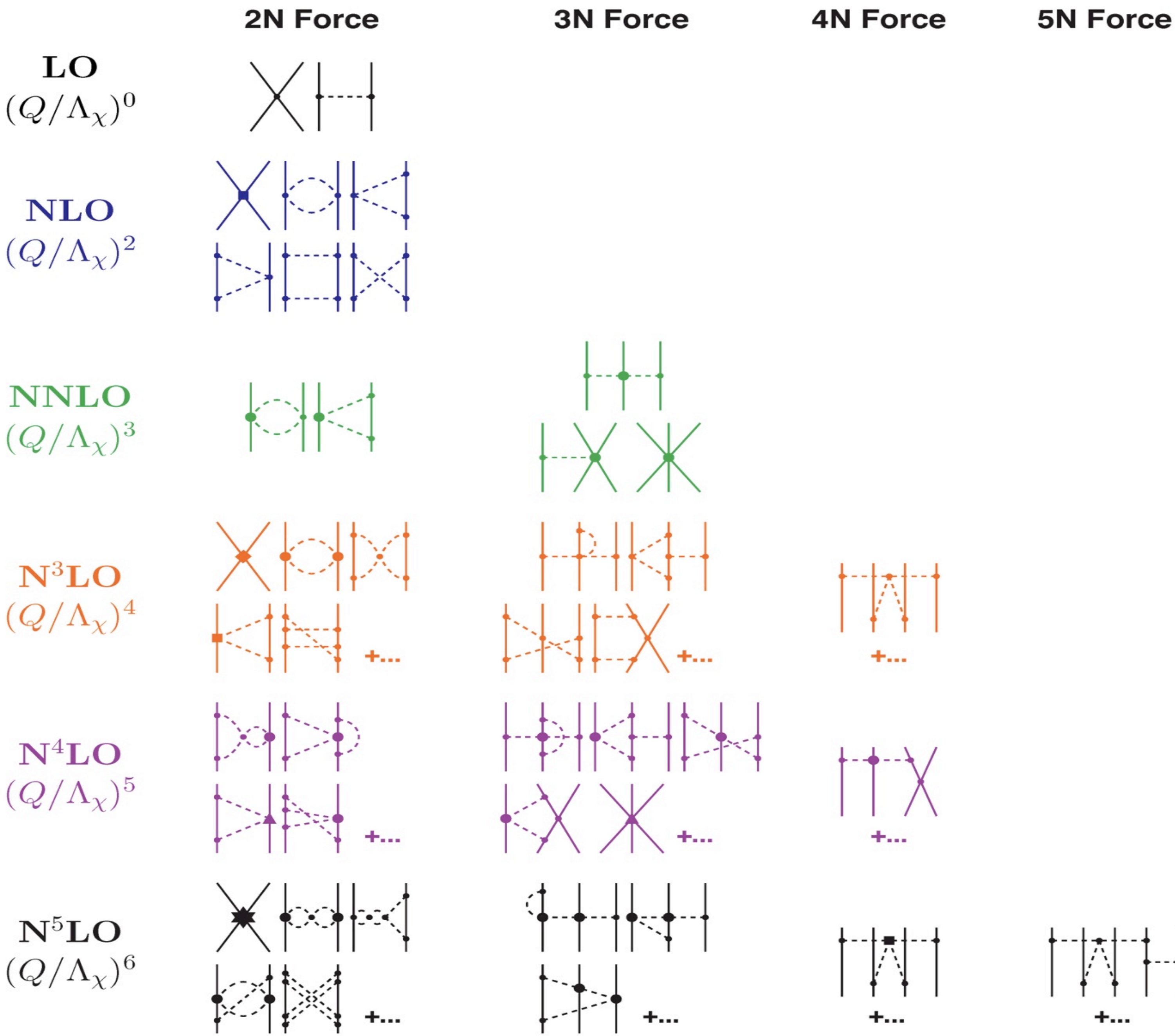
- Microscopic or *ab initio* nuclear structure has two ingredients

1. Quantum many-body theory
2. Nuclear forces

- Many-body methods essentially agree: No problem.
- Nuclear forces: large uncertainties.
- Therefore, we need to improve on nuclear forces, which is the focus of the rest of this talk.

WHAT NUCLEAR FORCES? CHIRAL EFFECTIVE FIELD THEORY (EFT) BASED NUCLEAR FORCES, BECAUSE …

- Related to low-energy QCD via symmetries and their breakings (particularly, chiral symmetry!).
- Allows for an order-by-order expansion/systematic improvement (and, thus, uncertainty quantification).
- Two- and many-nucleon forces derived on an equal footing.
- Long-range determined by pion-exchanges with the low-energy constants (LECs) independently fixed by pi-N data.
- Short-range 2NF ("contact terms", contact LECs) fit to NN data, short-range 3NF fit to 3N data.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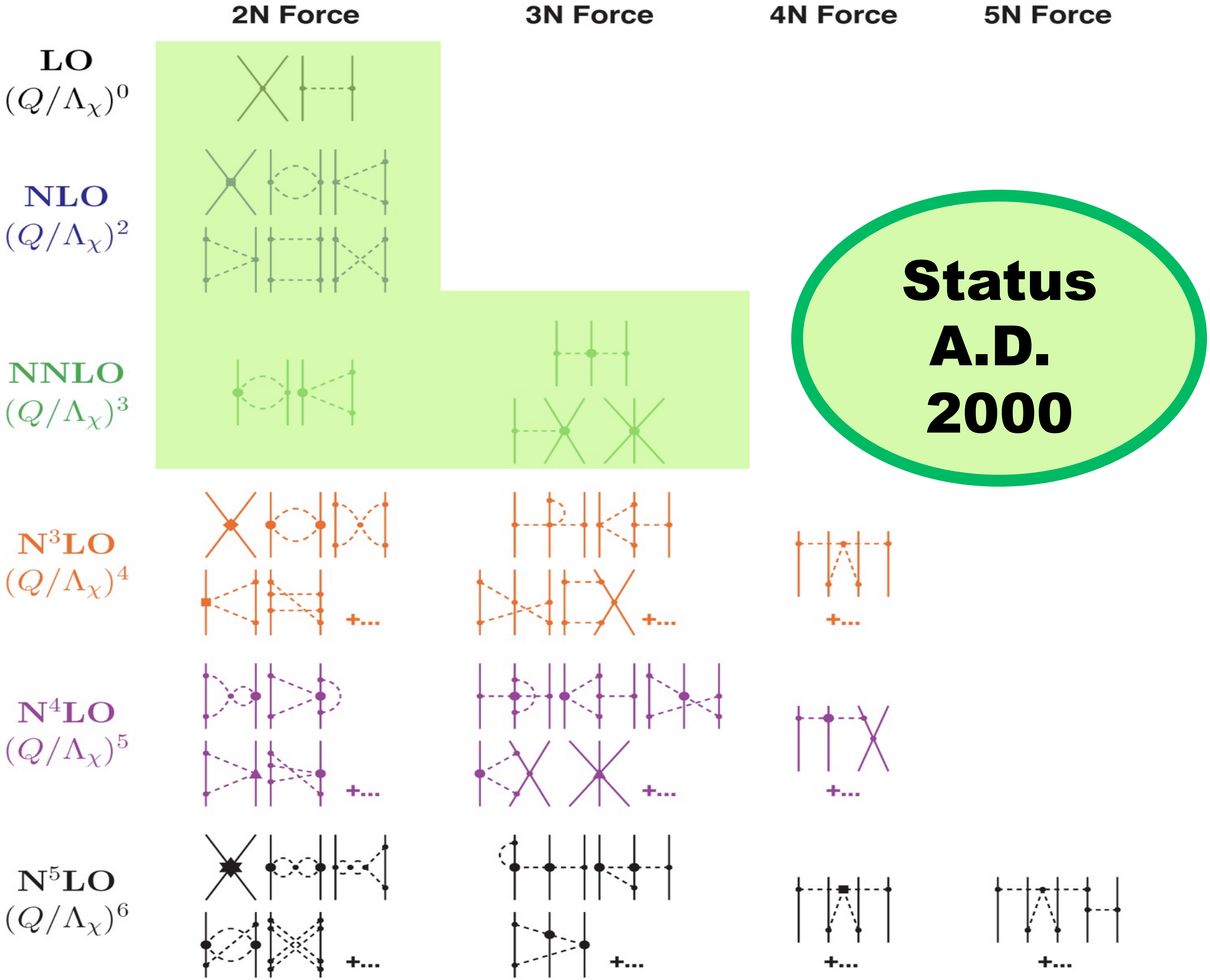
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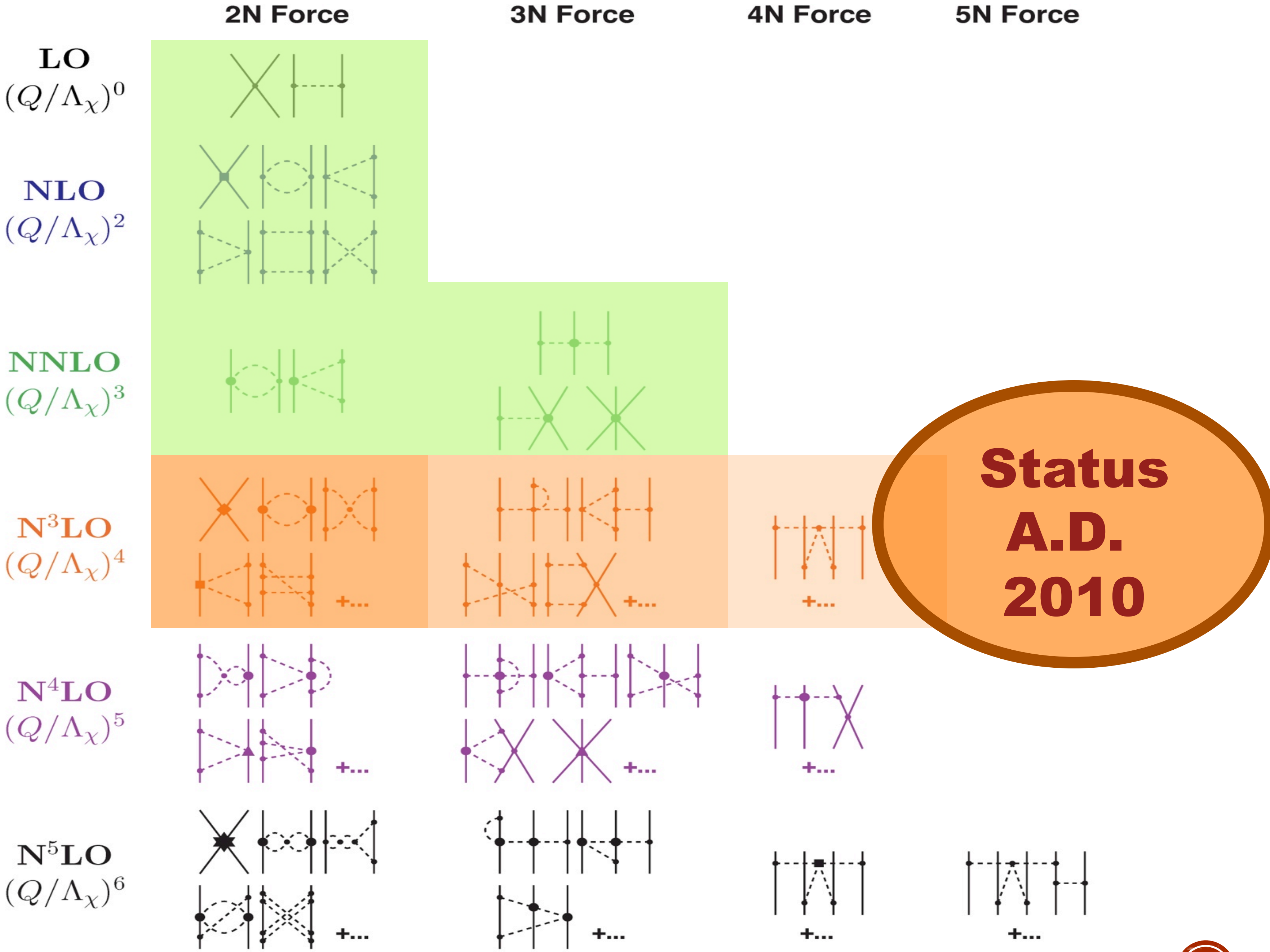

