AB INITIO NUCLEAR DENSITIES FROM LOW-RESOLUTION INTERACTIONS

Pierre Arthuis

Funded by
the European Union

From the LEES workshop to sake lees

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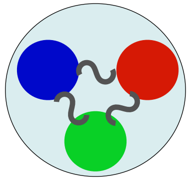
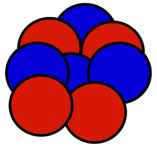
Or how sometimes it is good to leave time for things to precipitate

Ab initio many-body scheme



Particle physics

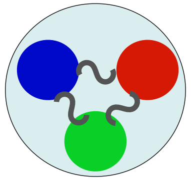
No direct application of
quantum chromodynamics
(Lattice QCD only for few nucleons)



Nuclear theory

3

Ab initio many-body scheme



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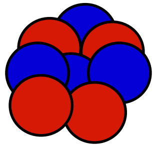


Nuclear theory

Interactions anchored in Effective Field Theory

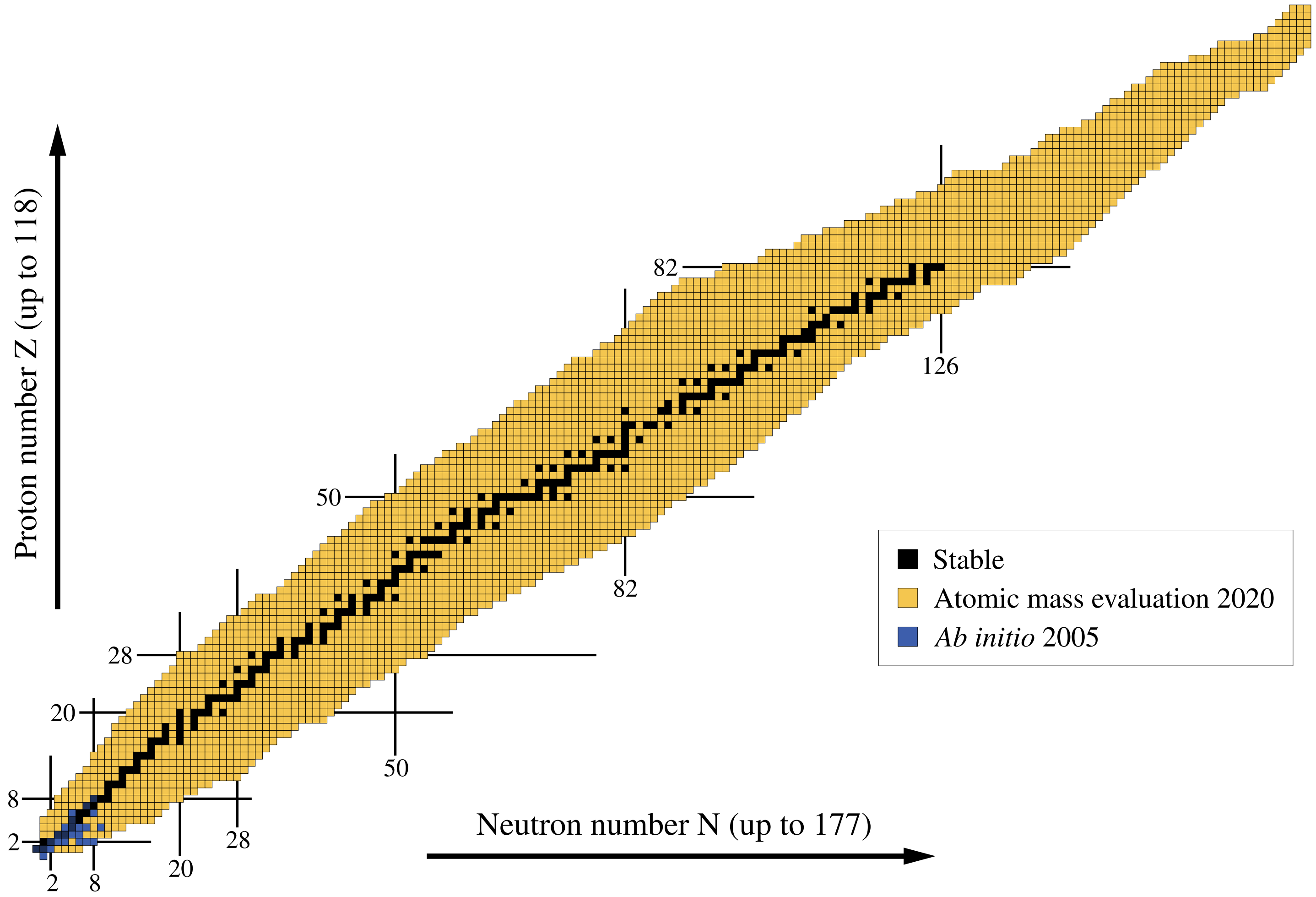
A-body Schrödinger equation

$$H|\Psi^A\rangle = E^A|\Psi^A\rangle$$

Obtain a description that is:

