NEUTRON-RICH NUCLEI AND NEUTRON SKINS FROM CHIRAL LOW-RESOLUTION INTERACTIONS

Pierre Arthuis

[Arthuis, Hebeler, Schwenk, arXiv:2401.06675]

WHAT IS LOW-ENERGY NUCLEAR PHYSICS?

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A-body system with:

Z protons

N neutrons

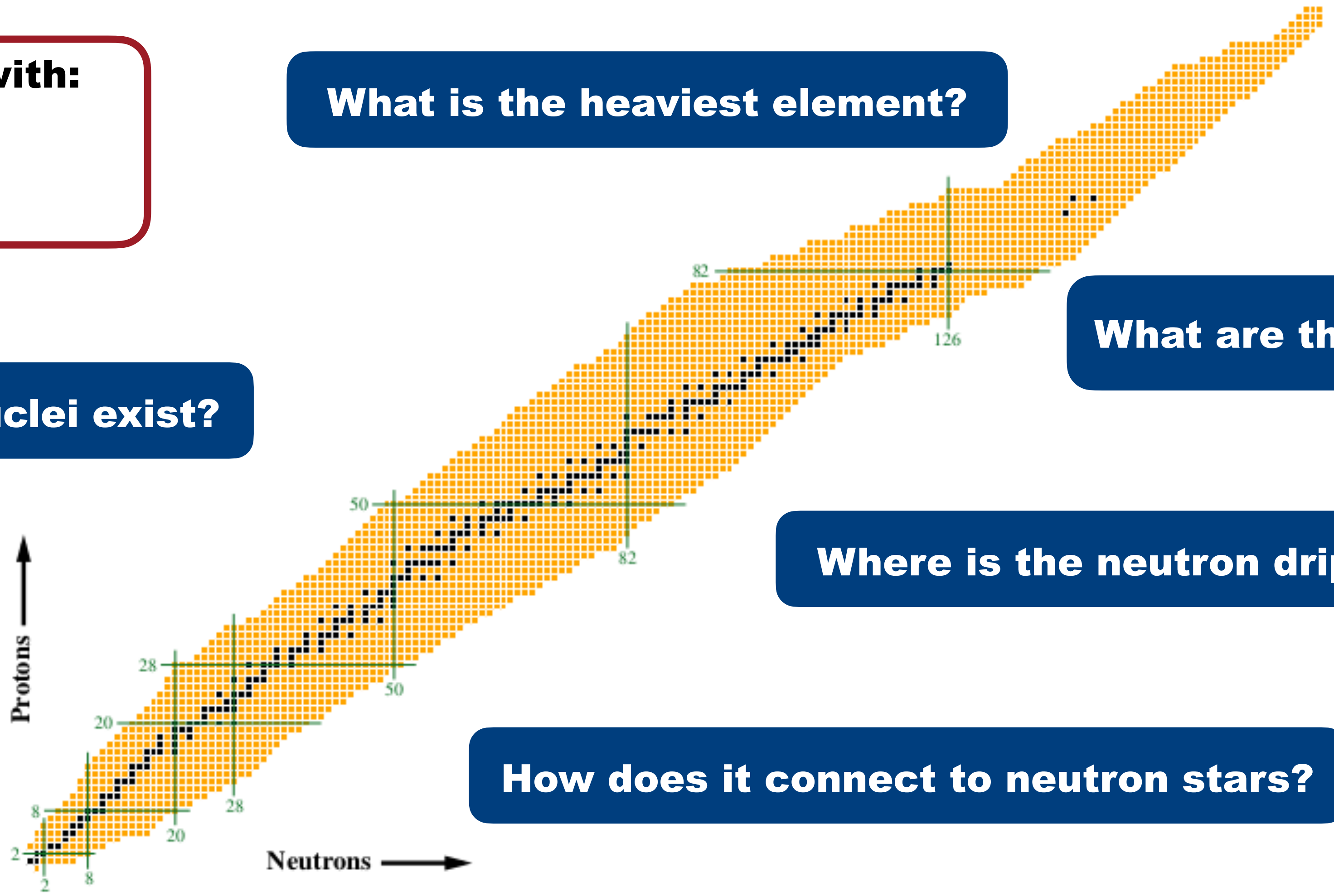
What is the heaviest element?

How many nuclei exist?

What are the magic numbers?

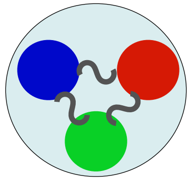
Where is the neutron dripline?

How does it connect to neutron stars?



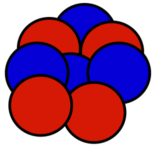
ON AB INITIO METHODS

AB INITIO MANY-BODY SCHEME



Particle physics

No direct application of
quantum chromodynamics
(Lattice QCD only for few nucleons)



Nuclear theory

Interactions anchored in Effective Field Theory

A-body Schrödinger equation

$$H\,|\Psi^{A}\rangle = \mathrm{E}^{A}\,|\Psi^{A}\rangle$$

Obtain a description that is:

- Consistent
- Systematic
- Accurate enough
- From inter-nucleon interactions
- Rooted in quantum chromodynamics

AB INITIO MANY-BODY METHODS RANGE

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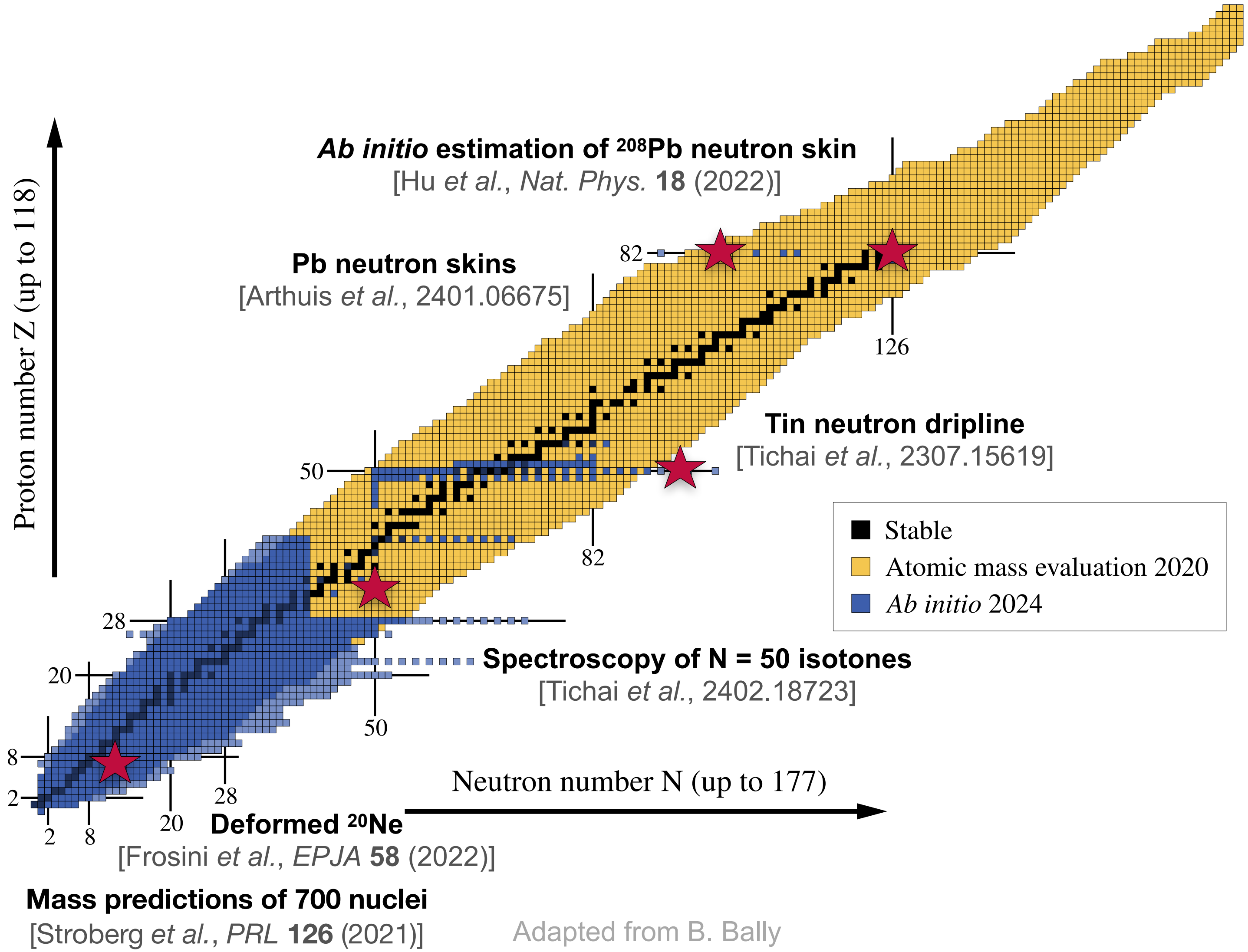


Adapted from B. Bally

Expansion methods

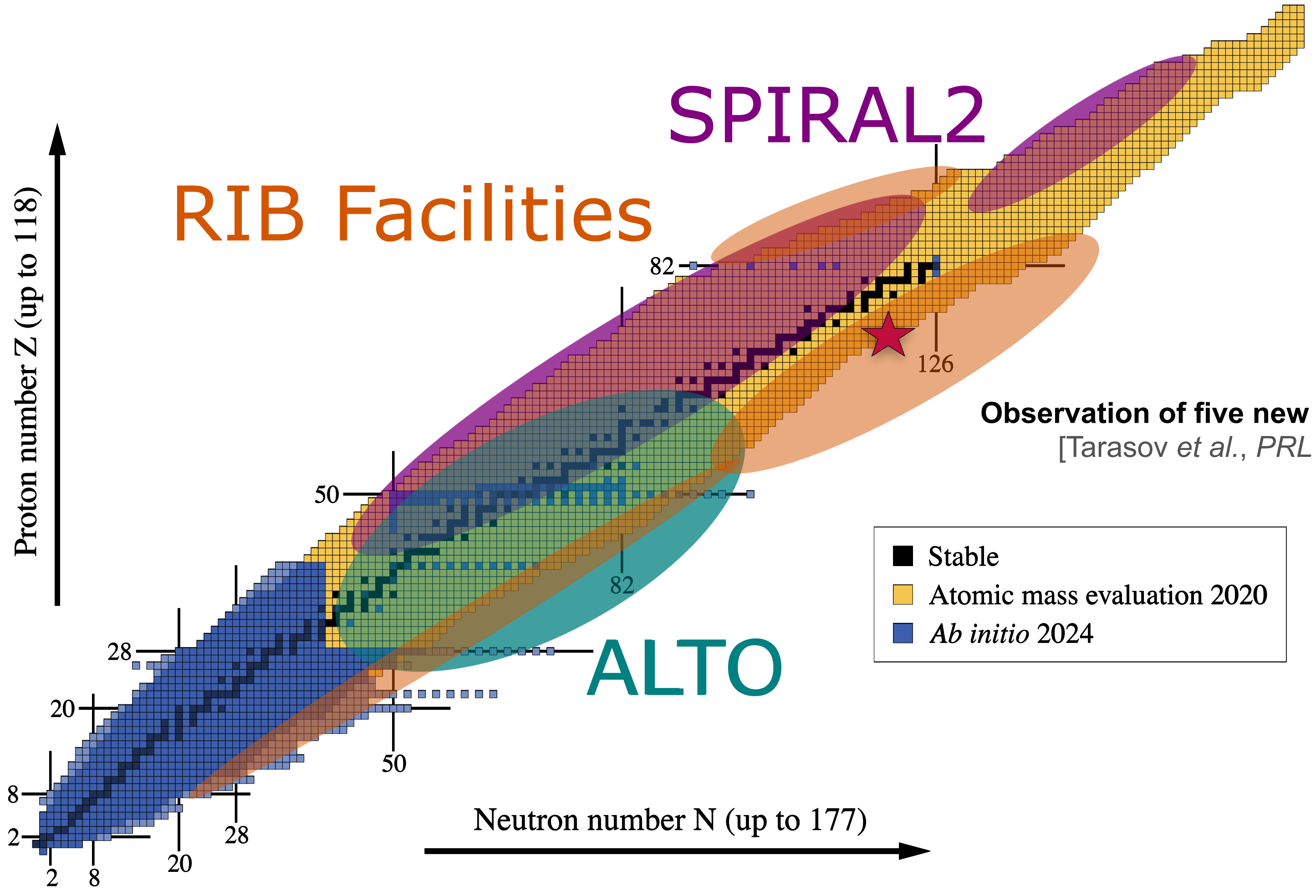
$$H|\Psi\rangle = U(\infty)|\Phi\rangle$$
$$= (U_1 + U_2 + U_3 + \ldots)|\Phi\rangle$$