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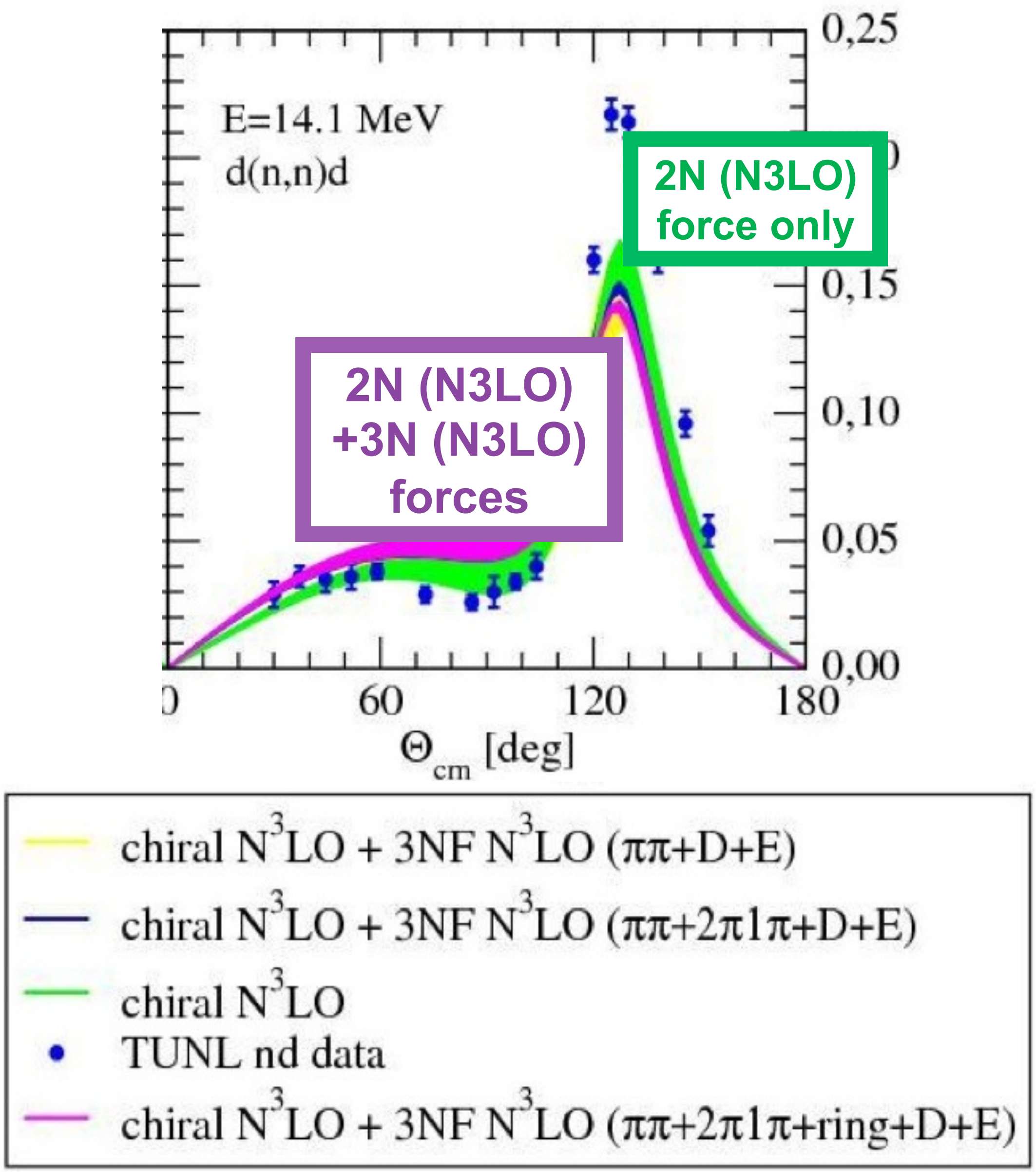
WHAT HAVE WE ACHIEVED WITH THOSE FORCES?

- **2NFs and 3NFs up to N3LO have been applied in nuclear few- and many-body systems.**
- **There has been some success, but there are also some persistent problems.**
- **In the few-body sector: Ay puzzle, N-d break-up, …**

N-d A_y calculations by Witala et al.



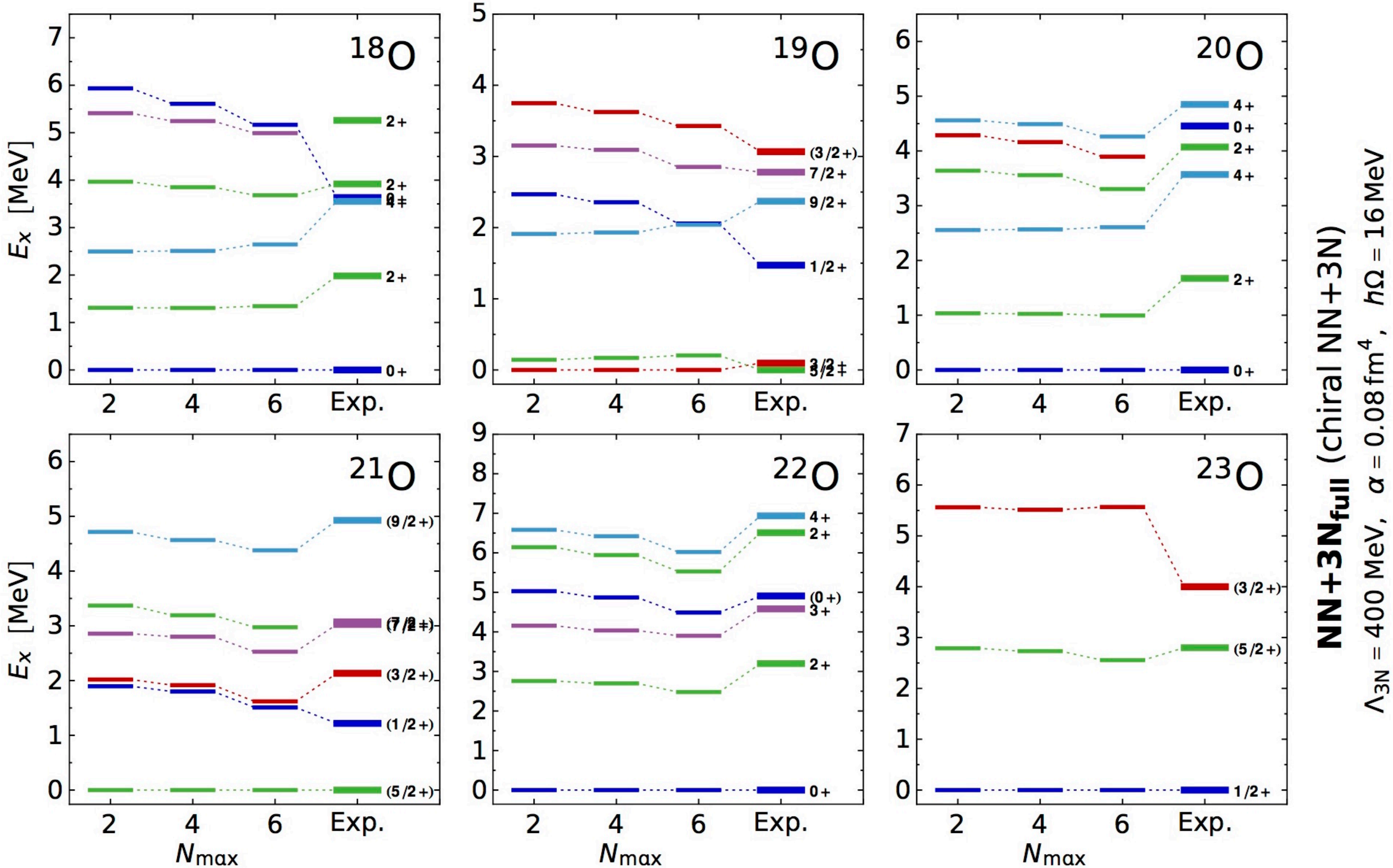
CURRENT STATUS AND OPEN ISSUES

- **Current status: 2NFs and 3NFs up to N3LO are applied in nuclear few- and many-body systems.**
- **In general, quite a bit of success, but some persistent problems remain.**
- **In the few-body sector: Ay puzzle, N-d break-up, …**
- **Light nuclei: Spectra not perfect.**

SPECTRA OF SOME OXYGEN ISOTOPES

Hergert et al., PRL 110, 242501 (2013) & in prep.