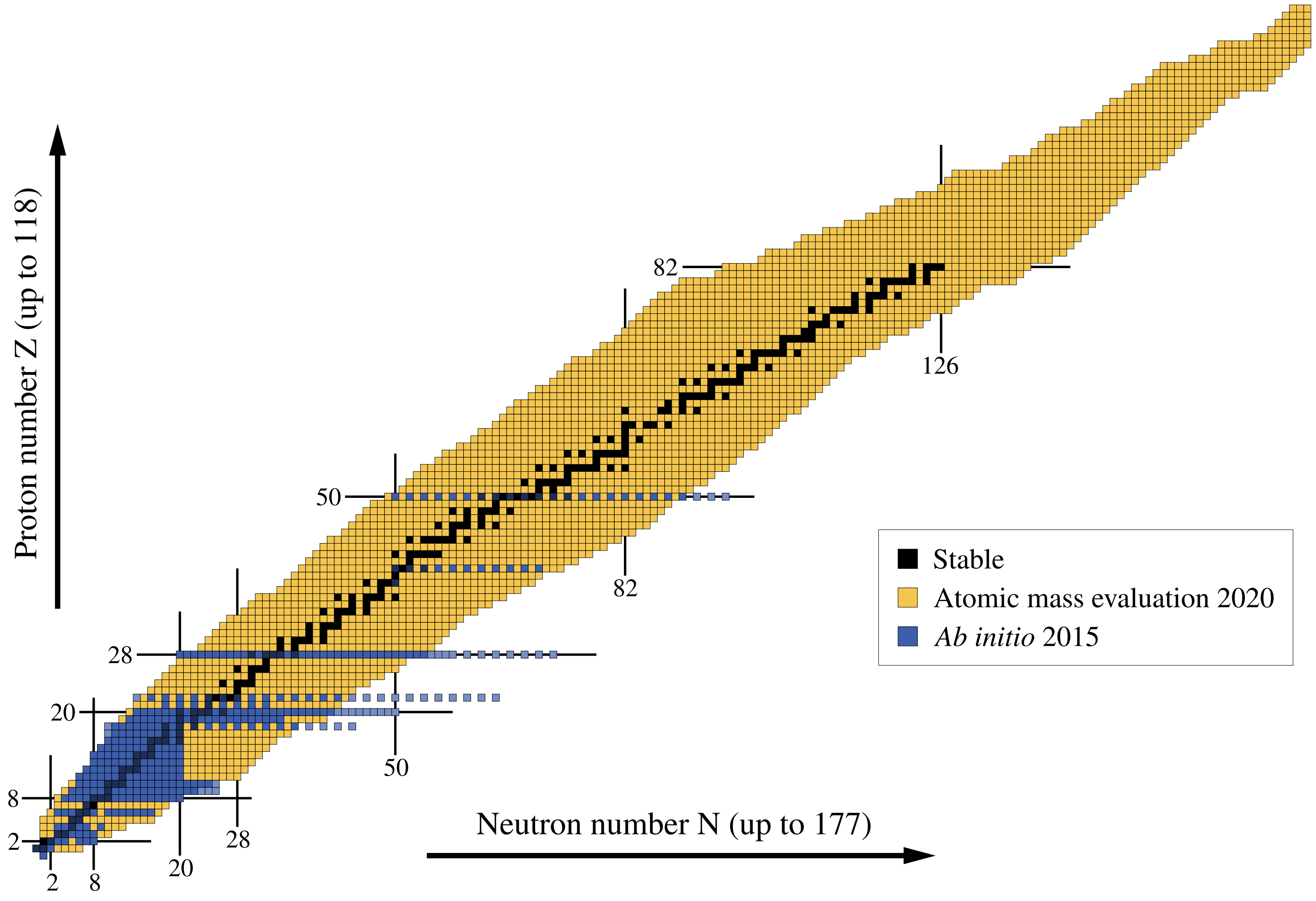
- Consistent
- Systematic
- Accurate enough
- From inter-nucleon interactions
- Rooted in quantum chromodynamics

Ab initio many-body methods range



Adapted from B. Bally

Ab initio many-body methods range



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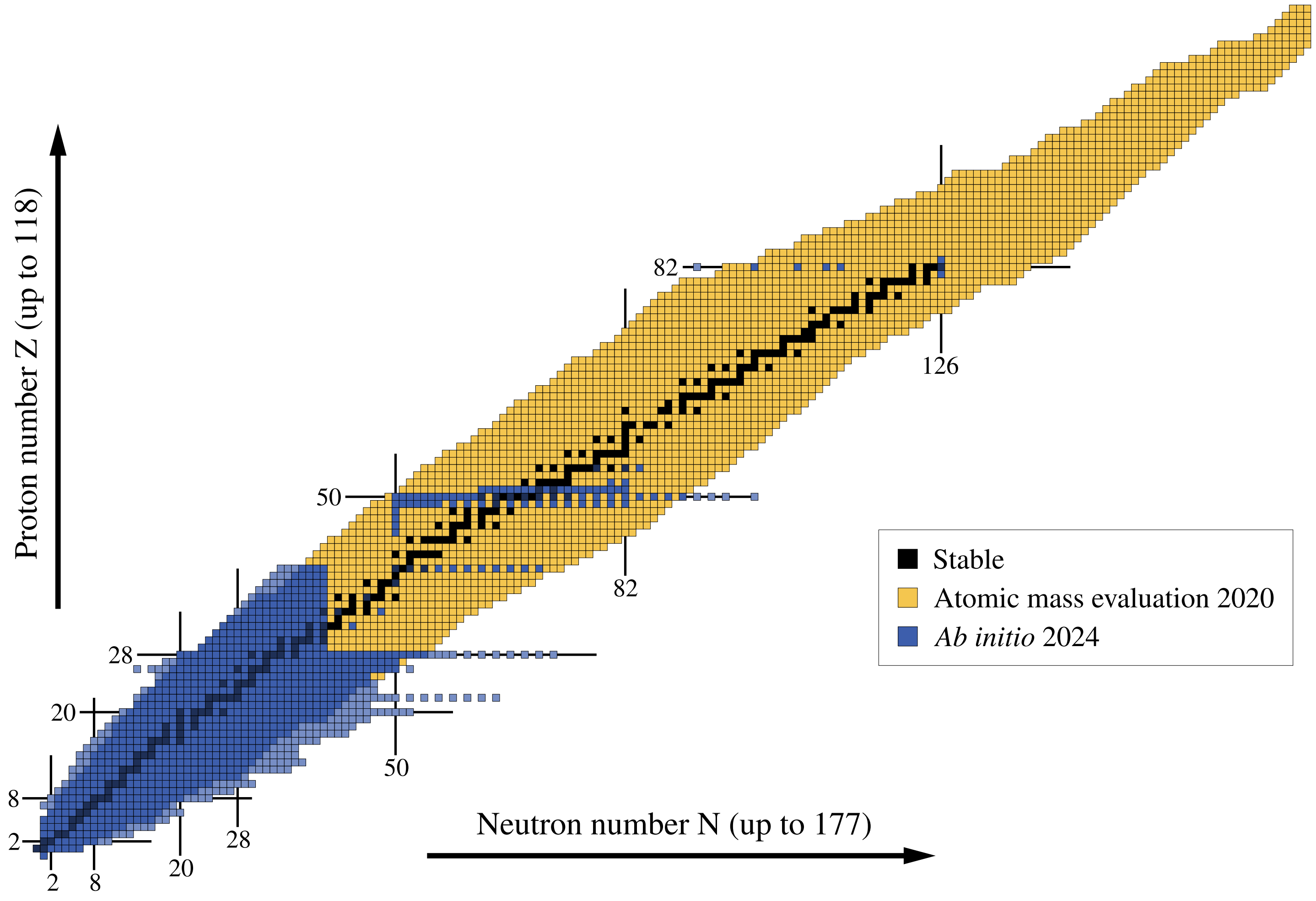