- Expand the correlations order by order
- Truncate at desired order
- Estimate uncertainties

Controlled expansion & uncertainty

Moderate cost

A LOOK AT EXPERIMENTAL FACILITIES



Observation of five new isotopes at FRIB
[Tarasov *et al.*, *PRL* **132** (2024)]

Adapted from B. Bally

New era of shared effort

Heaver nuclei

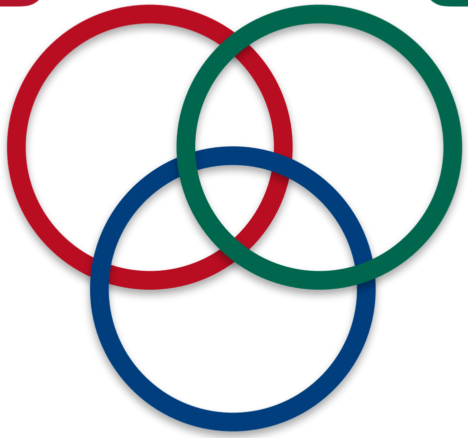
More exotic nuclei

NUCLEAR PHYSICS CHALLENGE(S)

Determine an observable O for a system S with precision η

Nuclear interaction

Many-body method



Numerical method

FOR A LESS BRIEF ONE: [HEBELER, PHYS. REP. 890 (2021)]

A VERY BRIEF HISTORY OF CHIRAL INTERACTIONS

CHIRAL EFT HAMILTONIANS: A LINK TO QCD

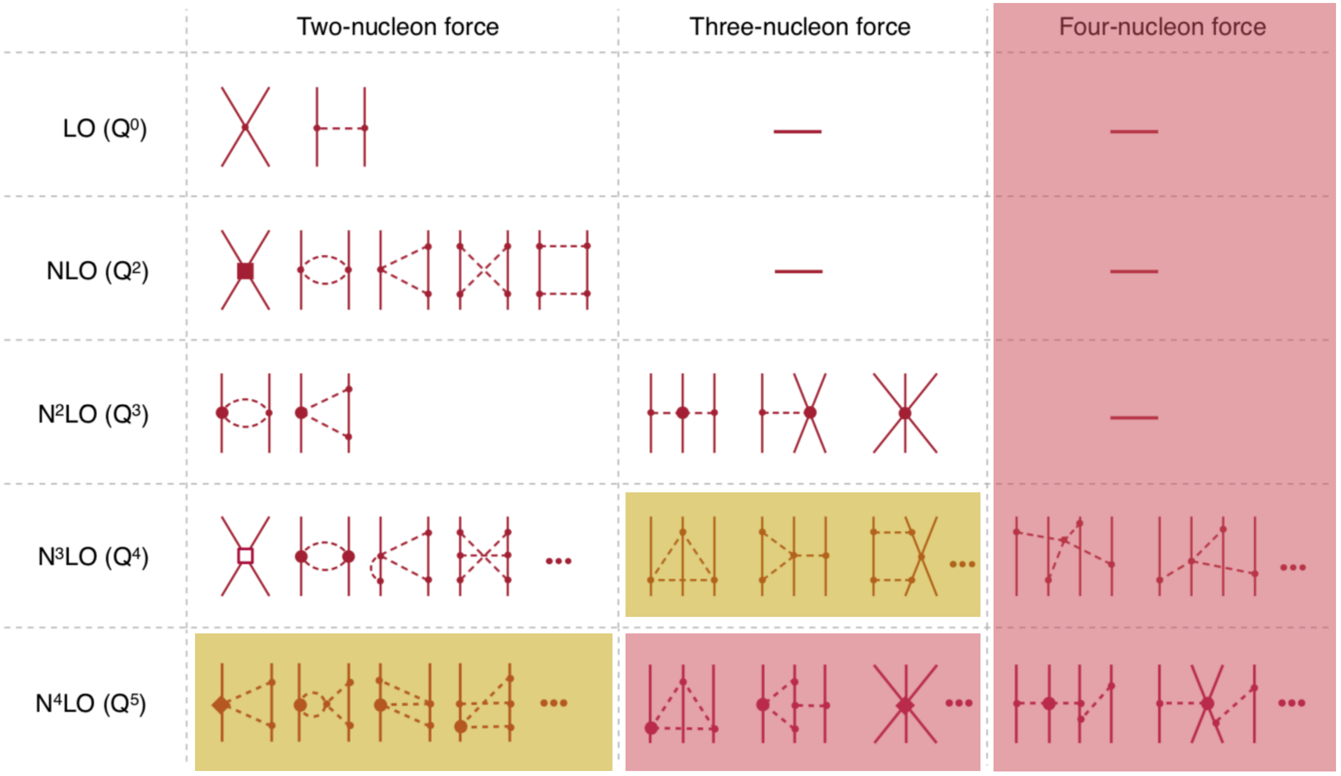
Rationale

- Nucleons and pions as degrees of freedom
- Link to QCD through Hamiltonian symmetries
- Natural hierarchy of terms
- Systematically improvable

$$M_{\text{low}} \sim m_\pi \qquad M_{\text{high}} \sim \Lambda_\chi \qquad \Lambda = \{\Lambda_{\text{NN}}, \Lambda_{\text{3N}}, \dots\}$$

In practice

- NN terms up to N⁴LO (though mostly N³/N²)
- 3N terms up to N³LO (though mostly N²LO)



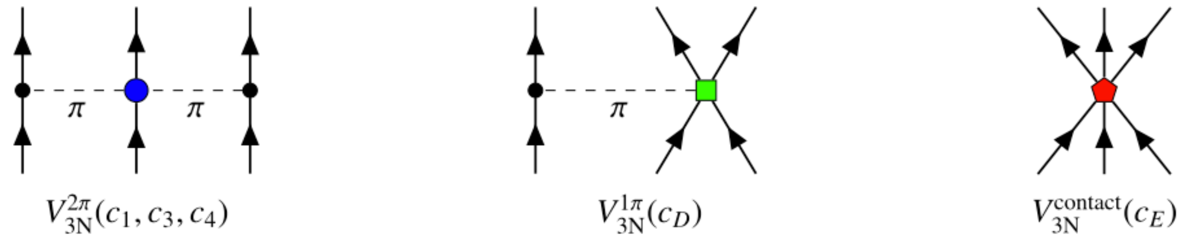
[Epelbaum, *PoS* CD15 (2016)]

Footnote: Similar expansion with Δ excitation

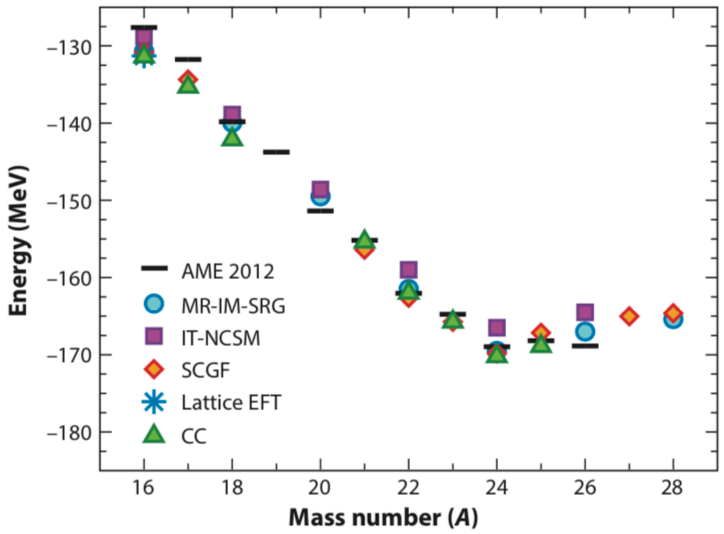
THE LEADING THREE-BODY FORCE

N2LO contributions

- Two-pion exchange: LECs set in the NN sector
- Two new LECs: one-pion exchange and contact term
- c_D, c_E only new parameters in 3N sector



[Hebeler, *Phys. Rept.* 890 (2021)]



[Hebeler *et al.*, *Annu. Rev. Nucl. Part. Sci. 65* (2015)]

Practical aspects

- Most often fitted in the 3N sector
- Bring repulsion necessary for a good qualitative description

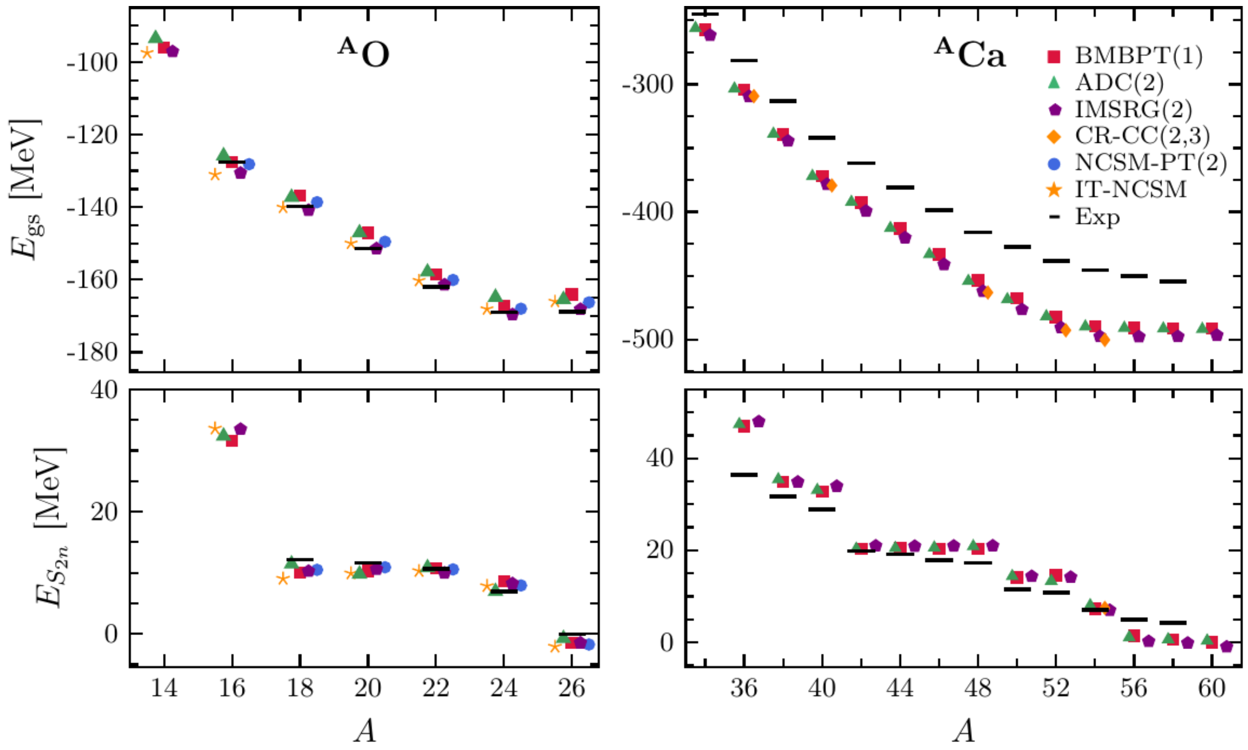
ENTEM-MACHLEIDT 500 (2003)