From Roth



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- **The radii of nuclei**

PRL 117, 052501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JULY 2016

Radii and Binding Energies in Oxygen Isotopes: A Challenge for Nuclear Forces

V. Lapoux,[1,*] V. Somà,[1] C. Barbieri,[2] H. Hergert,[3] J. D. Holt,[4] and S. R. Stroberg[4]
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(Received 29 April 2016; published 27 July 2016)

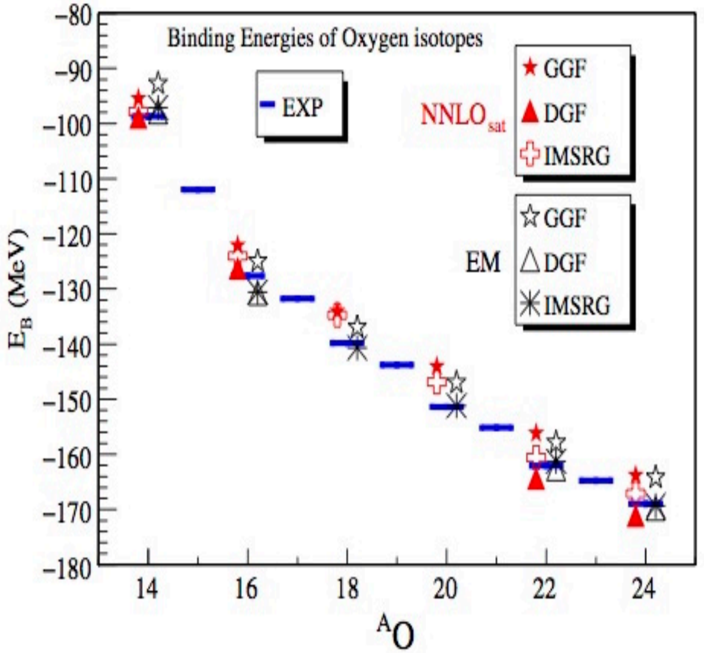

FIG. 1. Oxygen binding energies. Results from SCGF (DGF and GGF) and IMSRG calculations with EM and NNLO$_{sat}$ are displayed along with experimental data.

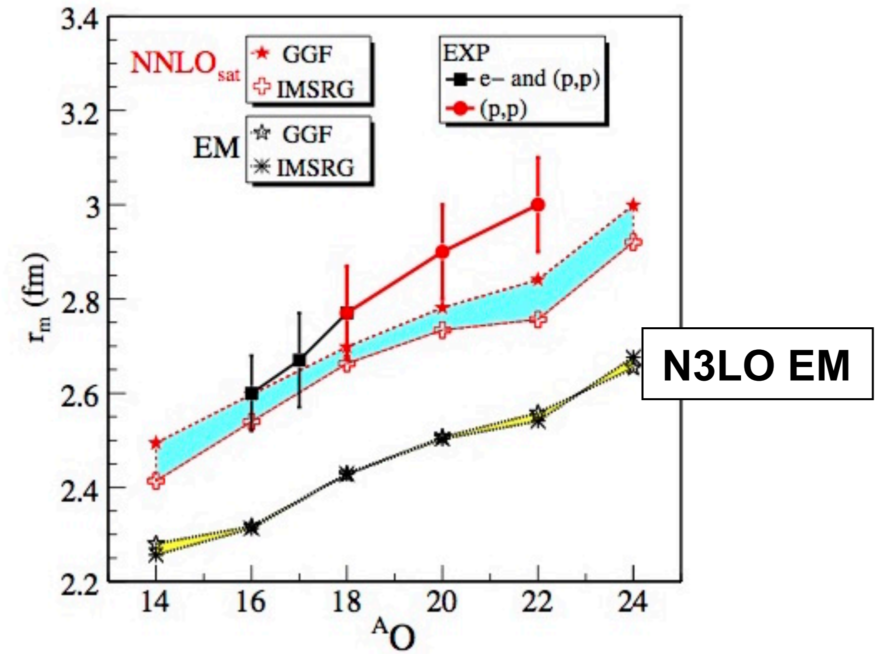

FIG. 5. Matter radii from our analysis and given in Table I, compared to calculations with EM [27–29] and NNLO$_{sat}$ [36]. Bands span results from GGF and MR-IMSRG schemes.

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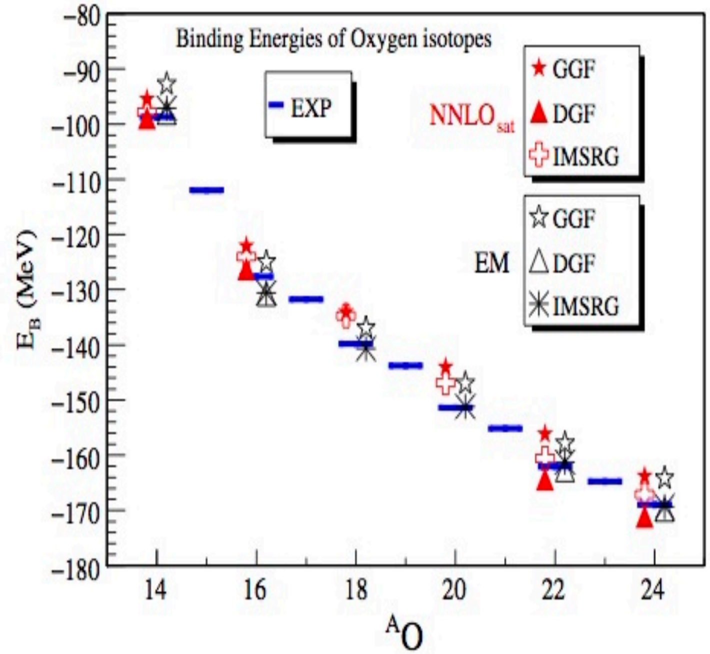
- **Overbinding of intermediate-mass nuclei**

Overbinding of intermediate-mass nuclei

Oxygen



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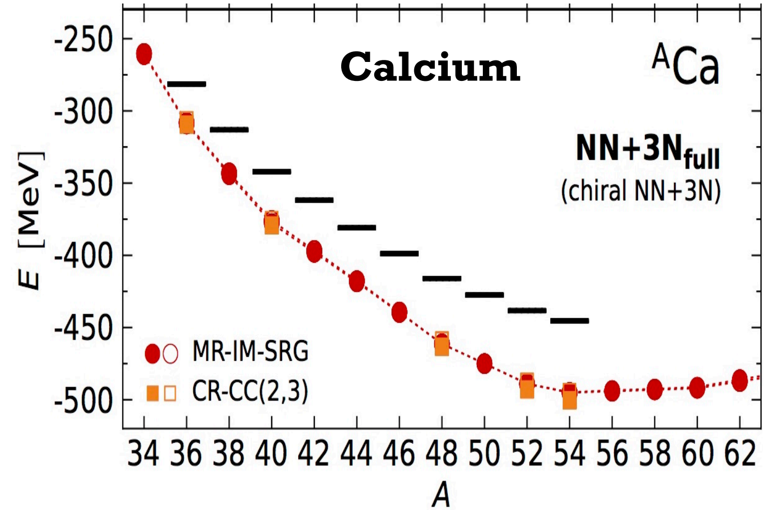

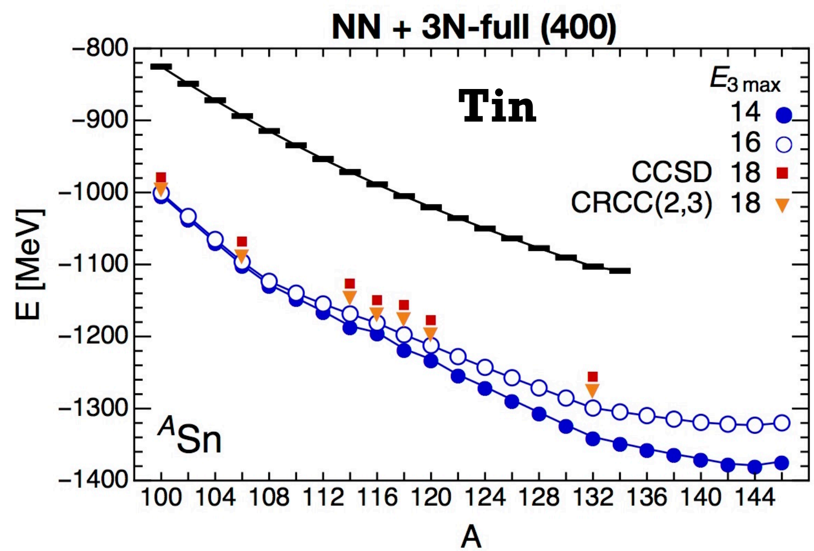

From Hergert et al., PRC 90, 041302 (2014).

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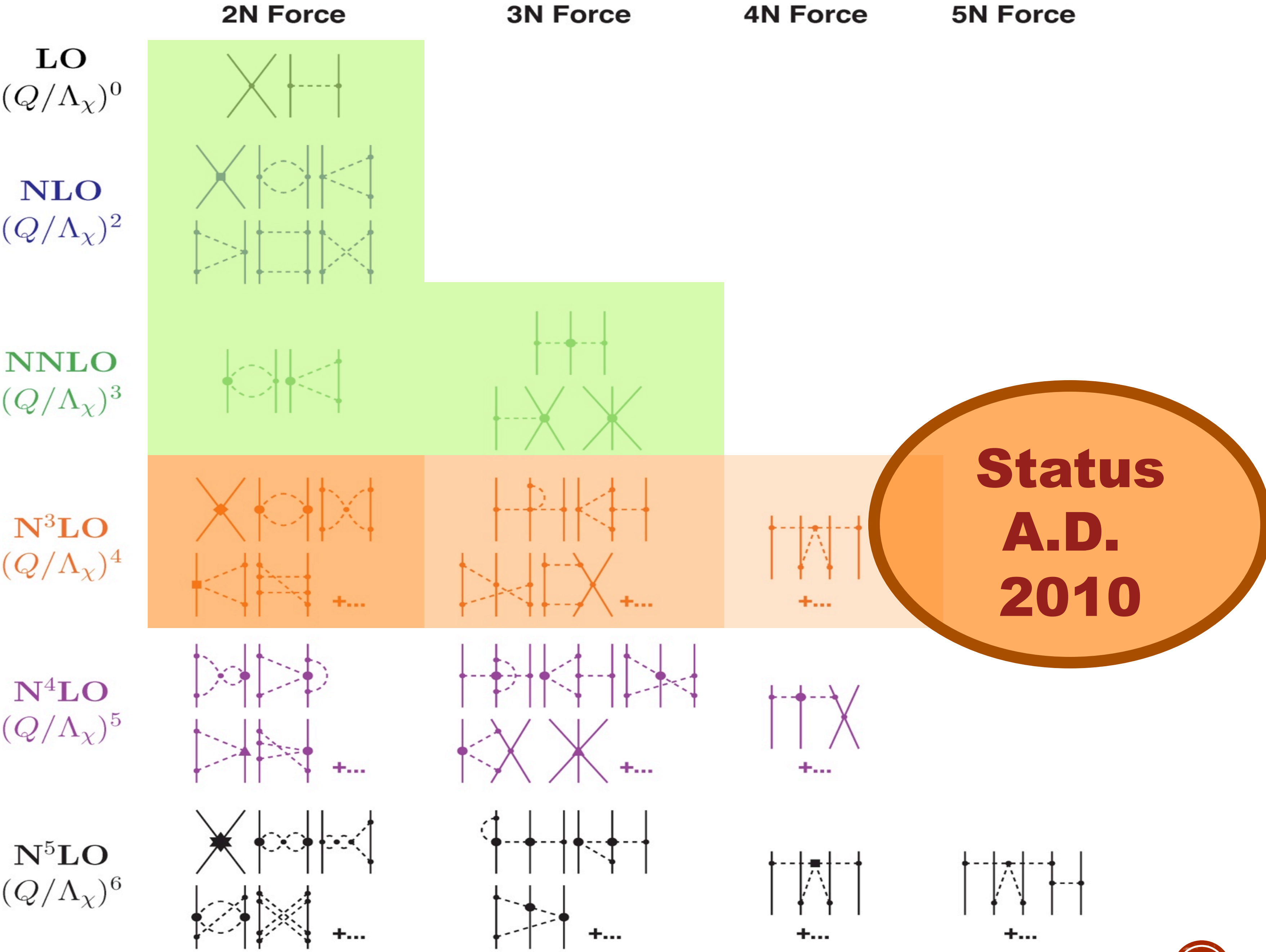
BECAUSE OF THE PROBLEMS JUST POINTED OUT, IMPROVEMENT OF CURRENT NUCLEAR FORCES IS CALLED FOR.