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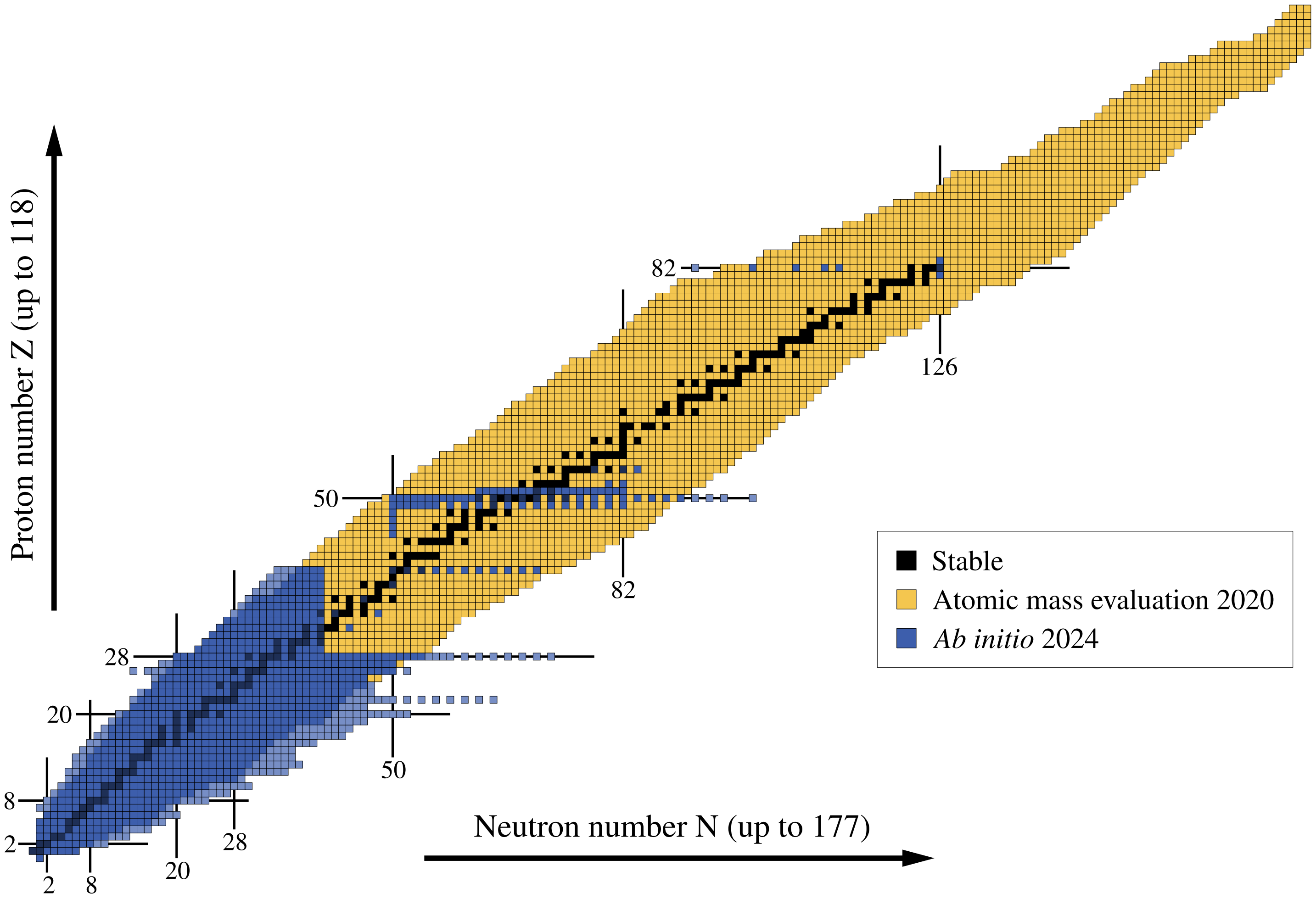