Pioneering work

- Reproduce quality of phenomenological potentials
- Fitting by reproducing NN phaseshifts
- Had to be supplemented with a 3N force

Legacy

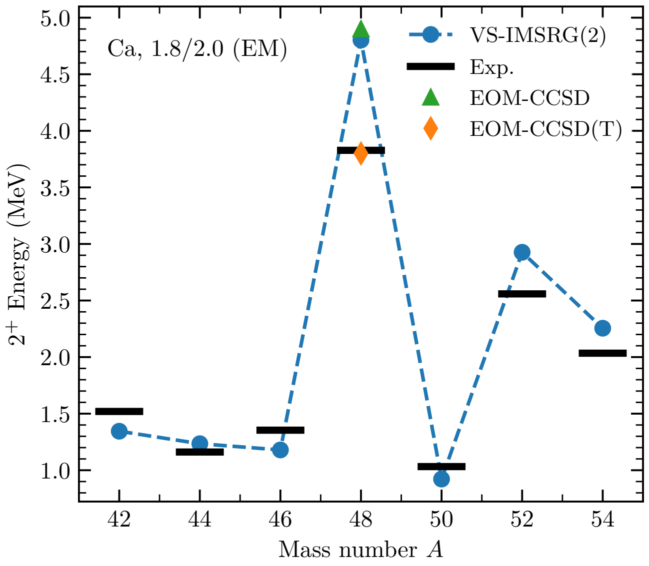
- Still one of the most used NN forces
- NN+3N combinations often fell short
- Hard interaction: require large model spaces



[Tichai, Arthuis *et al.*, *PLB* **786** (2018)]

[HEBELER, BOGNER, FURNSTAHL, NOGGA, SCHWENK, PRC 83 (2011)]

THE λ/Λ FAMILY AND THE 1.8/2.0 (EM) (2011)



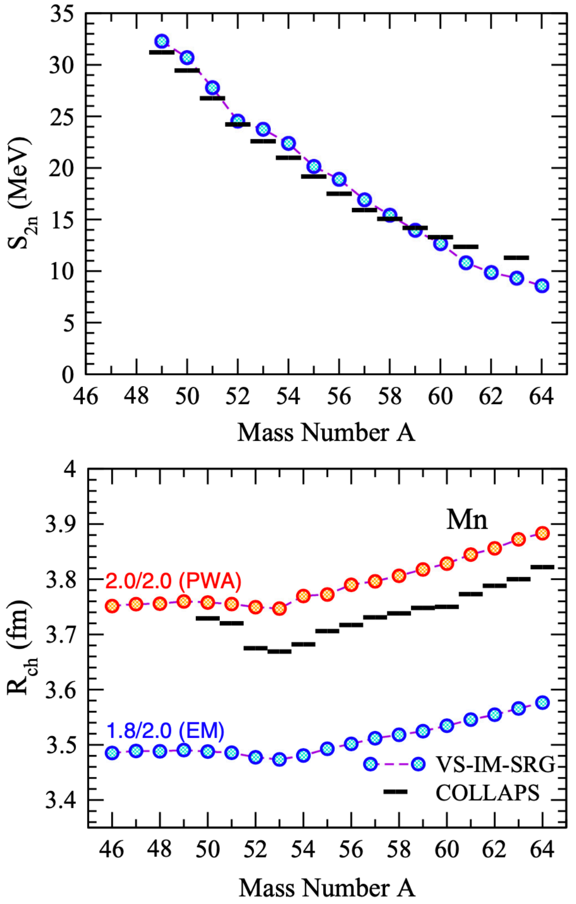
IMSRG: [Simonis, Stroberg, *et al.*, *PRC* **96** (2017)]
CC: [Hagen, Jansen, Papenbrock, *PRL* **117** (2016)]

Rationale

- Build on the success of the EM500
- SRG-evolve the EM, add bare 3N on top
- Low-Λ re-fit of c_D, c_E for 3NF absorb missing physics

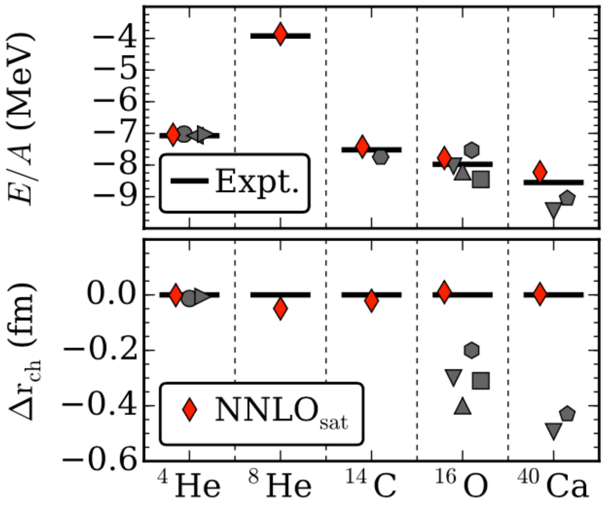
Legacy

- Vastly successful with energies
- Underpredicts radii
- Soft interaction, made for very broad use



[Simonis, Stroberg *et al.*, *PRC* **96** (2017)]

INCORPORATING MANY-BODY DATA: NNLO$_{\mathrm{SAT}}$ (2015)



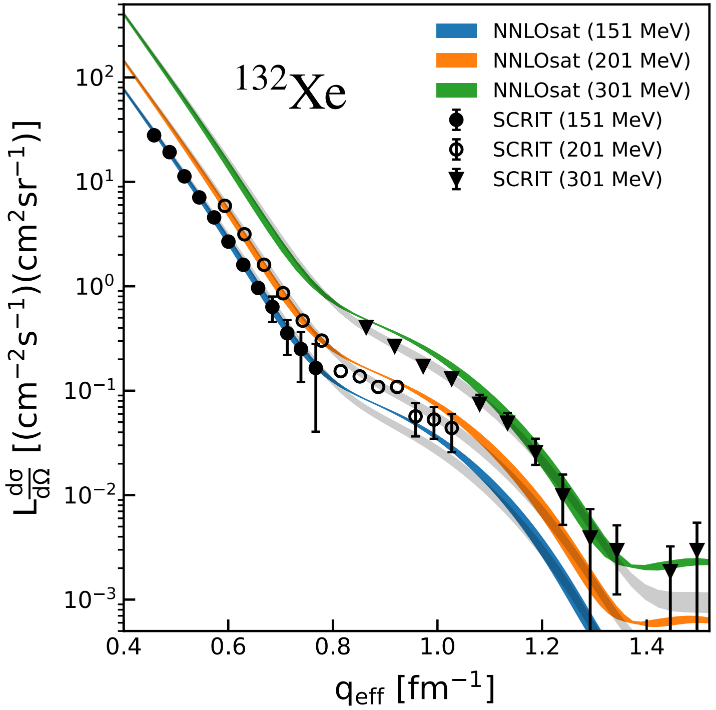
[Ekström, Jansen *et al.*, *PRC* **91** (2015)]

Rationale

- Interactions fitted on NN, 3N underpredict radii
- Incorporate *low-energy* many-body data in the fit
- Simultaneous fit of all LECs

Legacy

- Excellent radii and associated quantities
- Underbinds in the heavy sector
- Pioneered the use of many-body data



[Arthuis, Barbieri, *et al.*, *PRL* **125** (2020)]

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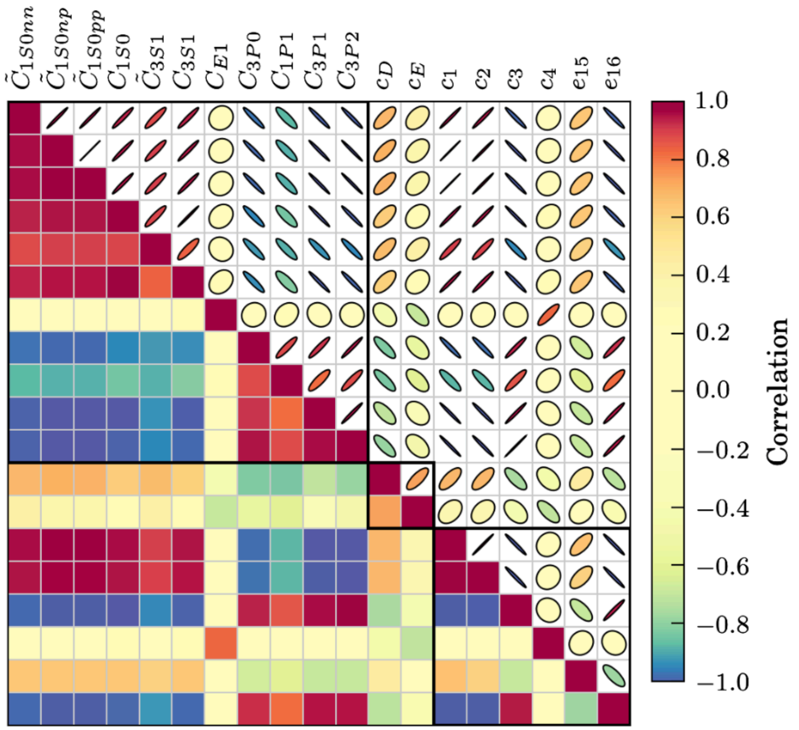
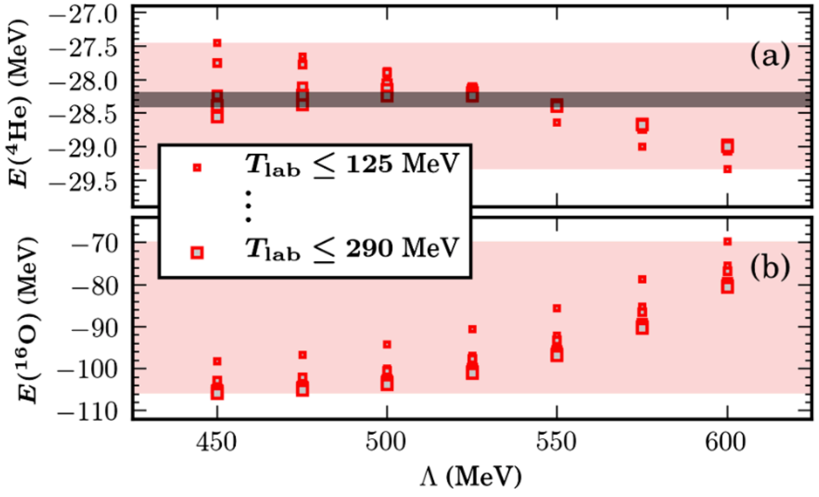
SIMULTANEOUS FITTING: $\mathrm{NNLO_{SIM}}$/$\mathrm{NNLO_{SEP}}$ (2016)

Rationale

- NN, 3N sector equals only in name
- Study the importance of NN+3N fitting approach
- Order-by-order fits, various cutoffs
- NN+3N consistently from the very start



[Carlsson, Ekström, *et al.*, *PRX* **6** (2016)]



[Carlsson, Ekström, *et al.*, *PRX* **6** (2016)]

Legacy

- Introduced detailed correlation studies
- Barely ever used in practical applications

THE ENTEM-MACHLEIDT-NOSYK INTERACTIONS (2017)