- **How?**
- **Go backwards: Revisit the lower orders**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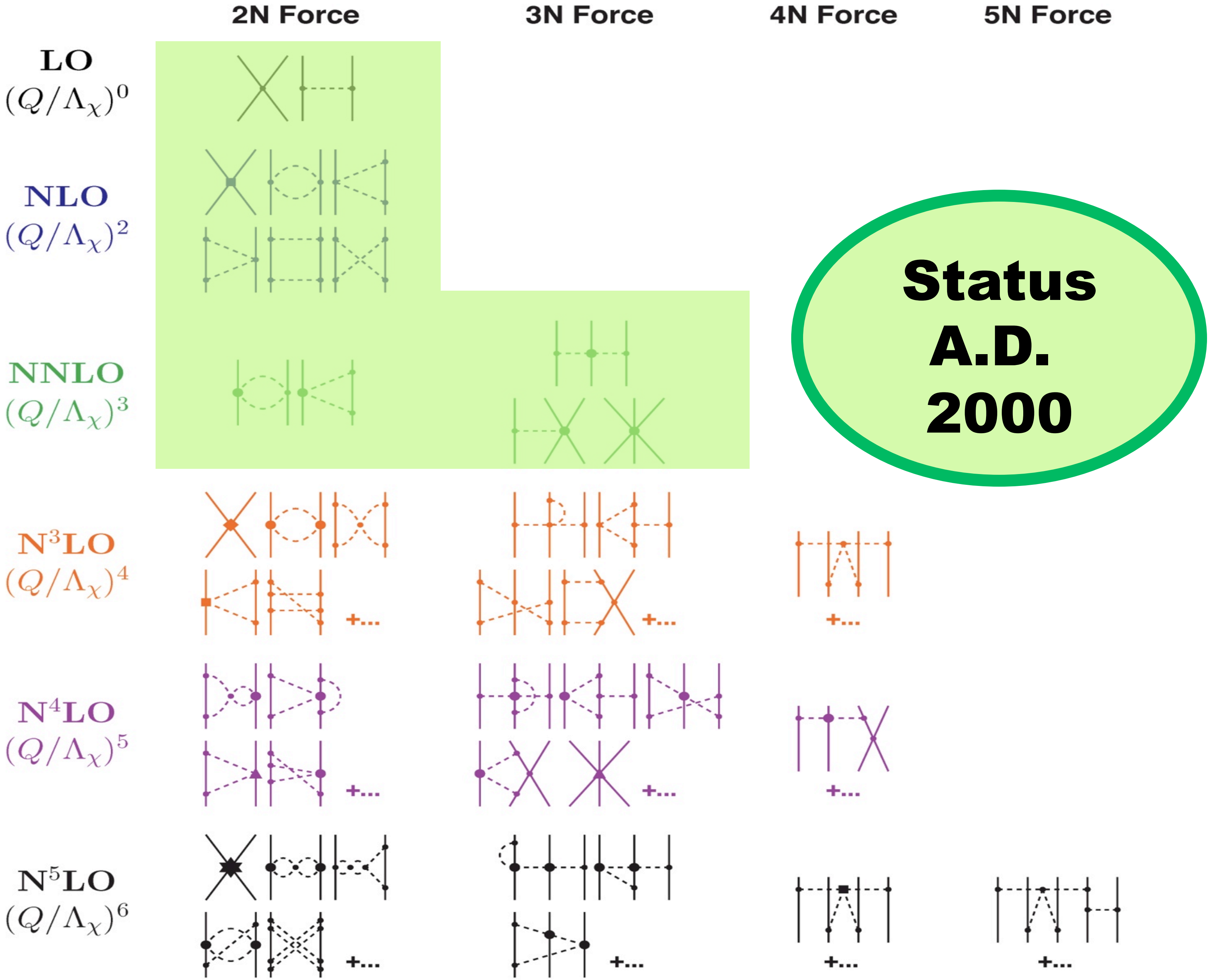
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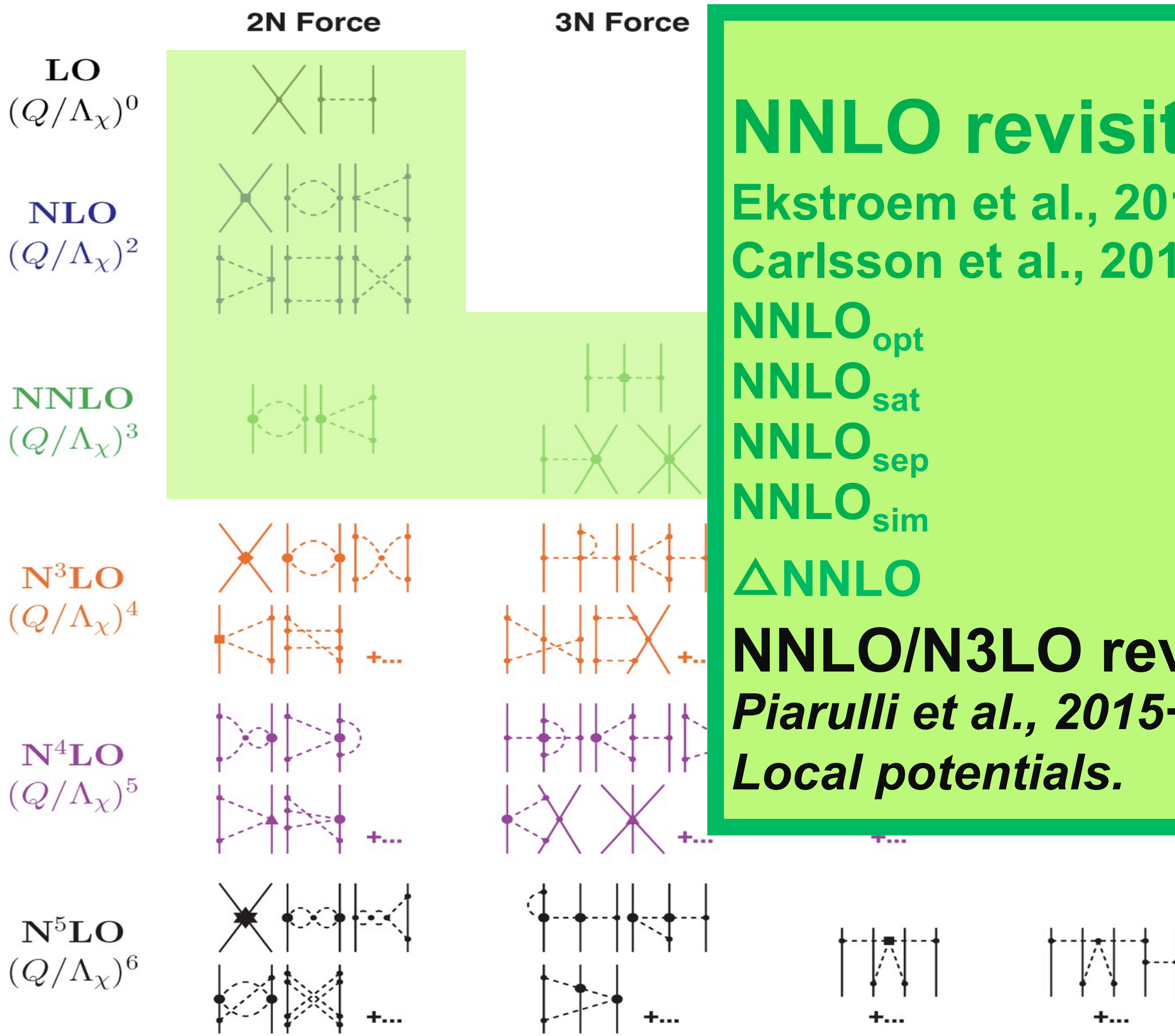

NNLO revisited:

Ekstroem et al., 2013+

Carlsson et al., 2016

NNLO_{opt}

NNLO_{sat}

NNLO_{sep}

NNLO_{sim}

ΔNNLO

NNLO/N3LO revisited:

Piarulli et al., 2015+

Local potentials.

BECAUSE OF THE PROBLEMS JUST POINTED OUT, IMPROVEMENT OF CURRENT NUCLEAR FORCES IS CALLED FOR.