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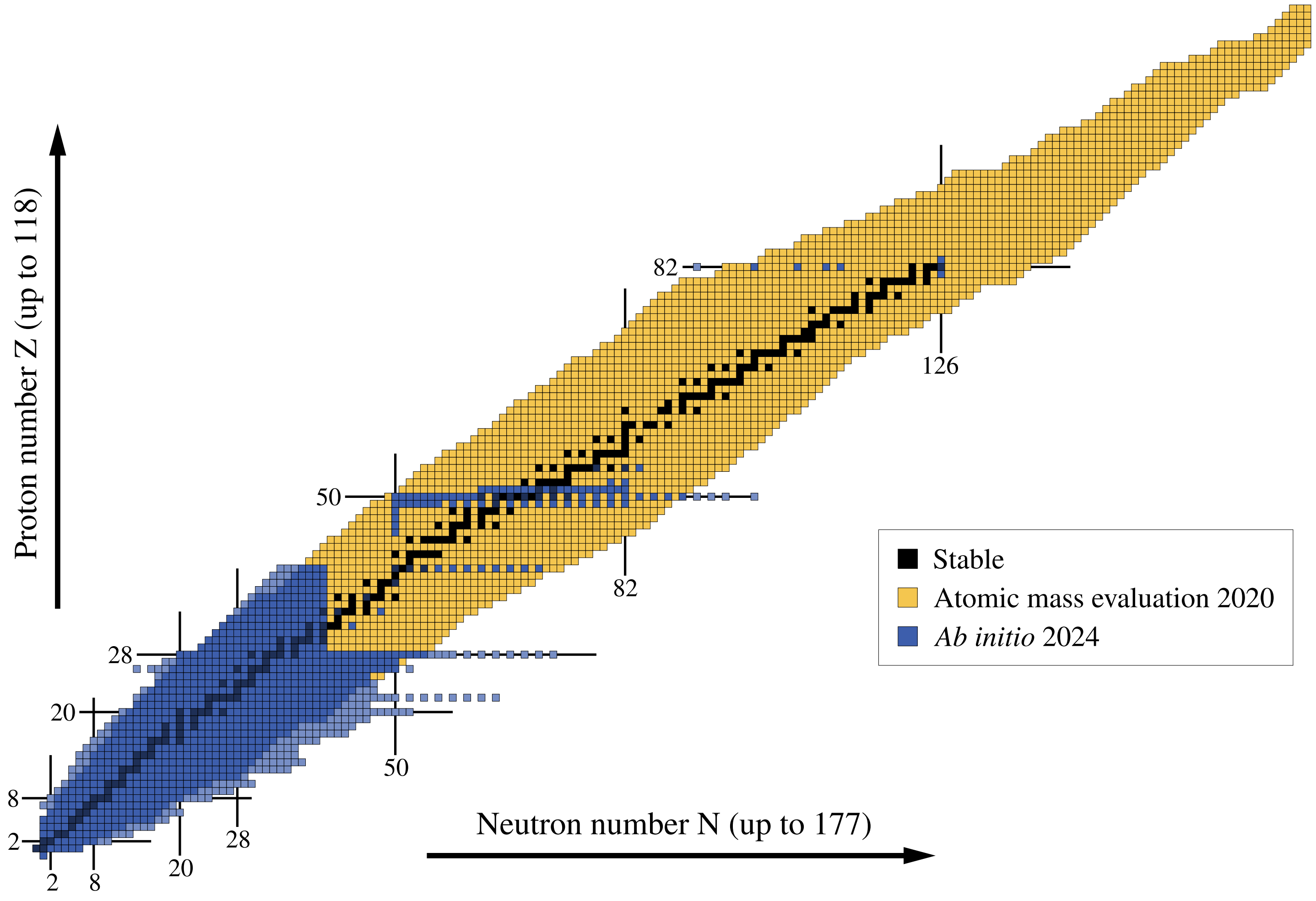
Expansion methods

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

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

Controlled expansion & uncertainty

Moderate cost



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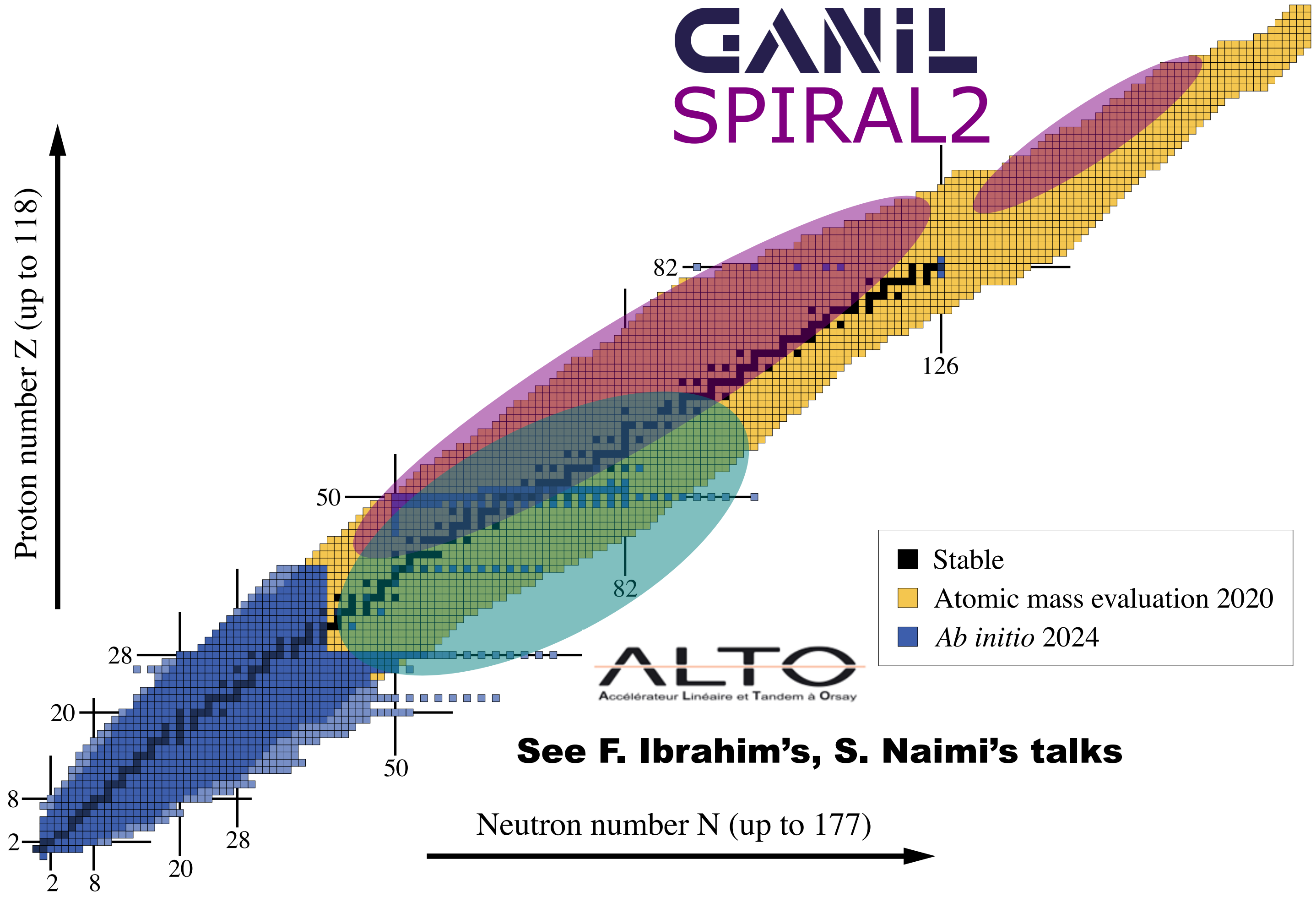
A look at experimental facilities