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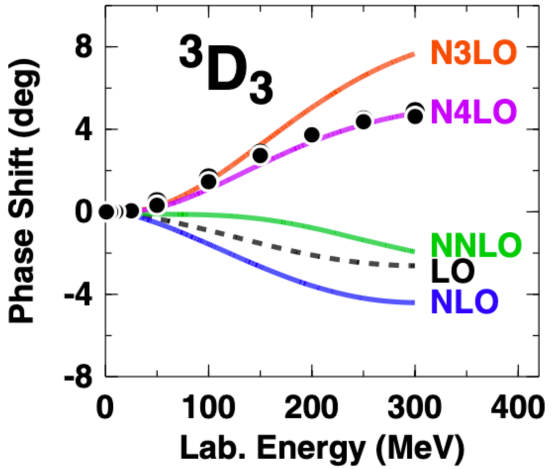


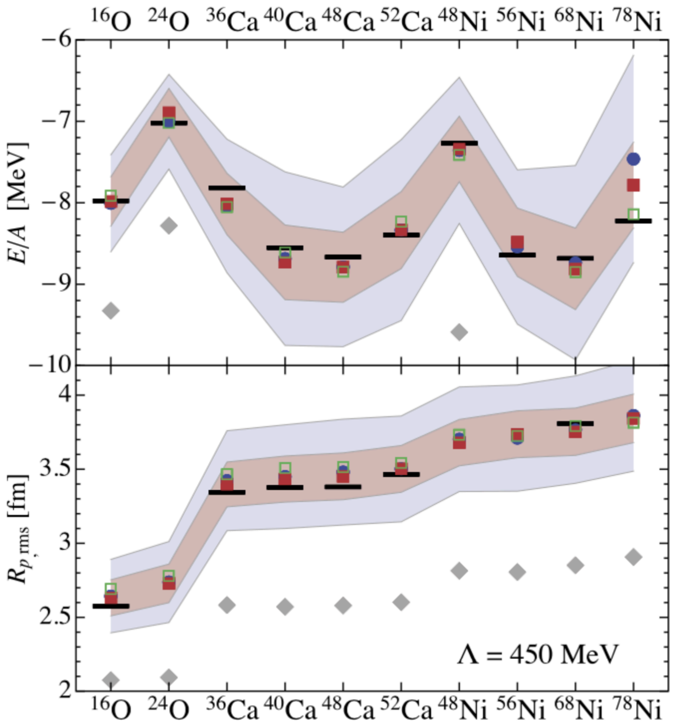
[Entem, Machleidt, Nosyk, *PRC* **96** (2017)]

Rationale

- Revisit the EM500 strategy: focus on phaseshifts
- Use πN scattering analysis data for c_i's
- Order-by-order fits, various cutoffs
- Still NN-only: needs to be supplemented

Legacy

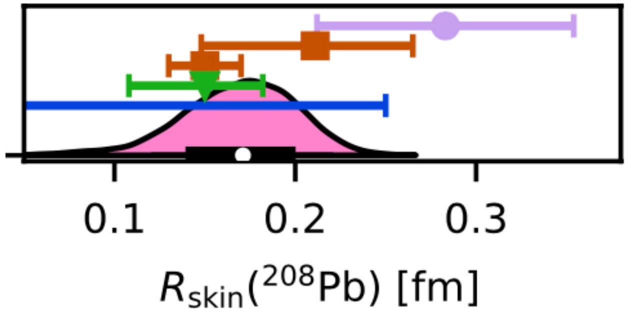
- Helped systematised chiral order studies
- Extended in multiple ways to the 3N sector



[Hüther, Vobig, *et al.*, *PLB* **808** (2020)]

[JIANG, EKSTRÖM, FORSSÉN, HAGEN, JANSEN, PAPENBROCK, PRC 102 (2020), …]

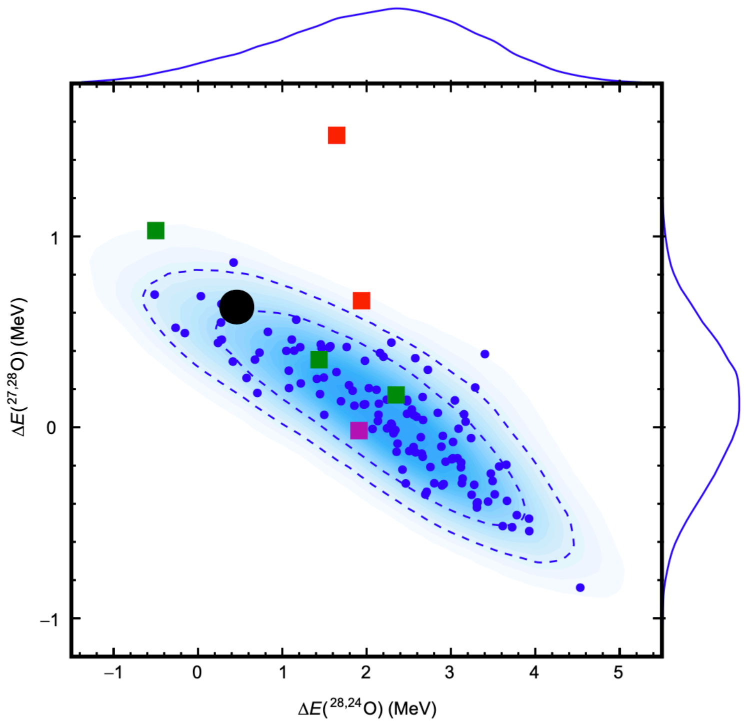
EXPLICIT Δ: ΔNNLO$_{GO}$ & THE NON-IMPLAUSIBLES (2019+)



[Hu, Jiang *et al.*, *Nat. Phys.* **18** (2022)]

Rationale

- Δ excitation is relatively low in energy
- Study convergence of deltaful chiral EFT
- Use many-body data from the start
- NLO, NNLO interactions
- More exhaustive strategy: non-implausible int.



[Kondo *et al.* (SAMURAI 21), *Nature* **620** (2023)]

Legacy

- Good simultaneous reproduction of radii & ground-state energy
- Very encouraging order-by-order convergence

[SOMÀ, NAVRÁTIL, RAIMONDI, BARBIERI, DUGUET, PRC 101 (2020)]

THE LOCAL-NON LOCAL (2020)

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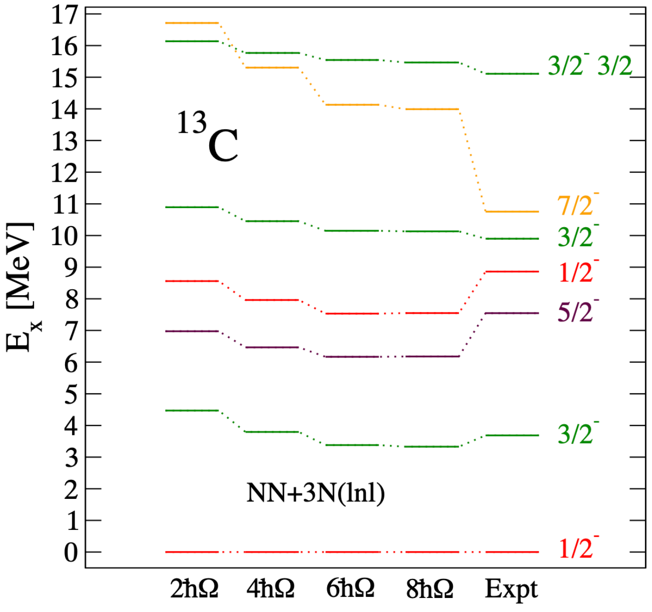


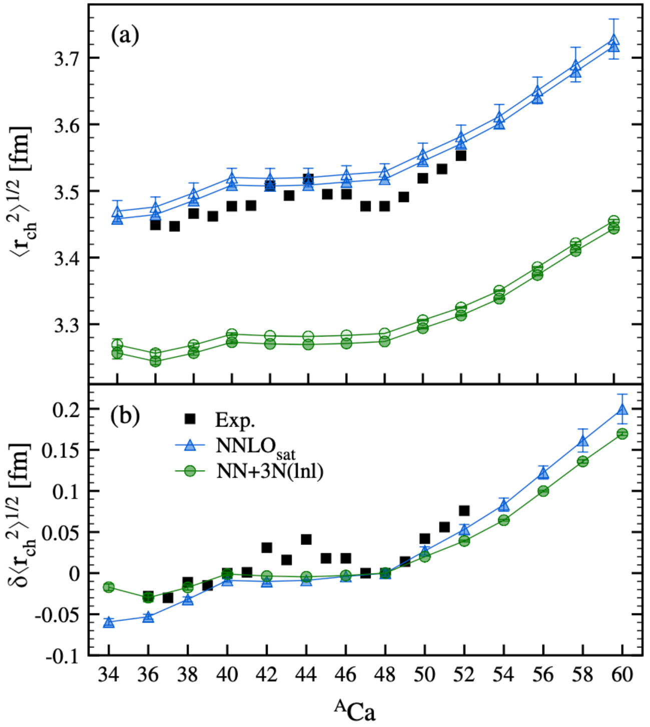
[Somà, Navrátil, *et al.*, *PRC* **101** (2020)]

Rationale

- Combine qualities of local and non-local regulators
- Fit only in the few-body sector

Legacy

- Very succesful for spectroscopy
- Underpredicts radii in the medium and heavy sectors



[Somà, Barbieri, *et al.*, *EPJA* **57** (2021)]

A BRIEF CONCLUSION

Towards accurate chiral interactions

- Important development in the design of chiral interactions
- Great progress in the simultaneous reproduction of quantities
- Very active field of research, faster feedback from practitioners

Some work left to do

- Simultaneous reproduction of energies, radii, infinite matter out of reach
- Order-by-order convergence puzzling
- New many-body development offer more detailed (negative) feedback
- Entering an era of rapid trial and error approach

[ARTHUIS, HEBELER, SCHWENK, ARXIV:2401.06675]

NEW LOW-RESOLUTION INTERACTIONS, NEUTRON-RICH NUCLEI AND NEUTRON SKINS

WHY LOW-RESOLUTION INTERACTIONS?

Sufficient to describe bulk properties of nuclei

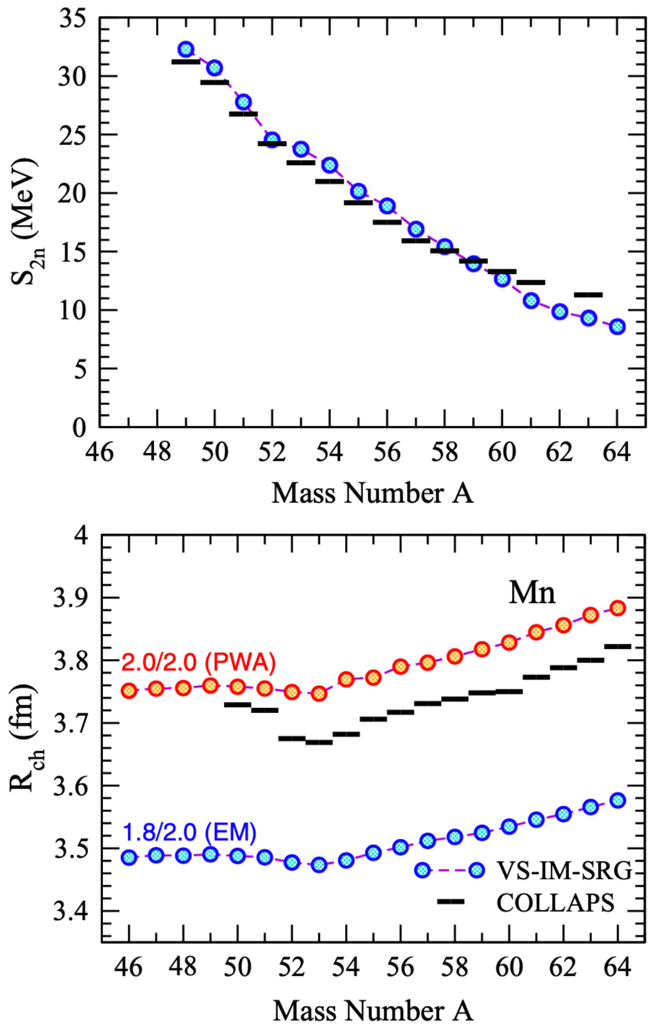
- Better convergence properties through softened interaction
- Proved successful for binding energies with the 1.8/2.0 (EM)
  [Hebeler *et al.*, *PRC* **83** (2011)]