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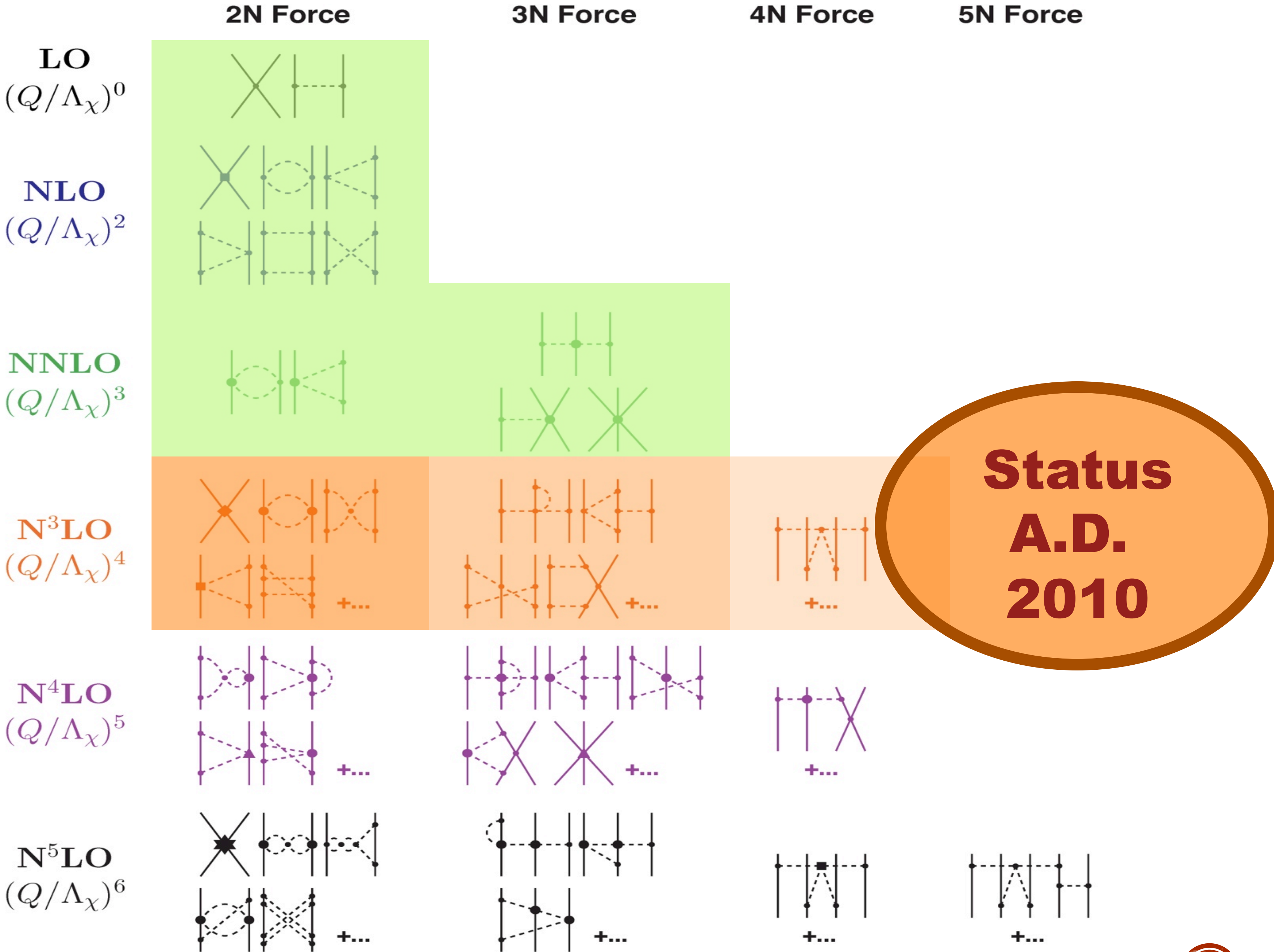
- **Go backwards: Revisit the lower orders – s. talk by Ekstroem**
- **Go forward: pick up again N3LO and advance to N4LO**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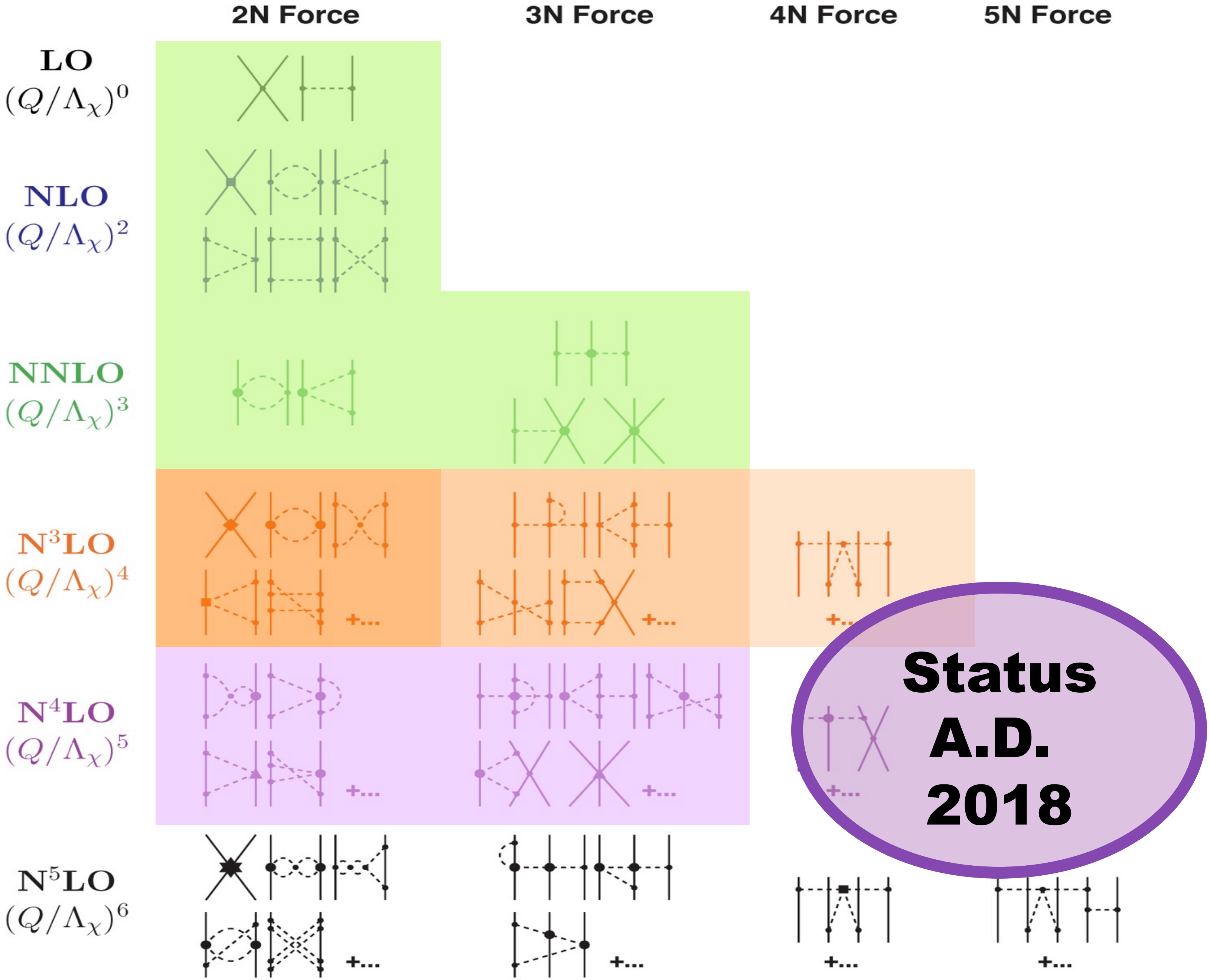
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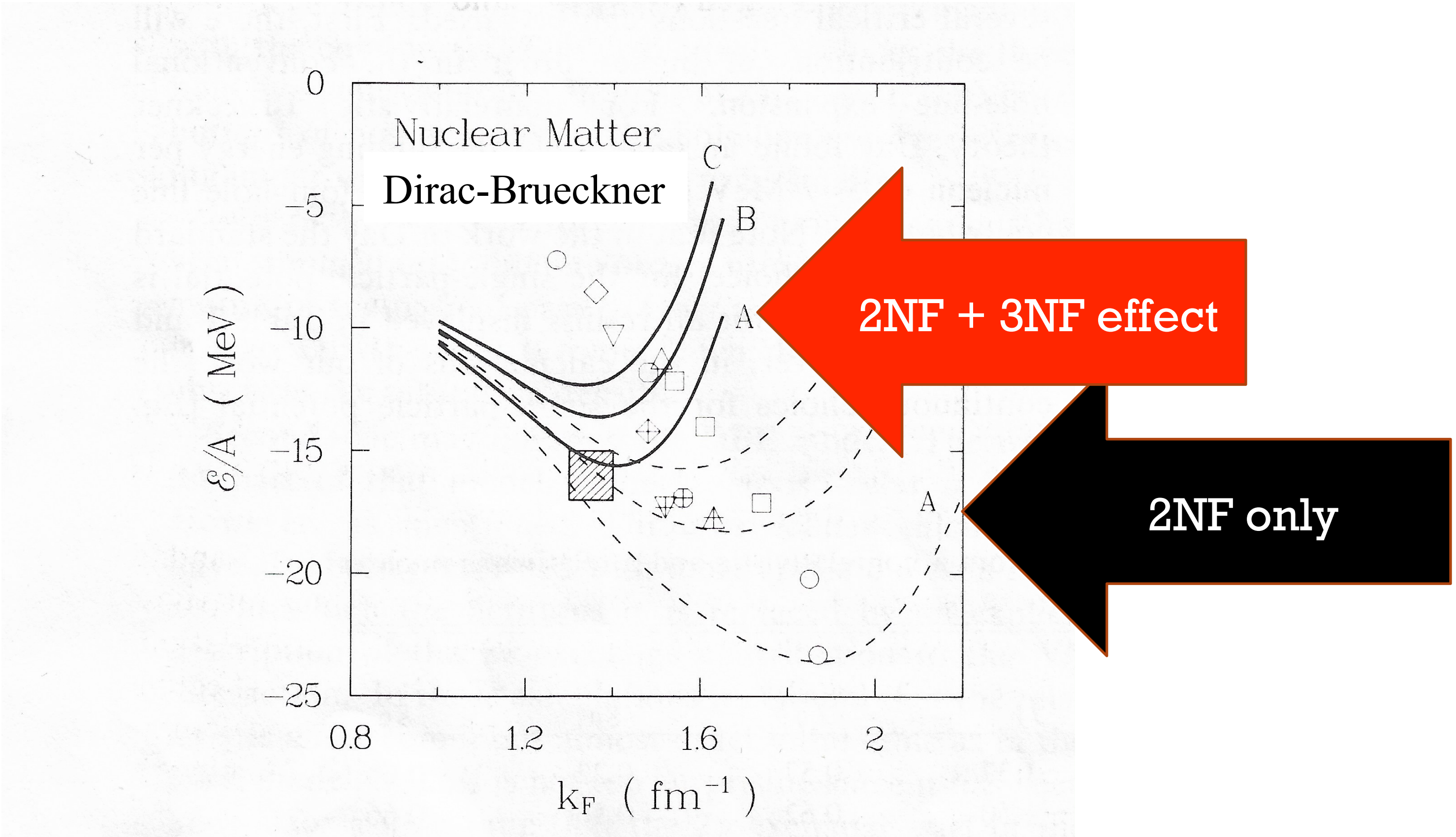
2018

BECAUSE OF THE PROBLEMS JUST POINTED OUT, IMPROVEMENT OF CURRENT NUCLEAR FORCES IS CALLED FOR.

- **How?**
- **Go backwards: Revisit the lower orders – s. talk by Ekstroem**
- **Go forward: pick up again N3LO and advance to N4LO: for radii and energies of intermediate-mass nuclei: get nuclear matter saturation right.**

But, how to get nuclear matter saturation right?

Let's learn from history – Dirac-Brueckner:
soft NN interaction plus repulsive 3NF effect



BUT, OF COURSE, ONE COULD ALSO THINK OF THE OPPOSITE: REPULSIVE NN INTERACTION PLUS 3NF WHICH IS ATTRACTIVE IN 3H AND 4HE.

EXAMPLE:
ARGONNE V18 2NF
+ URBANA IX 3NF

Akmal *et al.*, PRC **58**, 1804 (1998).

TABLE VI. The $E(\rho)$ of SNM in MeV.