See V. Lapoux' talk



See F. Ibrahim's, S. Naimi's talks

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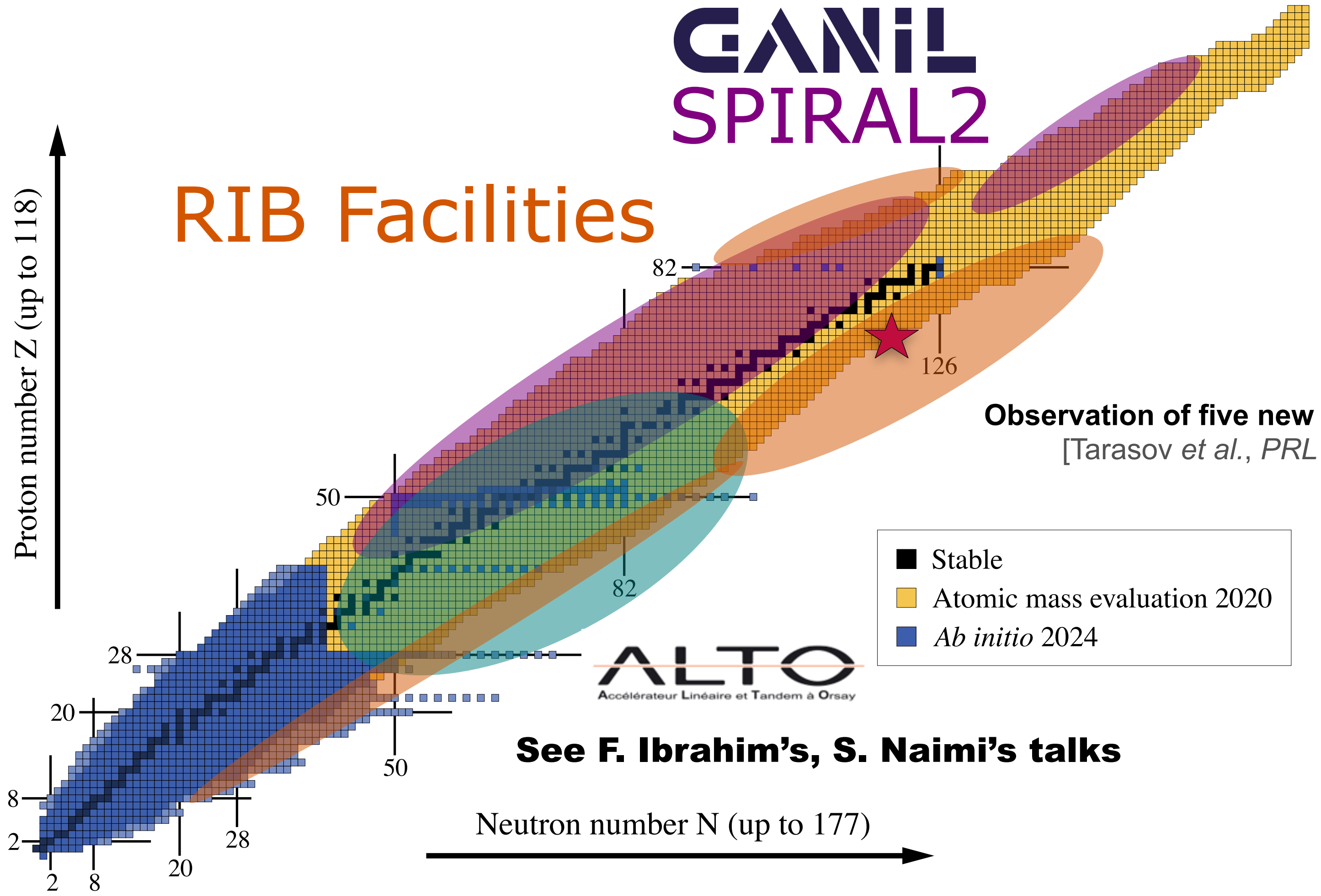
GANIL SPIRAL2