The 1.8/2.0 approach

- NN force SRG-evolved to 1.8 fm^{-1}
- 3N force with c_D, c_E refitted with a cutoff of 2.0 fm^{-1}

Revisit this approach

- Goal: Obtain good description of binding energy and radii
- Target: From light to heavy systems



[Simonis *et al.*, *PRC* **96** (2017)]

OUR STARTING INTERACTIONS

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EMN NNLO and the sim family

- Different initial fitting strategies
- Wide range of cutoffs
- Different powers for the regulator

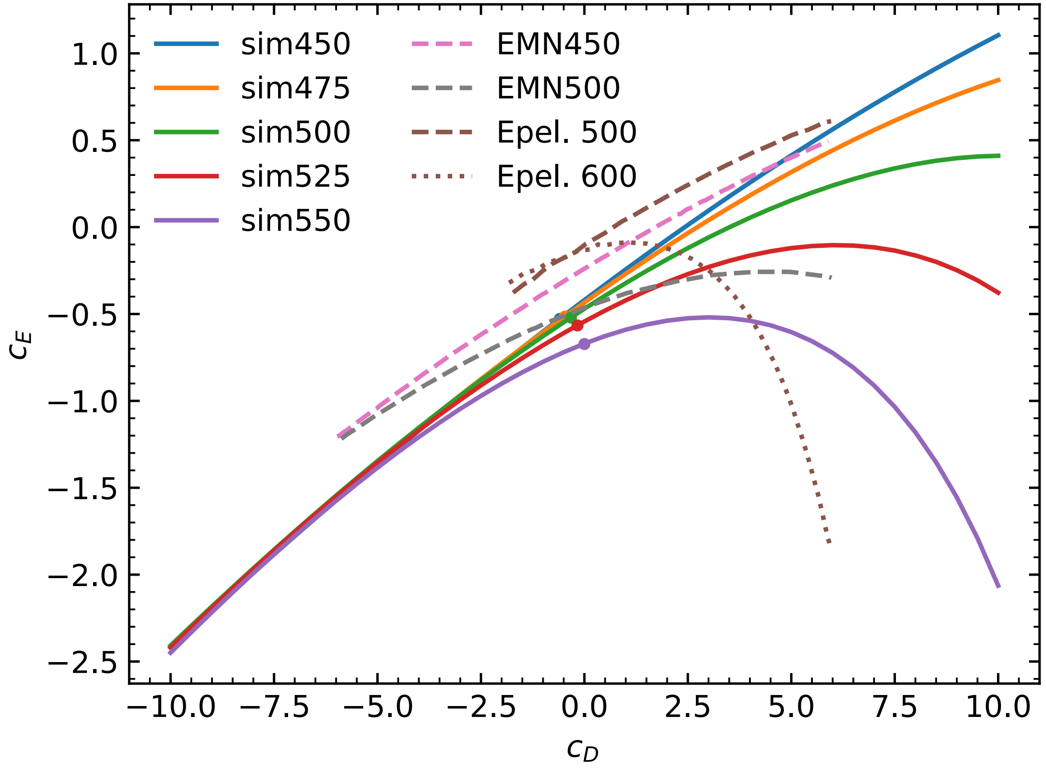
EMN: [Entem *et al.*, *PRC* **96** (2017)]
Sim: [Carlsson *et al.*, *PRX* **6** (2016)]

Three-body force regulator

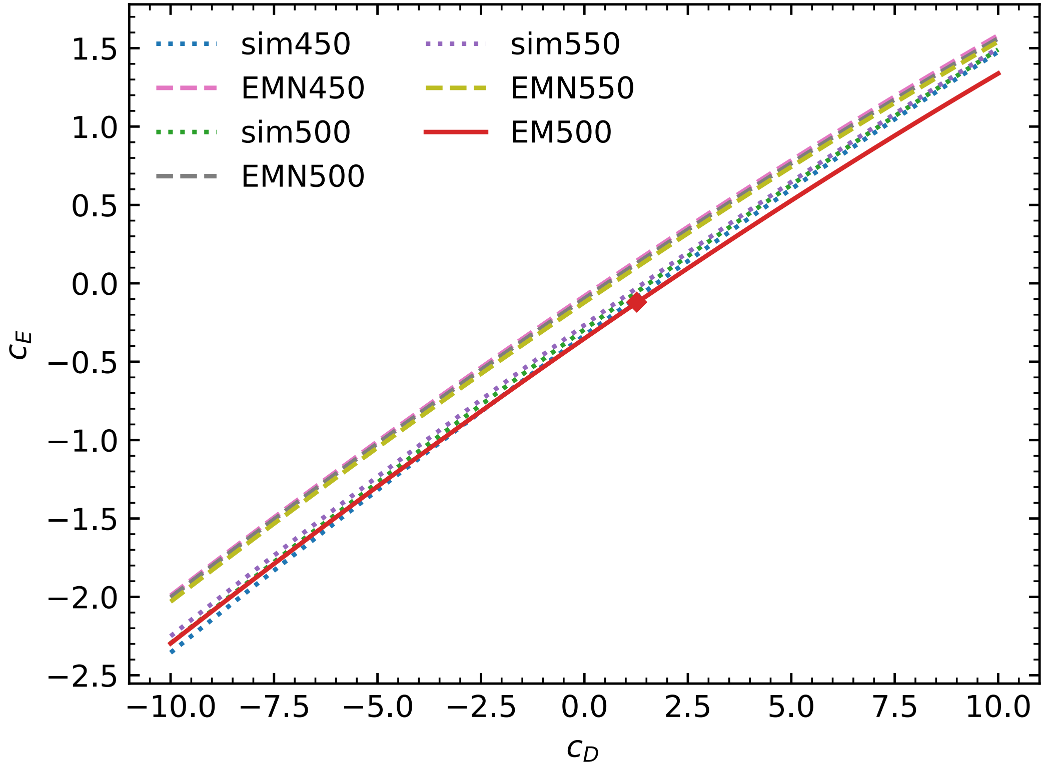
$$\exp\left[-\left(\frac{4p^2+3q^2}{4\Lambda^2}\right)^n\right]$$

LEC	EMN NNLO	EM	NNLOsim 450	NNLOsim 500	NNLOsim 550
c_1	-0.74	-0.81	-0.05	0.22	0.27
c_3	-3.61	-3.2	-3.45	-3.56	-3.56
c_4	2.44	5.4	4.235	3.933	3.644

THE 1.8/2.0 AND TRITON BINDING ENERGY



Epel. data: [Epelbaum et al., *PRC* **66** (2002)]



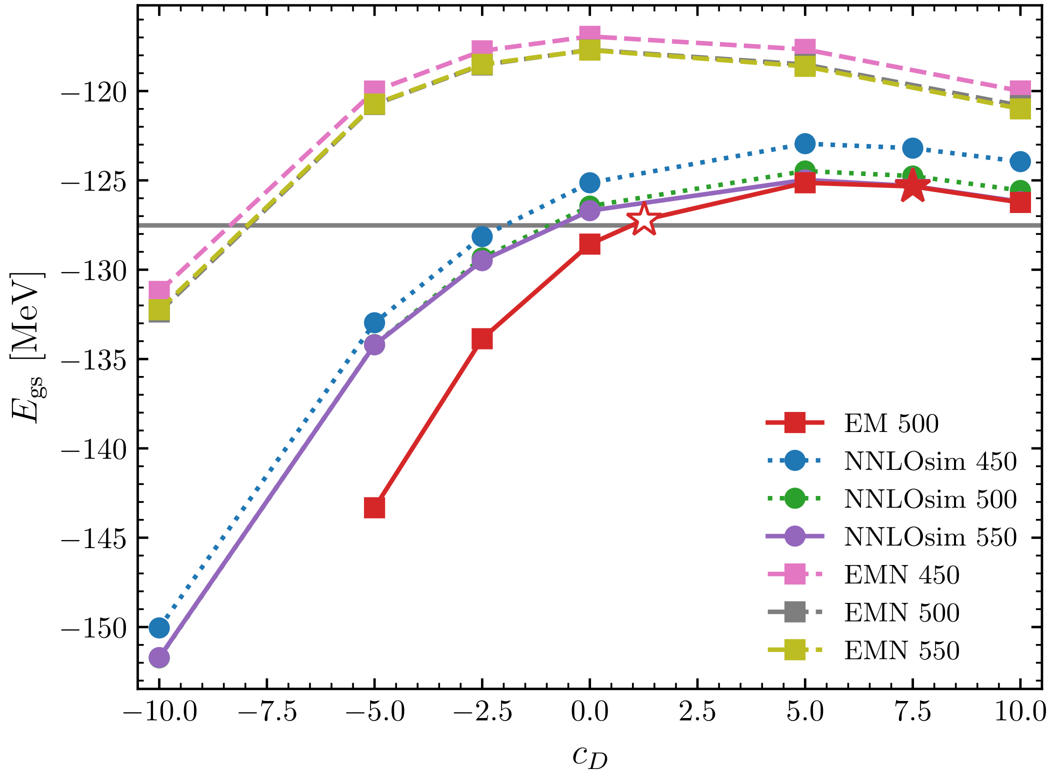
Bare interactions

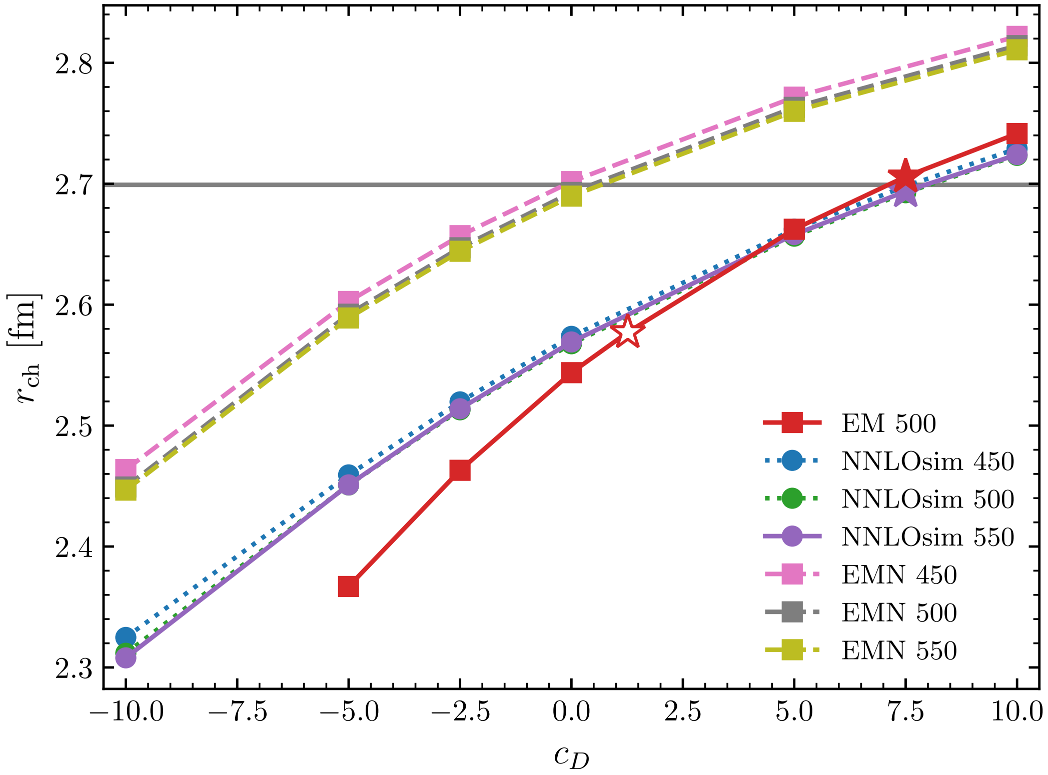
- Similar parabolic curves
- Larger cutoff means stronger bend