ρ	A18	A18+ δv	A18+UIX	A18+ δv +UIX*	corrected
0.04	−4.28	−4.08	−4.39	−4.31	−6.48
0.08	−8.72	−8.07	−8.06	−7.97	−12.13
0.12			−10.52	−10.54	−15.04
0.16	−14.59	−12.54	−11.85	−12.16	−16.00
0.20			−11.28	−12.21	−15.09
0.24	−17.61	−13.69	−8.99	−10.89	−12.88
0.32	−18.13	−11.87	0.84	−4.21	−5.03
0.40	−16.37	−7.70	12.23	2.42	2.13
0.48	−12.21	−1.01	32.18	15.56	15.46
0.56	−5.79	8.16	59.99	34.42	34.39
0.64	2.76	19.54	95.05	58.36	58.35
0.80	25.01	45.24	188.51	121.25	121.25
0.96	56.51	82.63	313.46	204.02	204.02

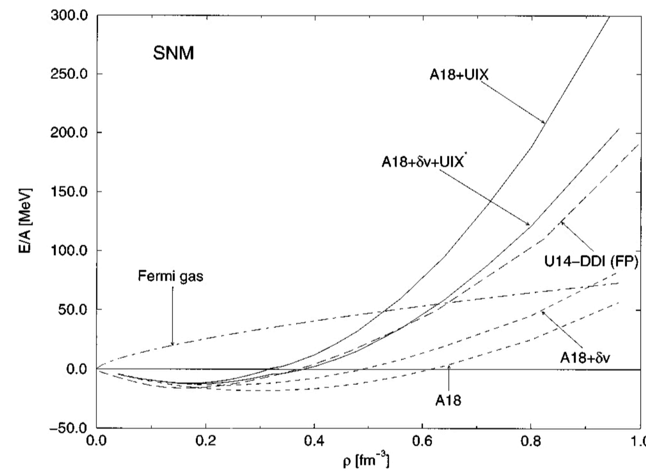


FIG. 2. The energy per nucleon, $E(\rho)$, of SNM for various interaction models.

Lonardoni *et al.*, PRC **96**, 024326 (2017).

Table VIII. Total energies (in MeV/A) and charge radii (in fm) in ^{16}O for different potentials.

obs	potential	CVMC	exp
$\langle E\rangle$	AV18	−5.51(2)	−7.98
	AV18+UIX	−5.15(2)	
$\sqrt{\langle r^2_{ch}\rangle}$	AV18	2.538(2)	2.699(5)
	AV18+UIX	2.745(2)	

Table IX. Total energies (in MeV/A) and charge radii (in fm) in ^{40}Ca for different potentials.

obs	potential	CVMC	exp
$\langle E\rangle$	AV18	−5.88(10)	−8.55
	AV18+UIX	−4.92(10)	
$\sqrt{\langle r^2_{ch}\rangle}$	AV18	3.361(2)	3.478(1)
	AV18+UIX	3.617(2)	

It does not work!

THUS, WE HAVE CONSTRUCTED A FAMILY OF SOFT CHIRAL NN POTENTIALS*, WHERE INDICATIONS OF SOFTNESS ARE …

*Entem, Machleidt, Nosyk, PRC **96**, 024004 (2017).

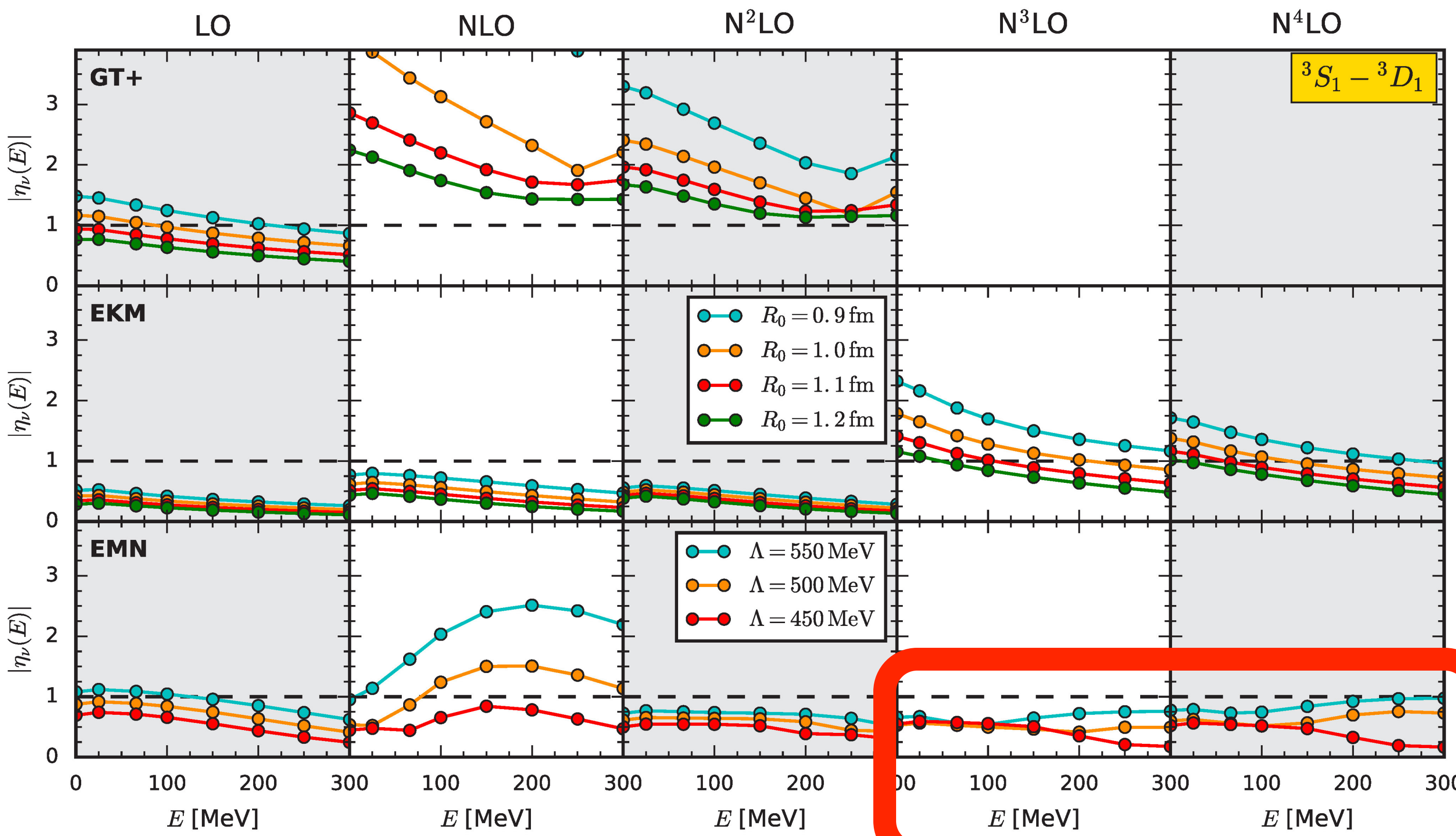
Indicators for the softness of NN potentials: the deuteron D-state probability, $P_{D,}$ and the triton binding energy, B_t

TABLE VII: Two- and three-nucleon bound-state properties as predicted by NN potentials at various orders of chiral EFT ($\Lambda = 500$ MeV in all cases). (Deuteron: Binding energy B_d, asymptotic S state A_S, asymptotic D/S state η, structure radius $r_{\rm str}$, quadrupole moment Q, D-state probability P_D; the predicted $r_{\rm str}$ and Q are without meson-exchange current contributions and relativistic corrections. Triton: Binding energy B_t.) B_d is fitted, all other quantities are predictions.

	LO	NLO	NNLO	N^3LO	N^4LO	Empirical[a]
Deuteron						
B_d (MeV)	2.224575	2.224575	2.224575	2.224575	2.224575	2.224575(9)
A_S (fm$^{-1/2}$)	0.8526	0.8828	0.8844	0.8853	0.8852	0.8846(9)
η	0.0302	0.0262	0.0257	0.0257	0.0258	0.0256(4)
$r_{\rm str}$ (fm)	1.911	1.971	1.968	1.970	1.973	1.97507(78)
Q (fm^2)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
P_D (%)	7.29	3.40	4.49	4.15	4.10	—
Triton						
B_t (MeV)	11.02	8.31	8.21	8.09	8.08	8.48

More indicators of softness: the Weinberg eigenvalues

J. Hoppe, C. Drischler, R. J. Furnstahl, K. Hebeler, and A. Schwenk
PHYSICAL REVIEW C 96, 054002 (2017)



Besides this, the potentials are of "High quality". what does that means?

- **Use π-N LECs determined in π-N analysis with the highest possible precision: Roy-Steiner Analysis (Hoferichter et al., PRL 115, 192301 (2015)).**

π-N LECs from Roy–Steiner Analysis

(Hoferichter et al., PRL 115, 192301 (2015))

TABLE II: The πN LECs as determined in the Roy-Steiner-equation analysis of πN scattering conducted in Ref. [35]. The given orders of the chiral expansion refer to the NN system. Note that the orders, at which the LECs are extracted from the πN system, are always lower by one order as compared of the NN system in which the LECs are applied. The c_i, $\bar{d}_i$, and $\bar{e}_i$ are the LECs of the second, third, and fourth order πN Lagrangian [26] and are in units of GeV^{-1}, GeV^{-2}, and GeV^{-3}, respectively. The uncertainties in the last digits are given in parentheses after the values.

	NNLO	N^{3}LO	N^{4}LO
c_1	–0.74(2)	–1.07(2)	–1.10(3)
c_2	—	3.20(3)	3.57(4)
c_3	–3.61(5)	–5.32(5)	–5.54(6)
c_4	2.44(3)	3.56(3)	4.17(4)
$\bar{d}_1 + \bar{d}_2$	—	1.04(6)	6.18(8)
$\bar{d}_3$	—	–0.48(2)	–8.91(9)
$\bar{d}_5$	—	0.14(5)	0.86(5)
$\bar{d}_{14} - \bar{d}_{15}$	—	–1.90(6)	–12.18(12)
$\bar{e}_{14}$	—	—	1.18(4)
$\bar{e}_{17}$	—	—	–0.18(6)

Very small errors!

Besides this, the potentials are of "High quality".
what does that means?