RIB Facilities



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

ALTO
Accélérateur Linéaire et Tandem à Orsay

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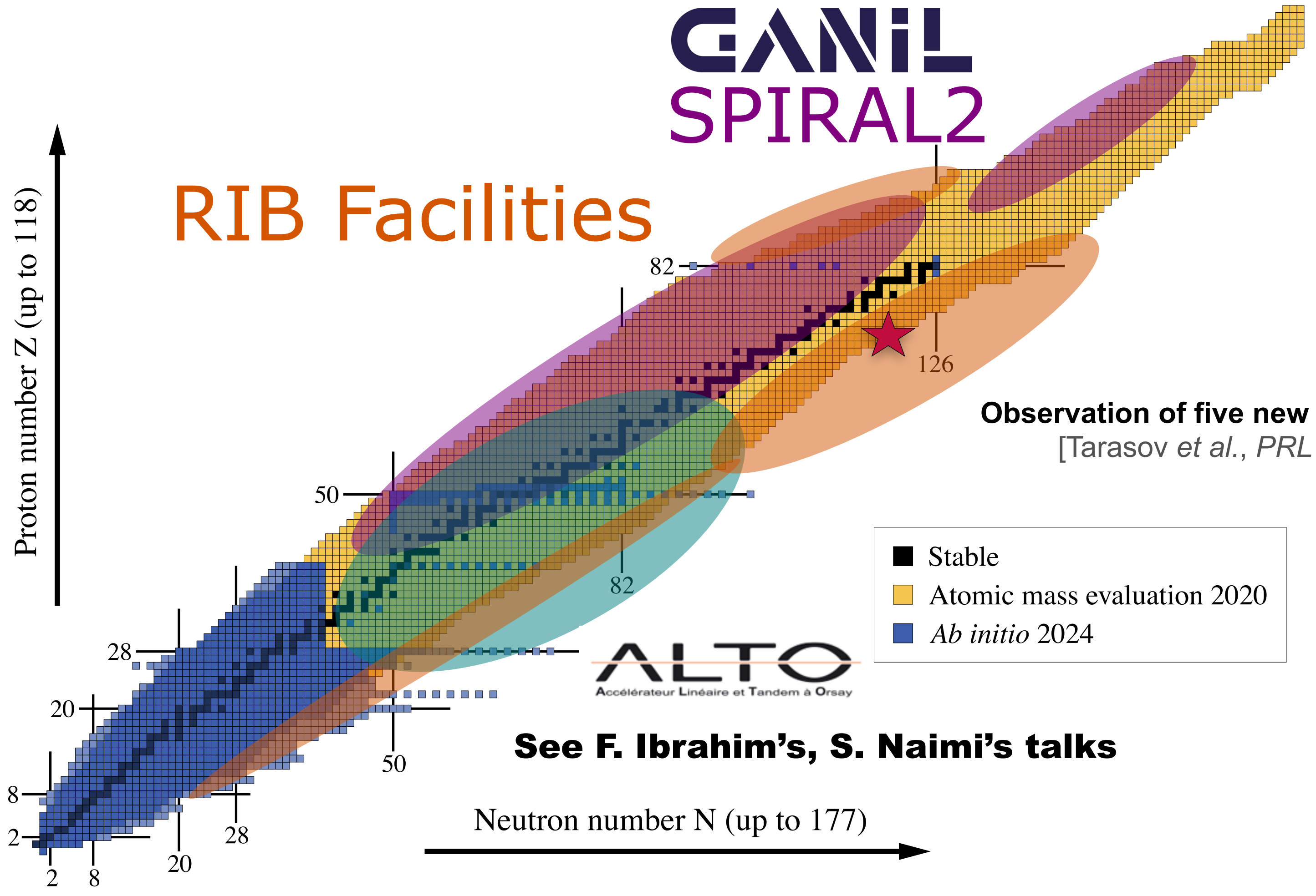

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New era of shared effort

Heaver nuclei

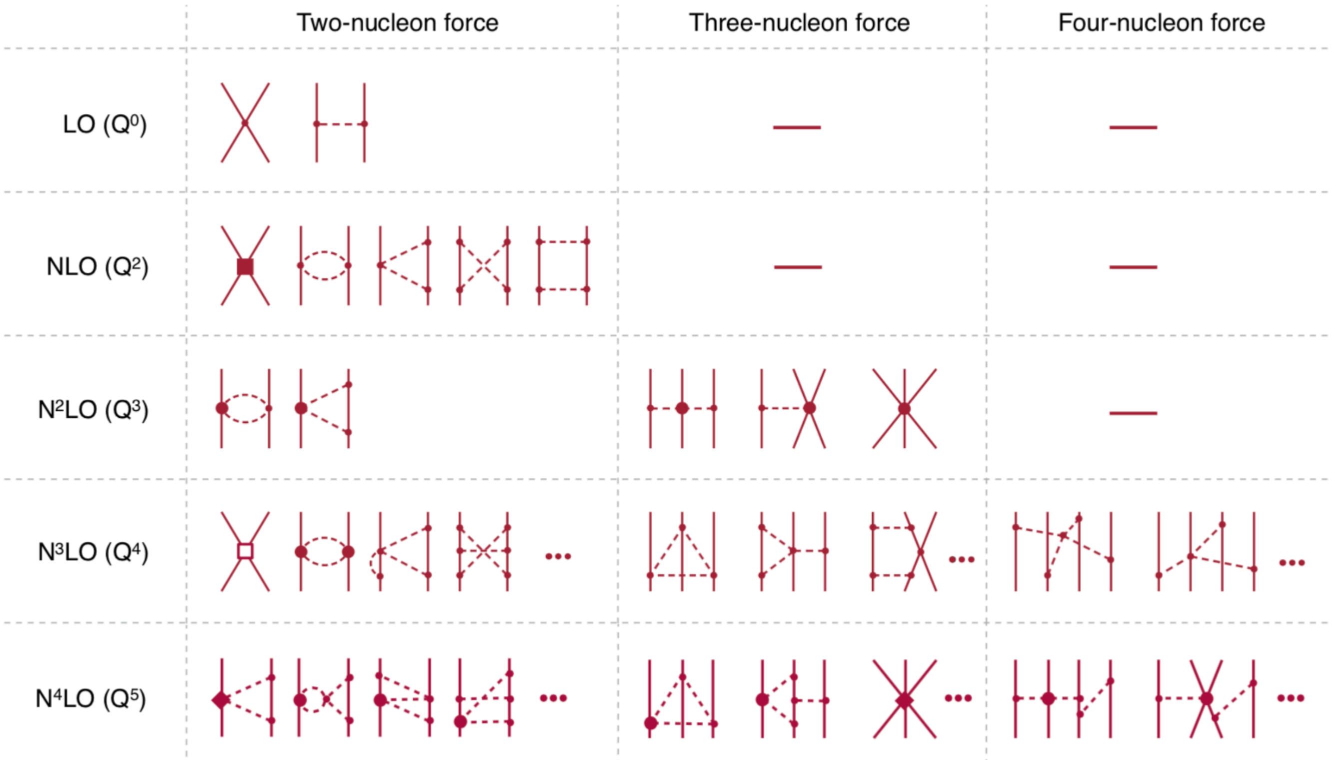
More exotic nuclei

A look at chiral interactions

Rationale

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

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



[Epelbaum, *PoS* CD15 (2016)]