‘1.8/2.0’ interactions

- Very similar, quasi-linear dependence
- Mild dependence on original LECs

ANCHORING THE INTERACTIONS ON 16O





Binding energy

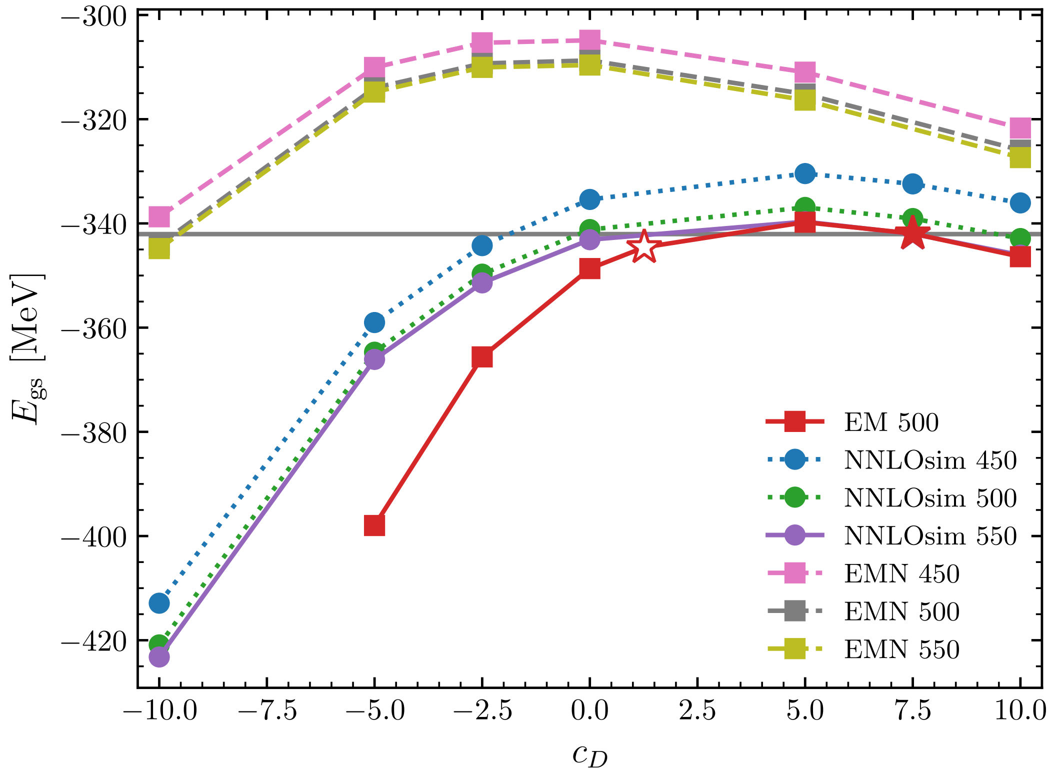
- NNLOsims and EM 500 stay close to exp. value
- EMNs only close for very negative c_D

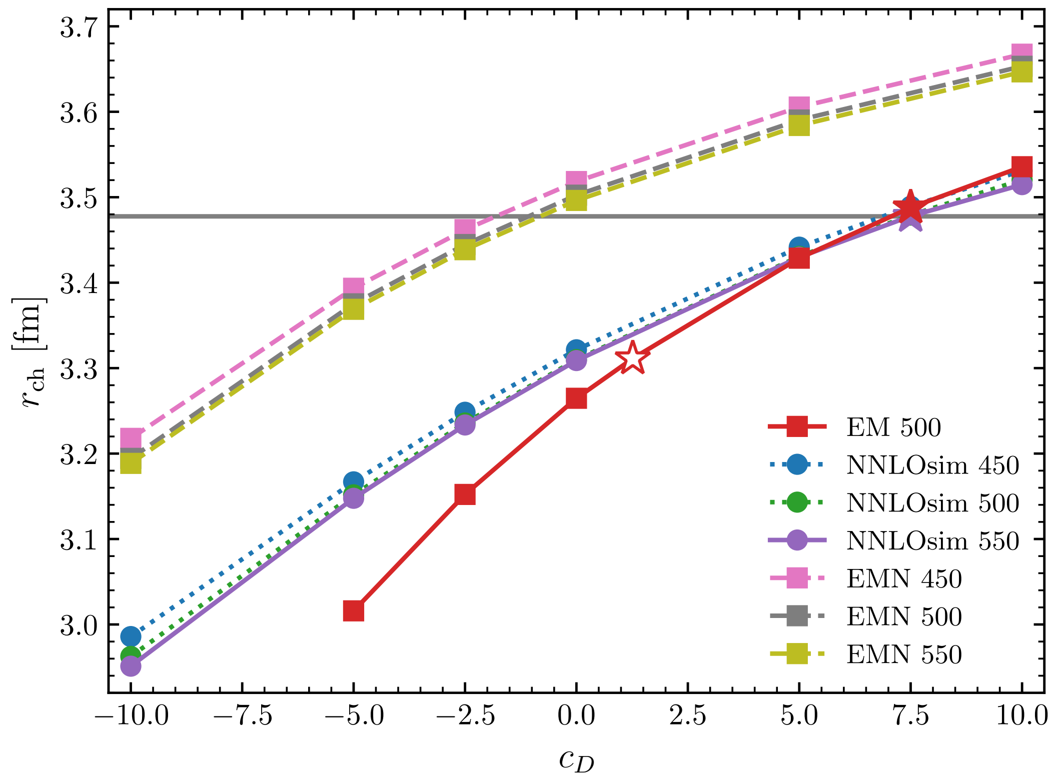
Charge radius

- Quasi-linear evolution with c_D
- $c_D = 7.5$ yields very good radius for NNLOsims and EM

[ARTHUIS, HEBELER, SCHWENK, ARXIV:2401.06675]

A CHECK AGAINST 40CA





Similar reproduction

- Excellent reproduction of binding energy for c_D = 7.5
- Almost unchanged picture for the charge radius

GROUND-STATE ACCURACY TOWARDS HEAVY SYSTEMS

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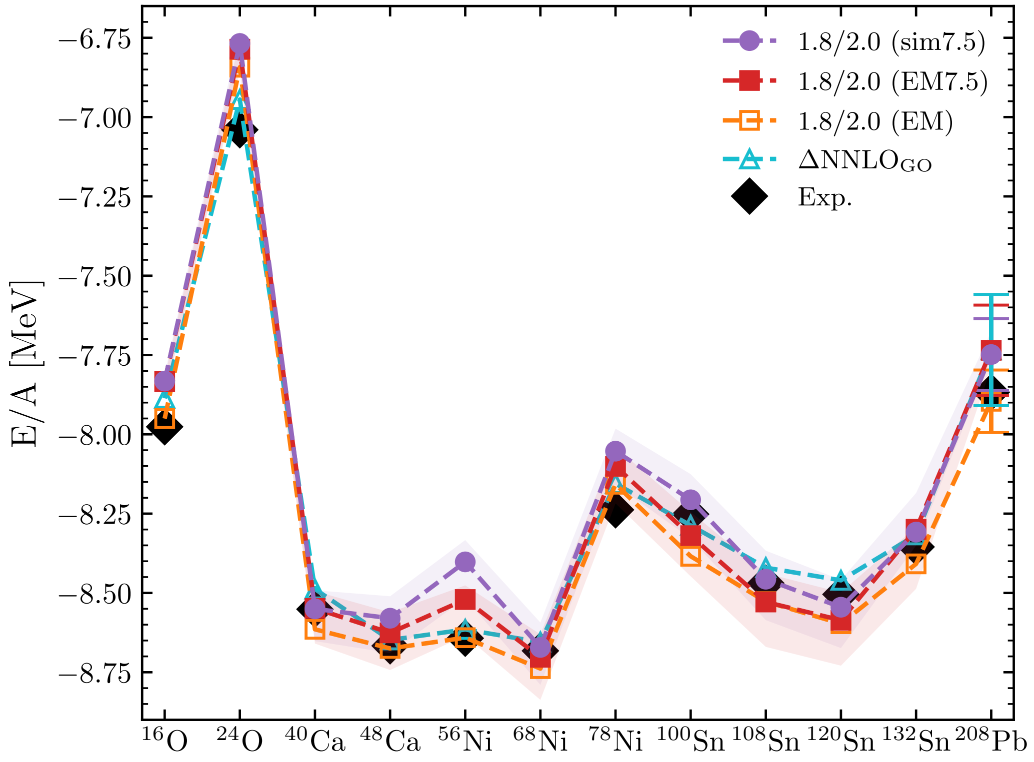

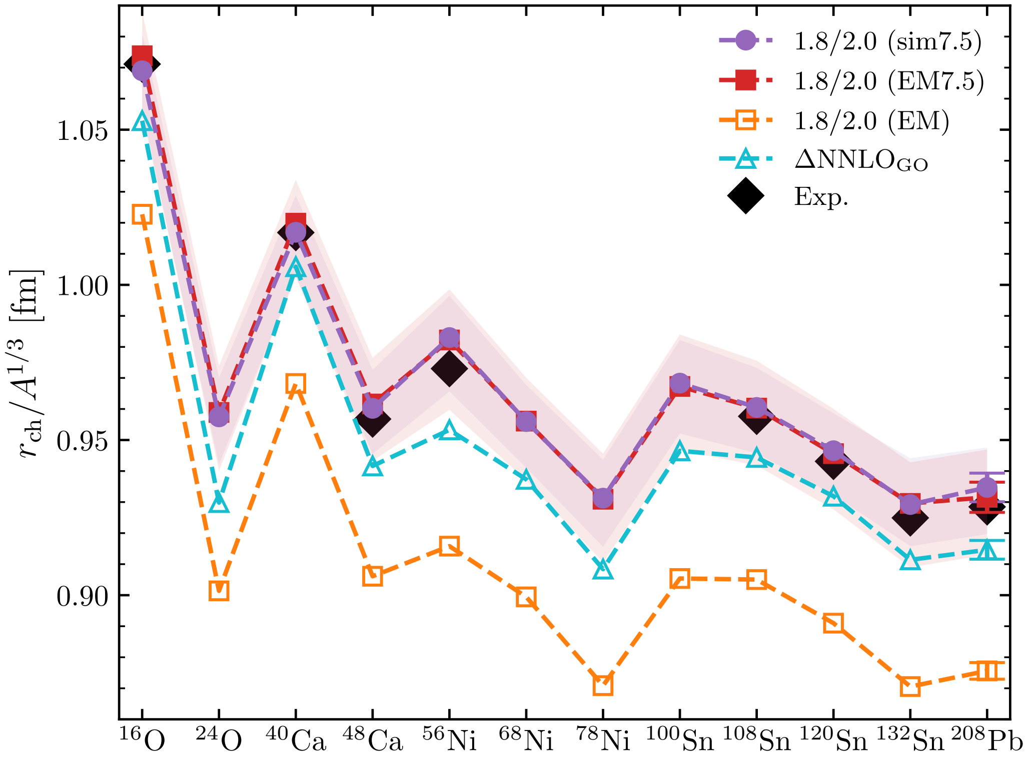

Binding energy

- Reasonable reproduction of experimental values
- Slight improvement for heavy systems w.r.t. 1.8/2.0 (EM)

Charge radius

- Quasi-exact reproduction over complete mass range
- Excellent combined reproduction of charge and mass