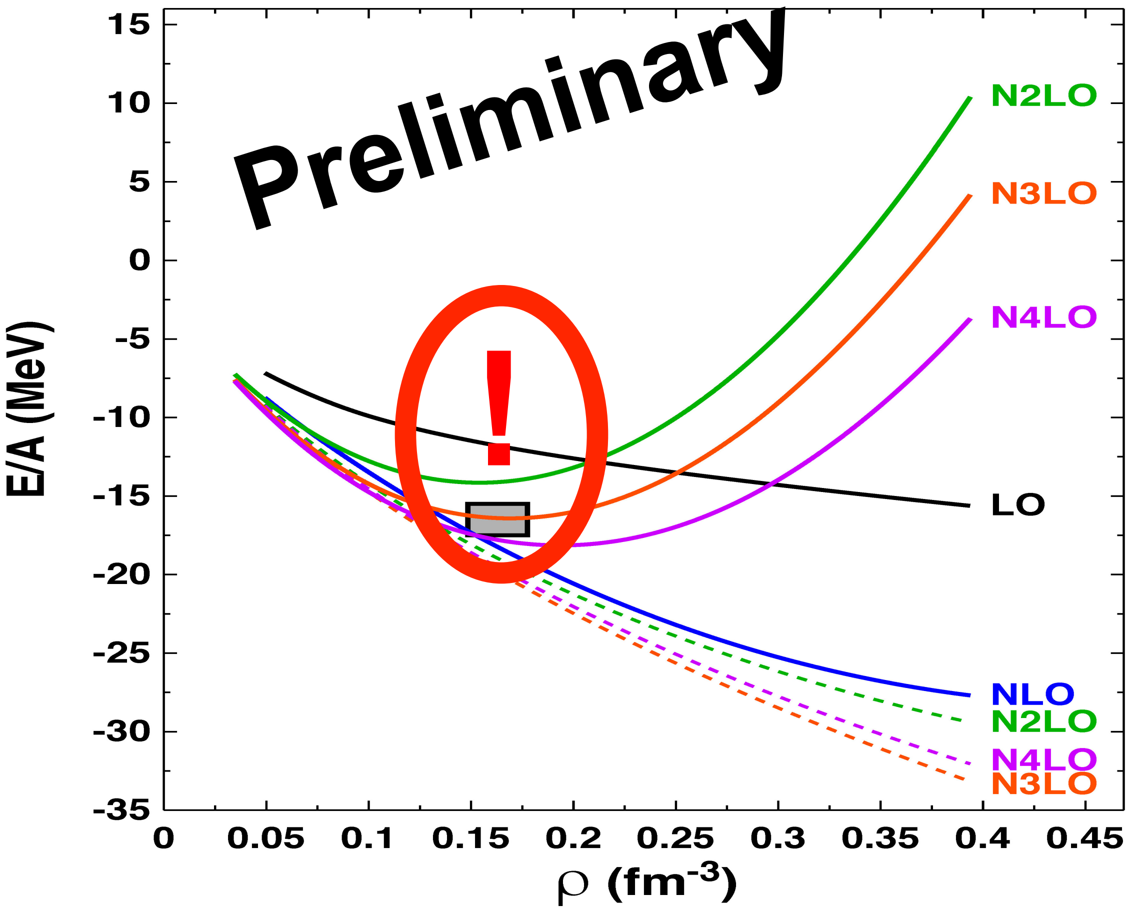
- **Use π-N LECs determined in π-N analysis with the highest possible precision: Roy-Steiner Analysis (Hoferichter et al., PRL 115, 192301 (2015)).**
- **NN potentials are fit to NN data (and not to phase shifts) using all NN data below pion production threshold published up to December 2016.**

Reproduction of the NN Data

TABLE V: χ^2/datum for the fit of the 2016 NN data base y NN potentials at various orders of chiral EFT ($\Lambda = 500$ MeV in all cases).

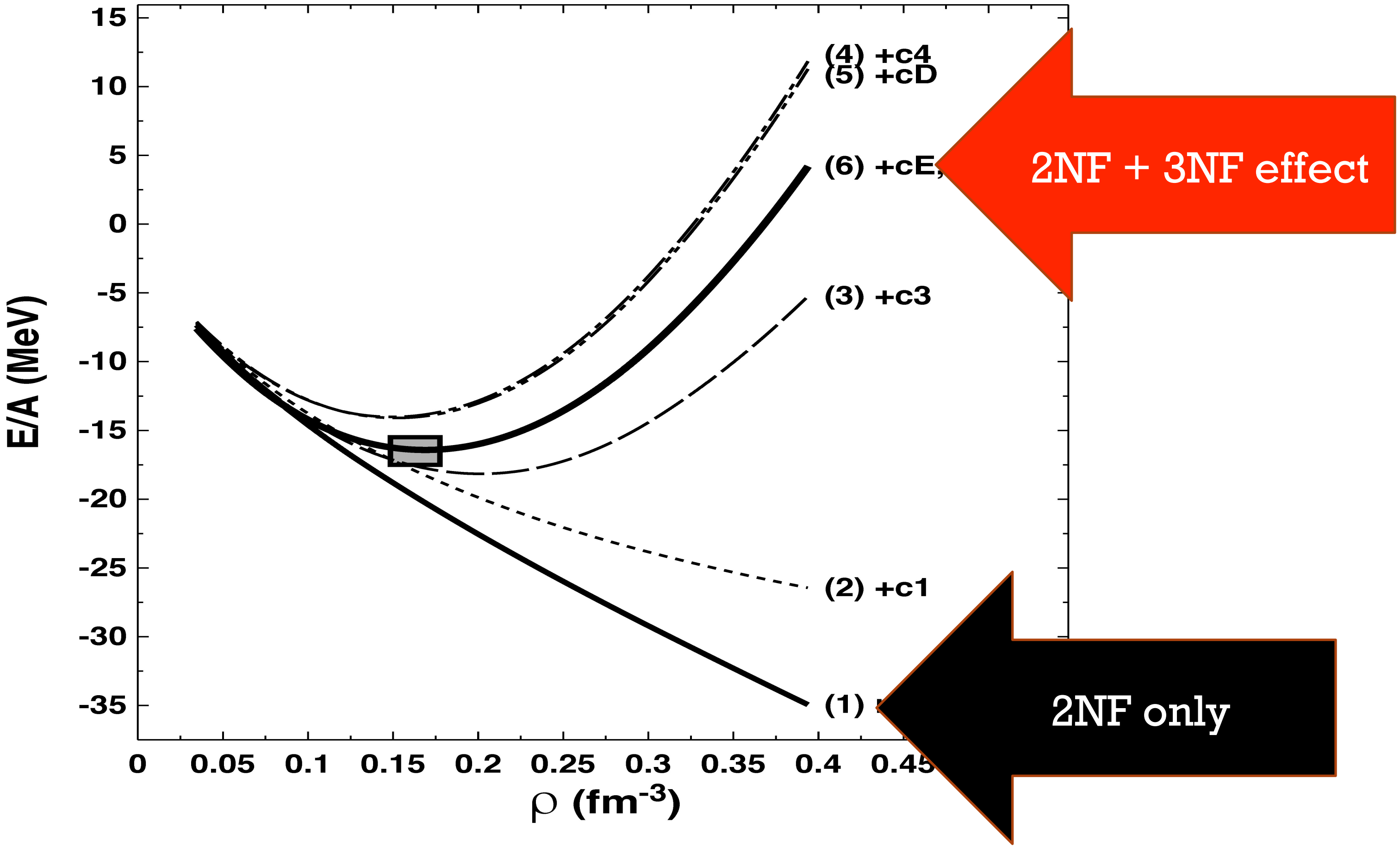
T_{lab} bin (MeV)	No. of data	LO	NLO	NNLO	N^3LO	N^4LO
			proton-proton			
0–100	795	520	18.9	2.28	1.18	1.09
0–190	1206	430	43.6	4.64	1.69	1.12
0–290	2132	360	70.8	7.60	2.09	1.21
			neutron-proton			
0–100	1180	114	7.2	1.38	0.93	0.94
0–190	1697	96	23.1	2.29	1.10	1.06
0–290	2721	94	36.7	5.28	1.27	1.10
			pp* plus *np			
0–100	1975	283	11.9	1.74	1.03	1.00
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0–290	4853	206	51.5	6.30	1.63	1.15

And now, what are the nuclear matter saturation properties of these potentials?

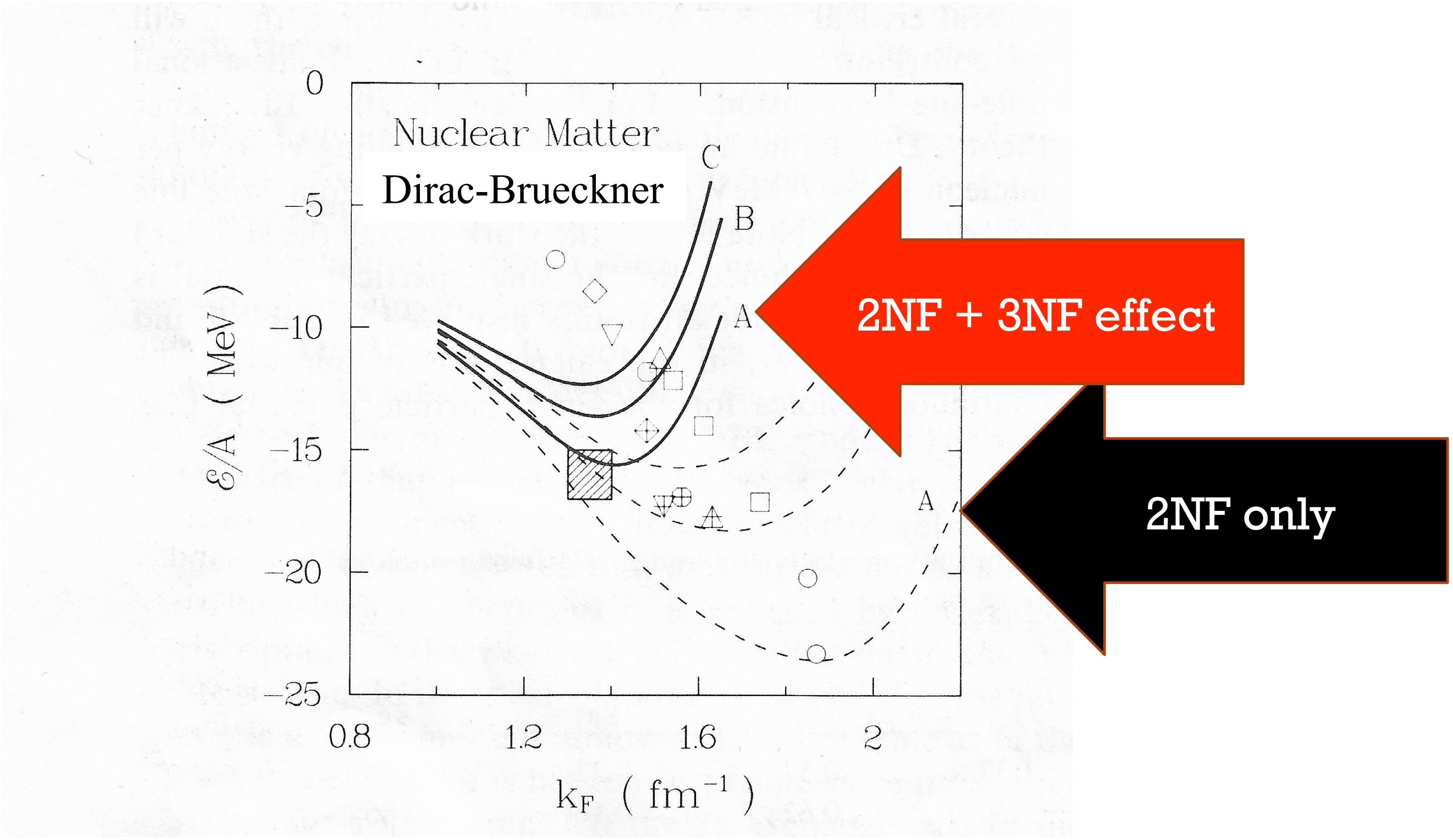


From F. Sammarruca *et al.,* to be published.