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A look at chiral interactions

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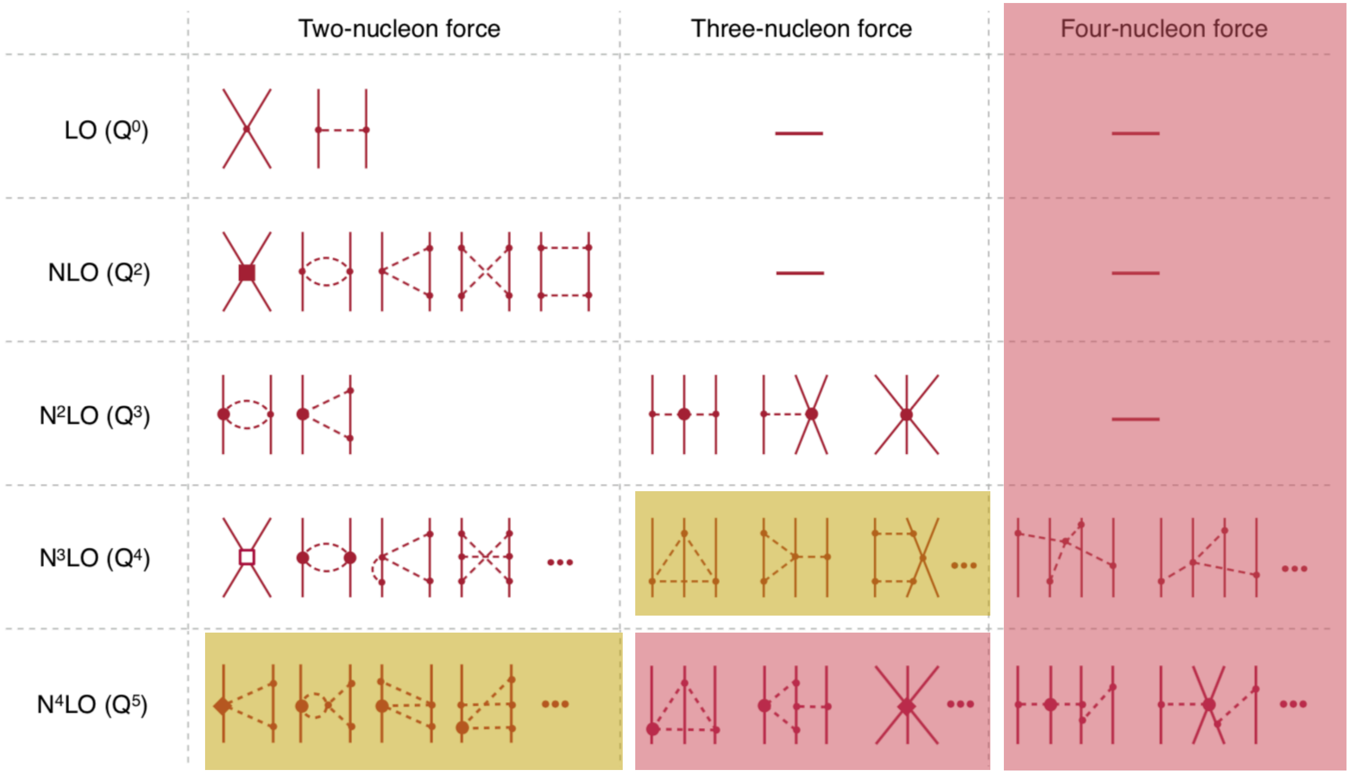
In practice

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



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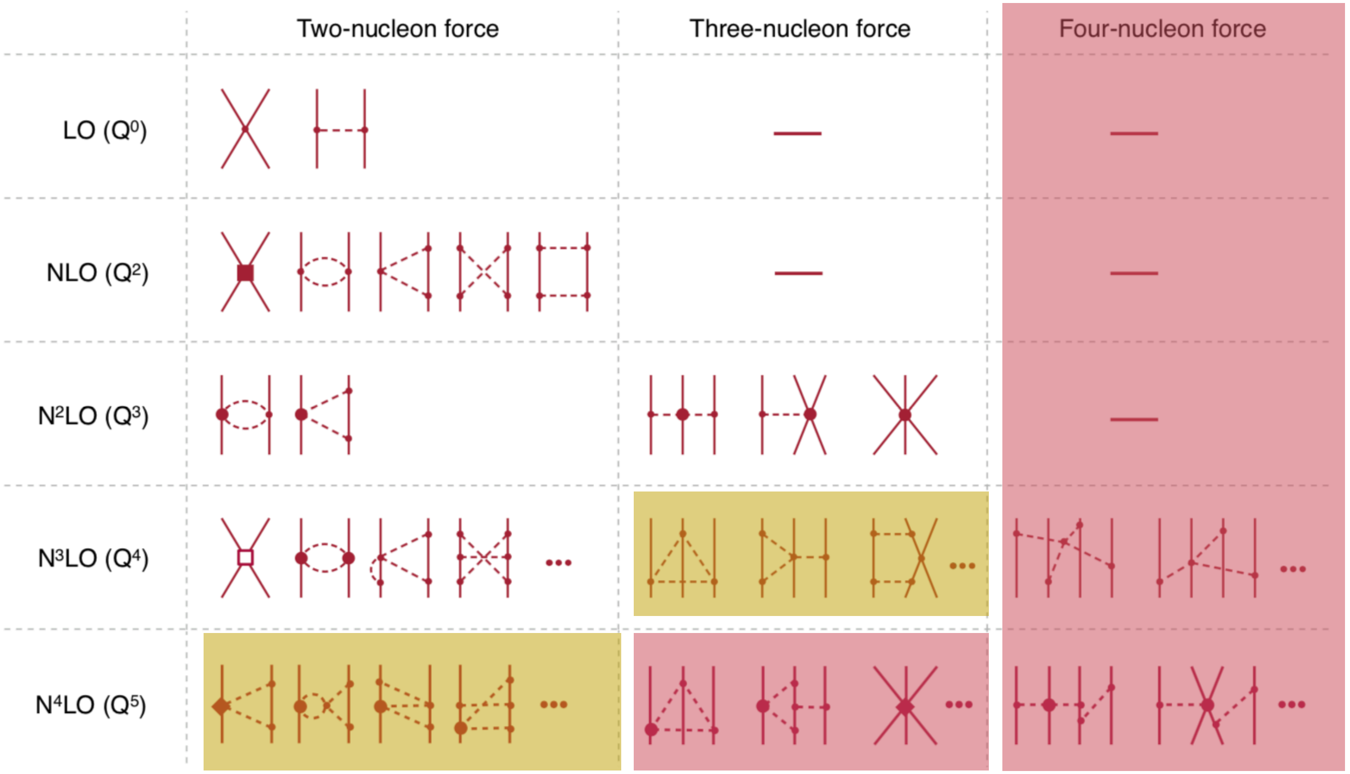
Footnote: Similar expansion with Δ excitation