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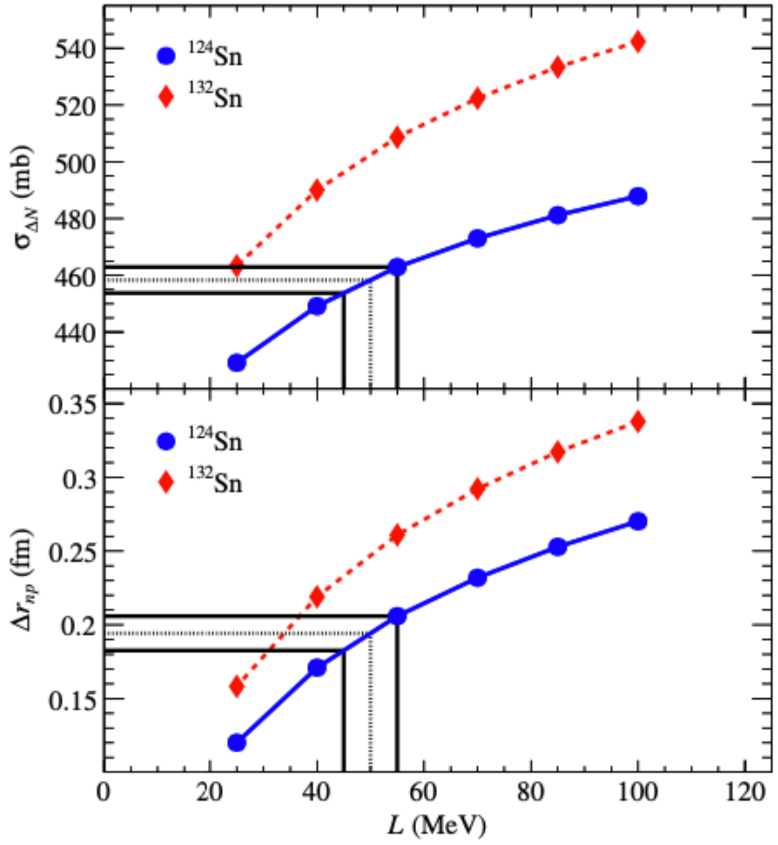
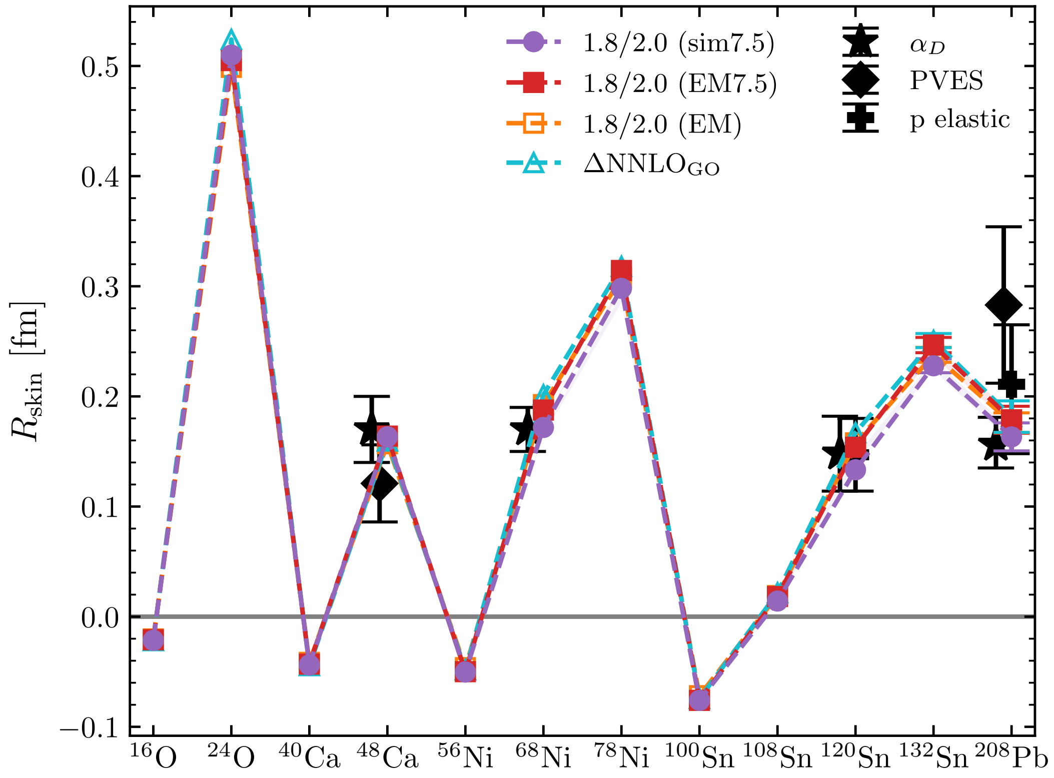
NEUTRON SKIN AND HEAVY SYSTEMS



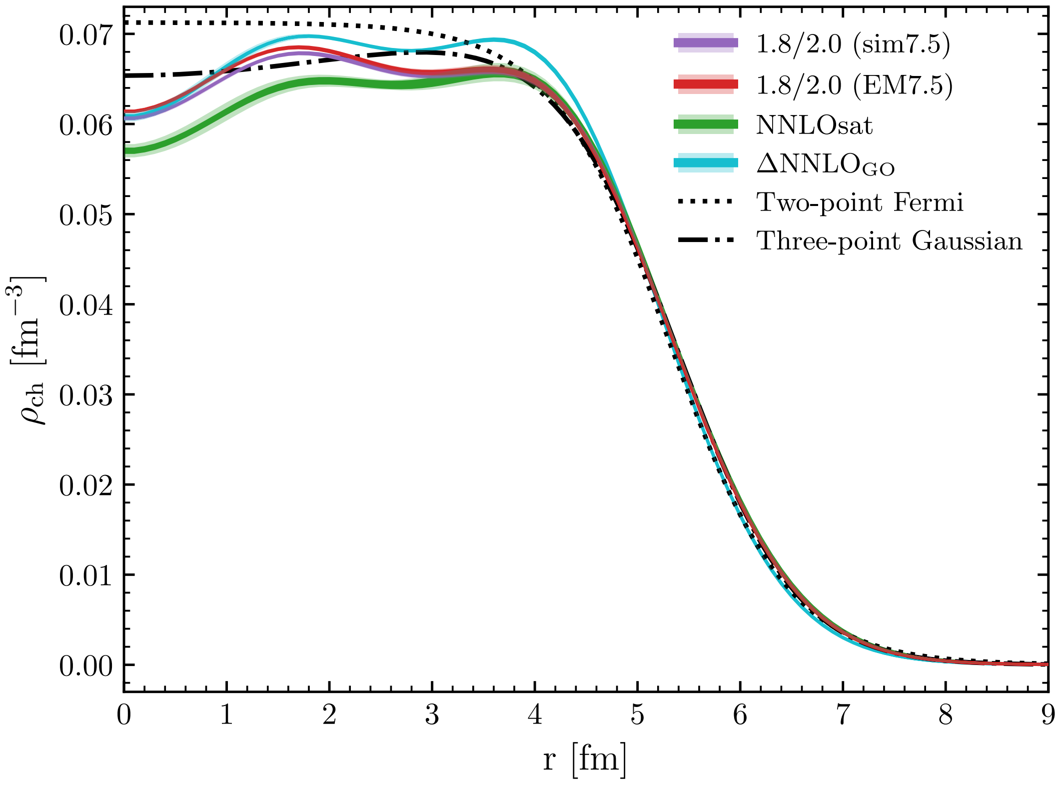
[Aumann *et al.*, *PRL* 119 (2017)]

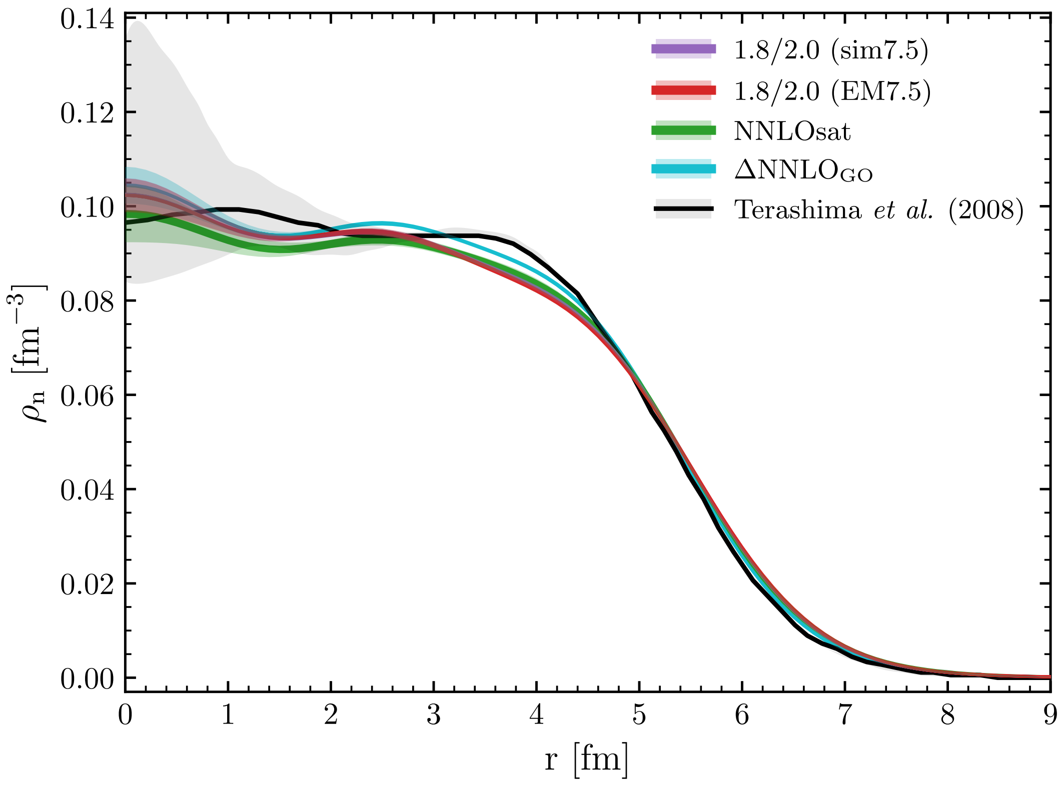
Neutron removal off Sn isotopes @ R3B/GSI

- Access L through the cross-section, need for theory input
- L correlated to neutron skin too: Great test case