How the right saturation comes about – in more detail



The Dirac-Brueckner trick repeated with chiral forces:
soft NN interaction plus repulsive 3NF effect



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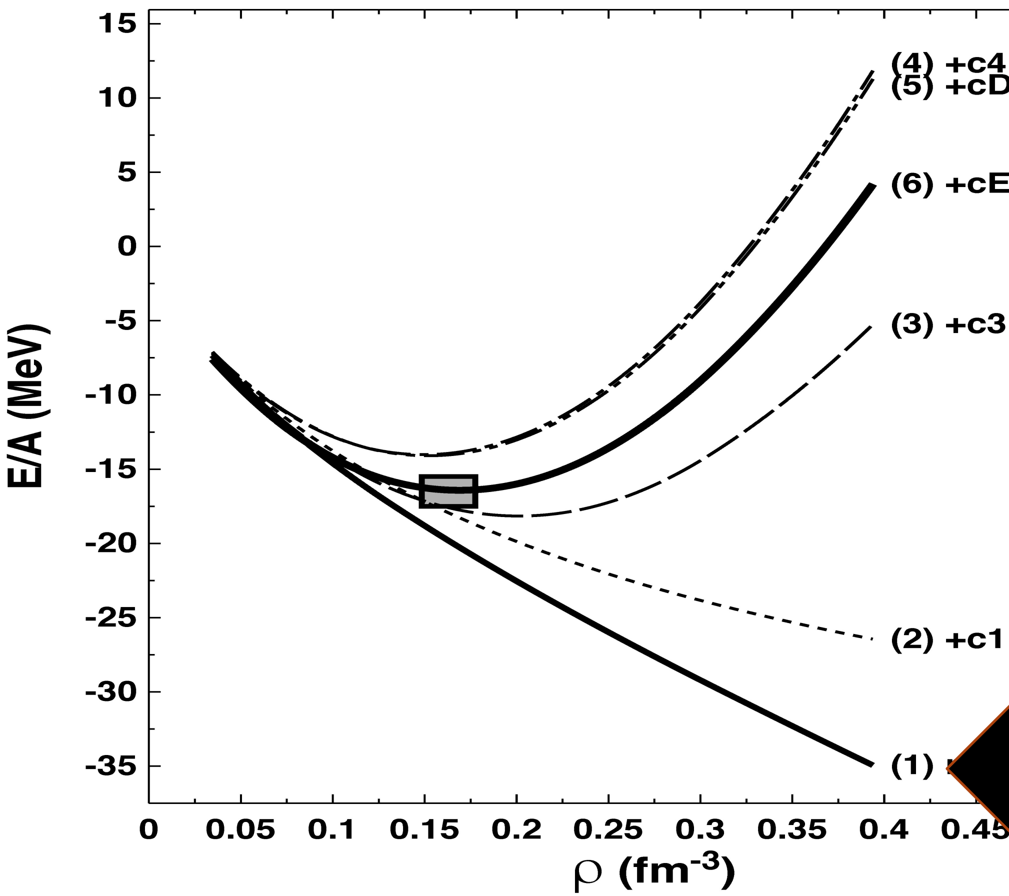
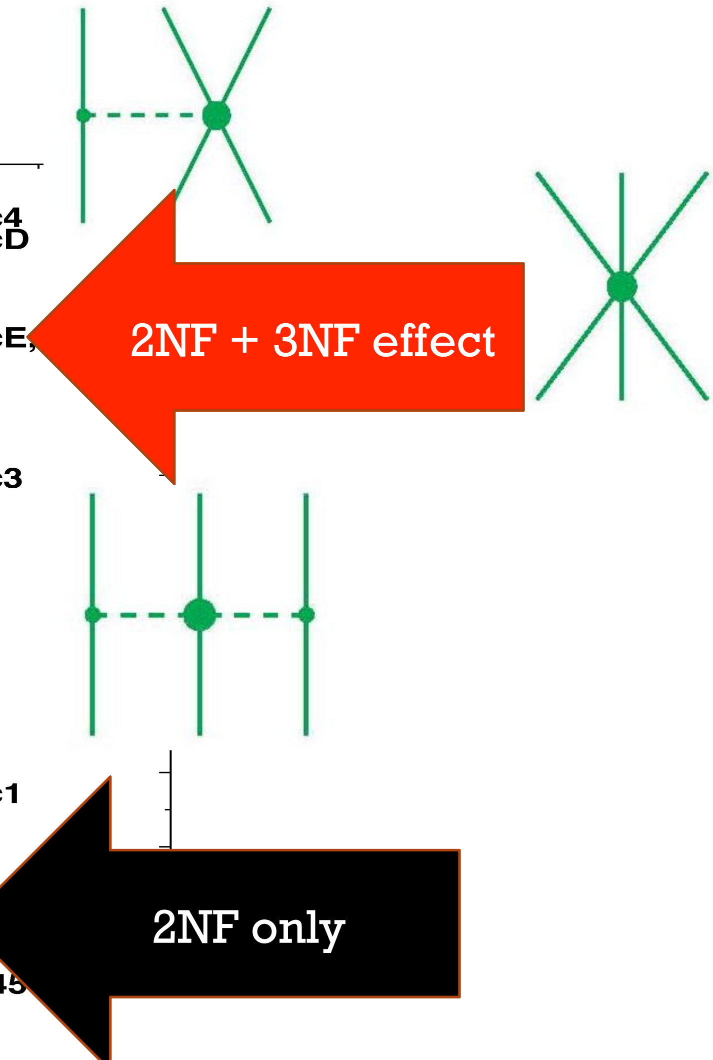
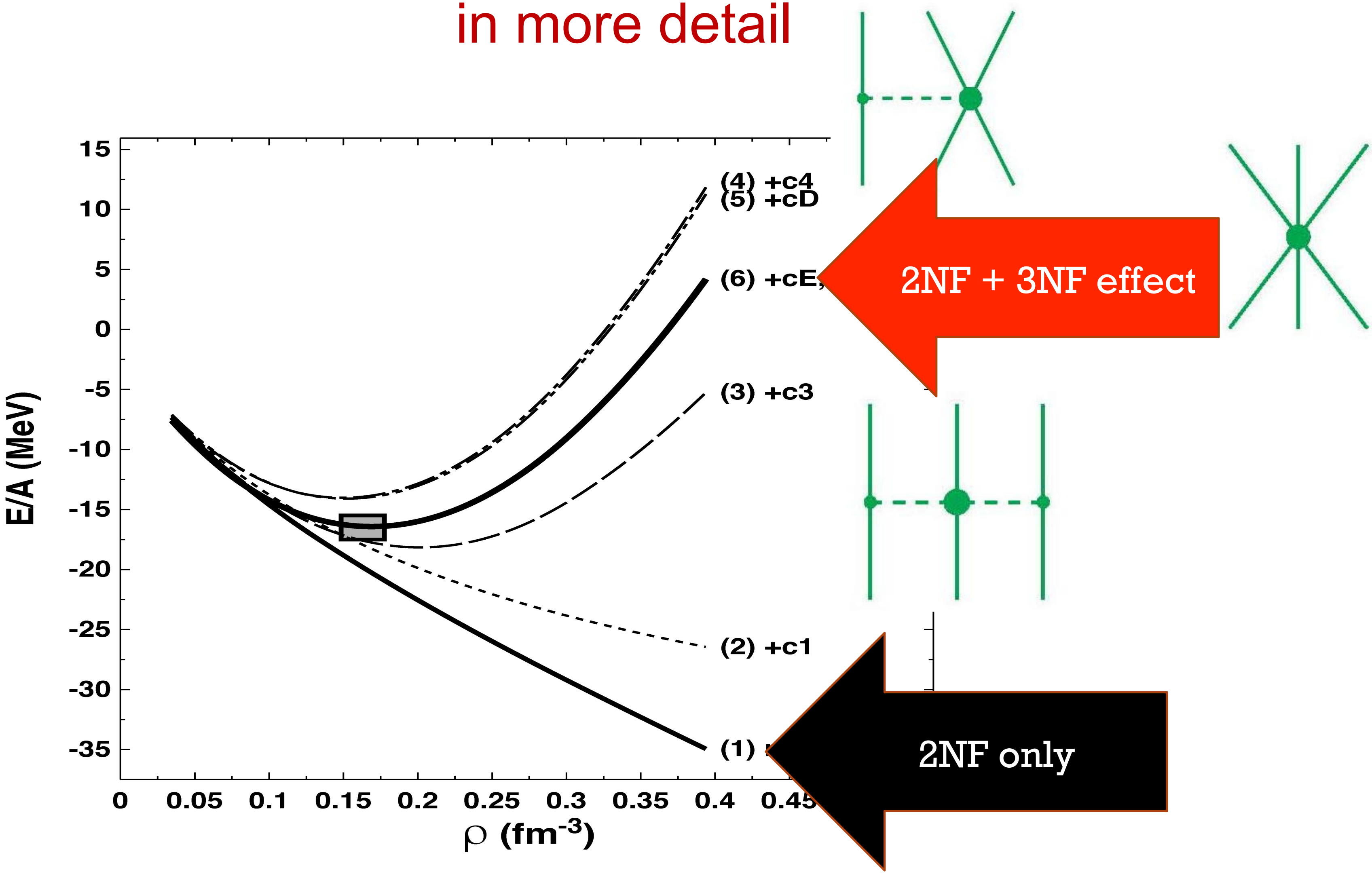




How the right saturation comes about – in more detail



CONCLUSIONS - WHAT WAS WRONG? AND HOW TO FIX IT?

- The nuclear interactions of the past are failing in medium-mass nuclei. They are either not tested in nuclear matter or do not get nuclear matter right.
- **Therefore, we have constructed chiral NN potentials that are soft and together with appropriate 3NFs saturate nuclear matter properly.**
- Besides this, the new chiral NN potentials have additional virtues:

1. They apply the high precision pi-N LECs from the Roy-Steiner analysis (strongly reducing the uncertainty budget).
2. They reproduce the NN data below 300 MeV with a chi^2/datum ~ 1 (again, implying small uncertainty).

- These high-quality **potentials carry the potential** to solve the outstanding problems with intermediate-mass and heavy nuclei.