AB INITIO DENSITIES FOR HEAVY SYSTEMS: 120SN

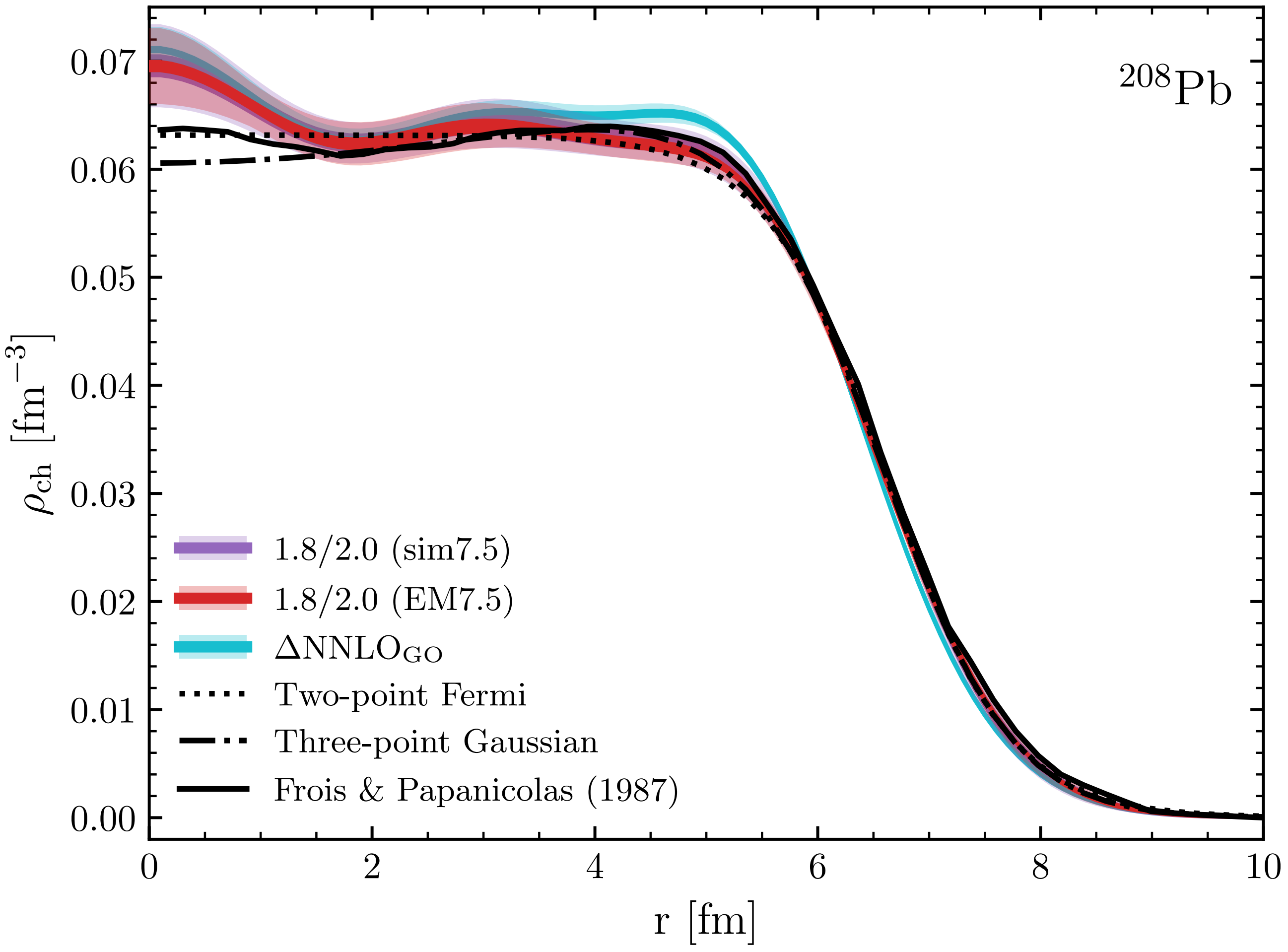




Excellent reproduction of ^{120}Sn densities

- Consistent picture over the different interactions
- Very moderate uncertainties

AB INITIO DENSITIES FOR HEAVIER SYSTEMS: 208PB



Charge density for ^{208}Pb

- Consistent picture over the different interactions
- 1.8/2.0s give excellent surface profile

1.8/2.0s consistent over the nuclear chart

ON NEUTRON SKINS

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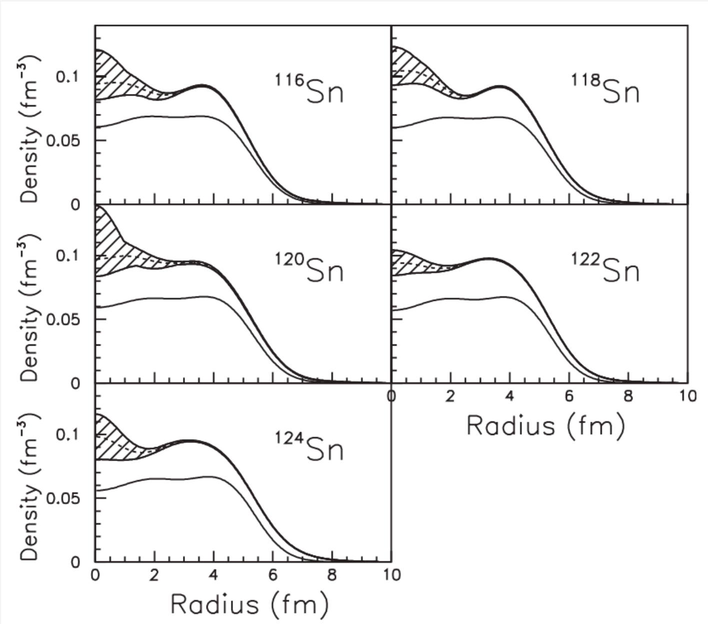
Evolution w.r.t. isospin

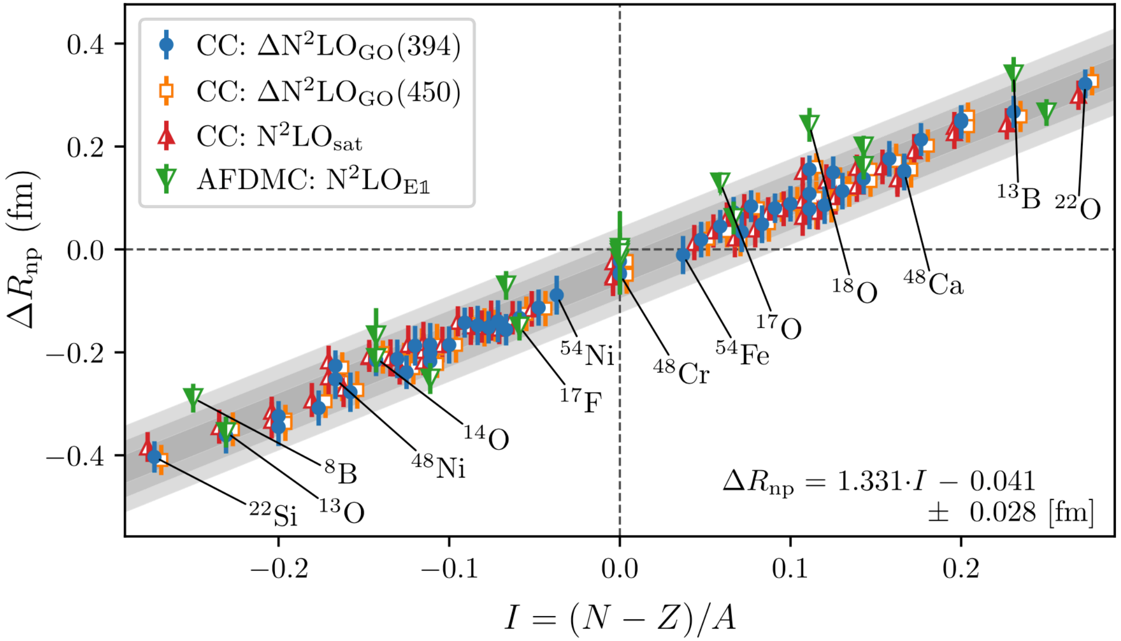


[Terashima *et al.*, *PRC* **77** (2008)]

Liquid droplet model

$$R_{\text{skin}} \propto \frac{2r_0}{3} \frac{S_S}{S_V + S_S A^{-1/3}} \frac{\mathrm{N-Z}}{\mathrm{A}}$$

Linear relation confirmed on *ab initio* basis



[Novario *et al.*, *PRL* **130** (2023)]

[ARTHUIS, HEBELER, SCHWENK, ARXIV:2401.06675]

NEUTRON SKINS IN NEUTRON-RICH ISOTOPES

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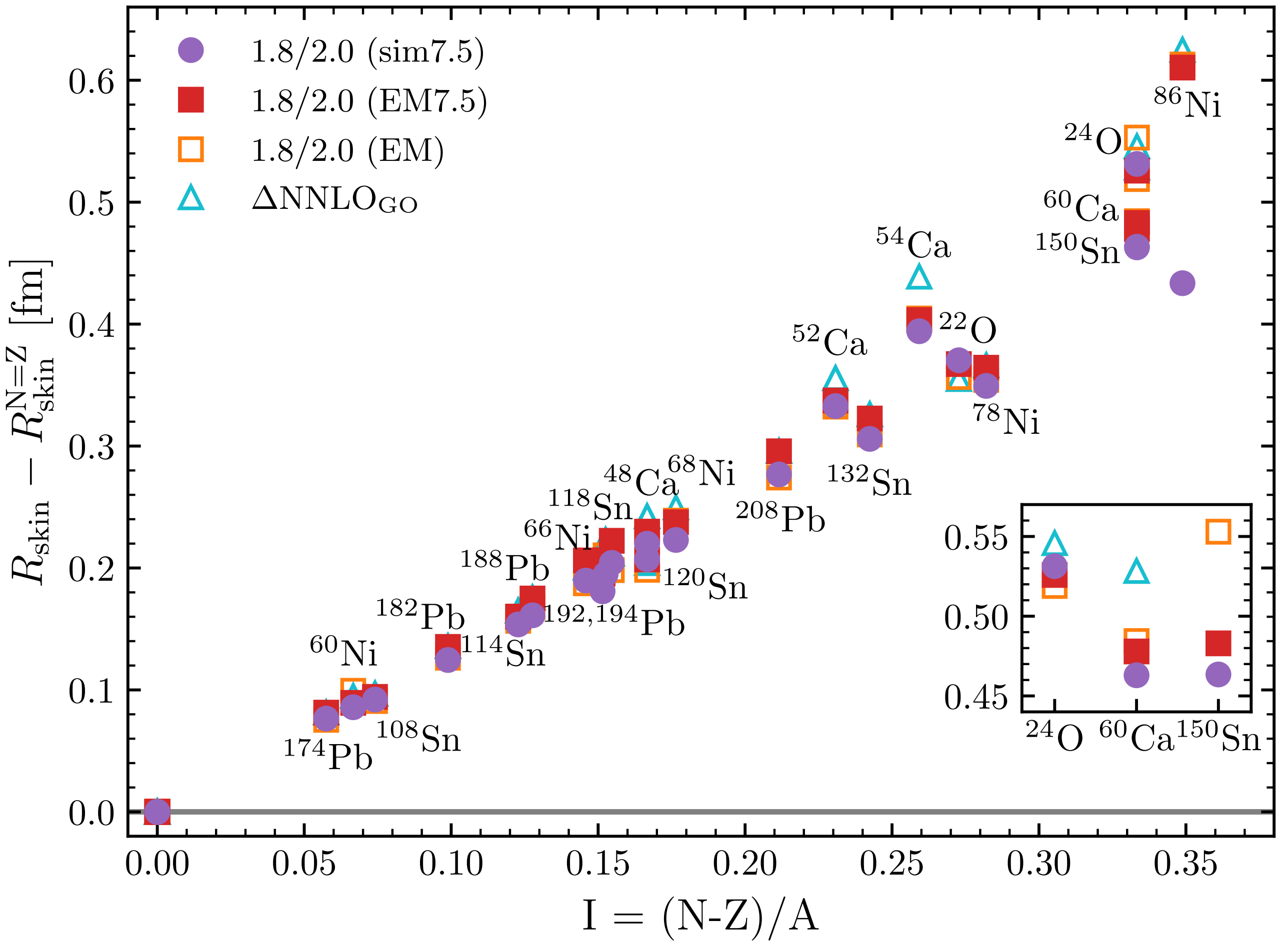

Evolution w.r.t. isospin

- Linear dependance confirmed in valley of stability
- Neutron-rich nuclei exhibit stronger dependence
- Highlight importance of interaction

Good physics cases to explore

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CONCLUSION AND OUTLOOK

Accurate interactions over the nuclear chart

- Novel interactions with good convergence properties
- Very good reproduction of binding energy, radii, neutron skins
- Now to extend to open-shell nuclei and infinite matter

Neutron skin dependence on isospin

- Enhanced dependance on system at the most neutron-rich
- Highlight differences in the interactions
- Neutron-rich nuclei to be more accessible with new RIB facilities

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Thank your for your attention!

SFB 1245

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