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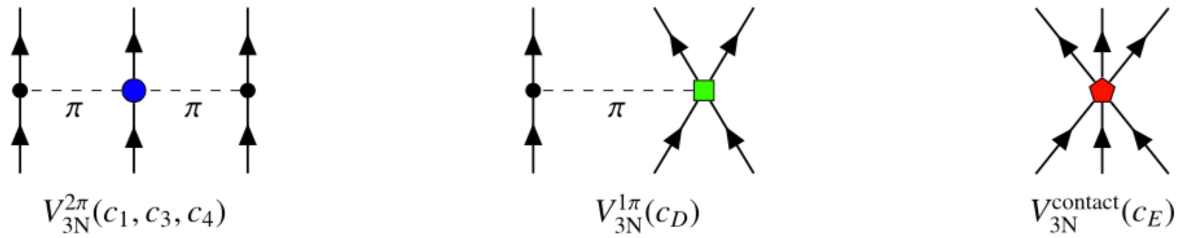
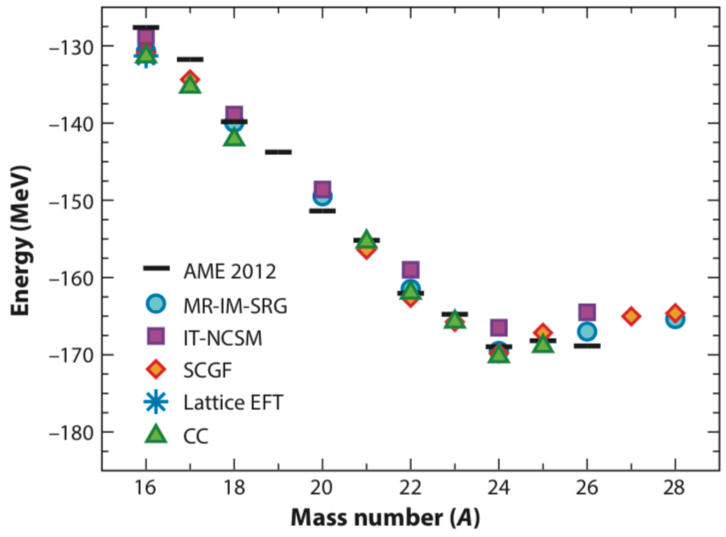
The leading three-body force

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)]



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Practical aspects

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

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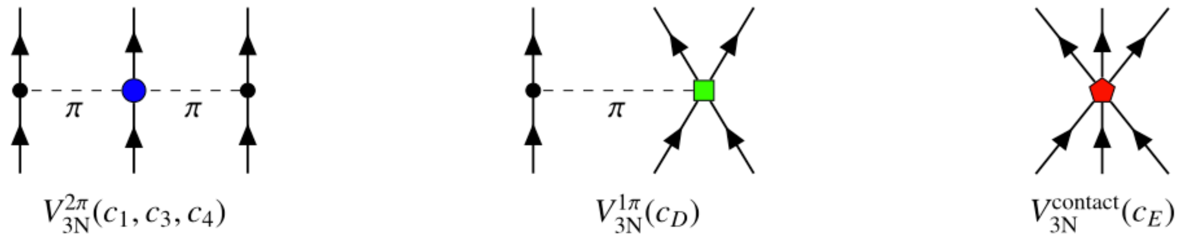

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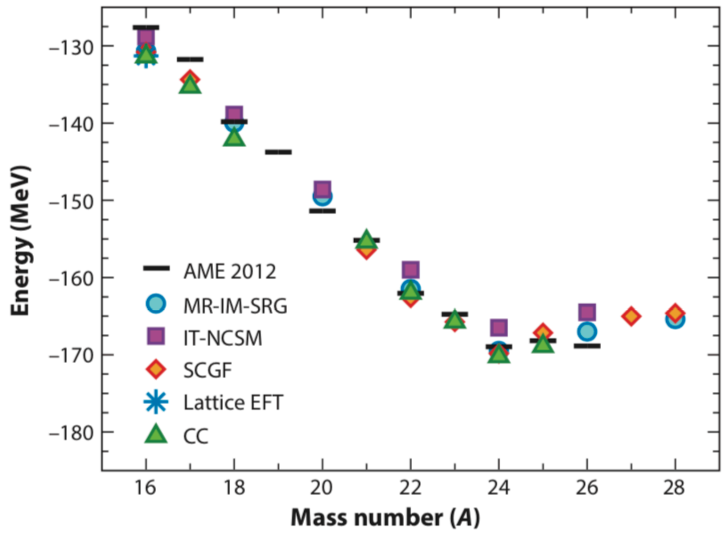


[Hebeler *et al.*, *Annu. Rev. Nucl. Part. Sci. 65* (2015)]

Practical aspects

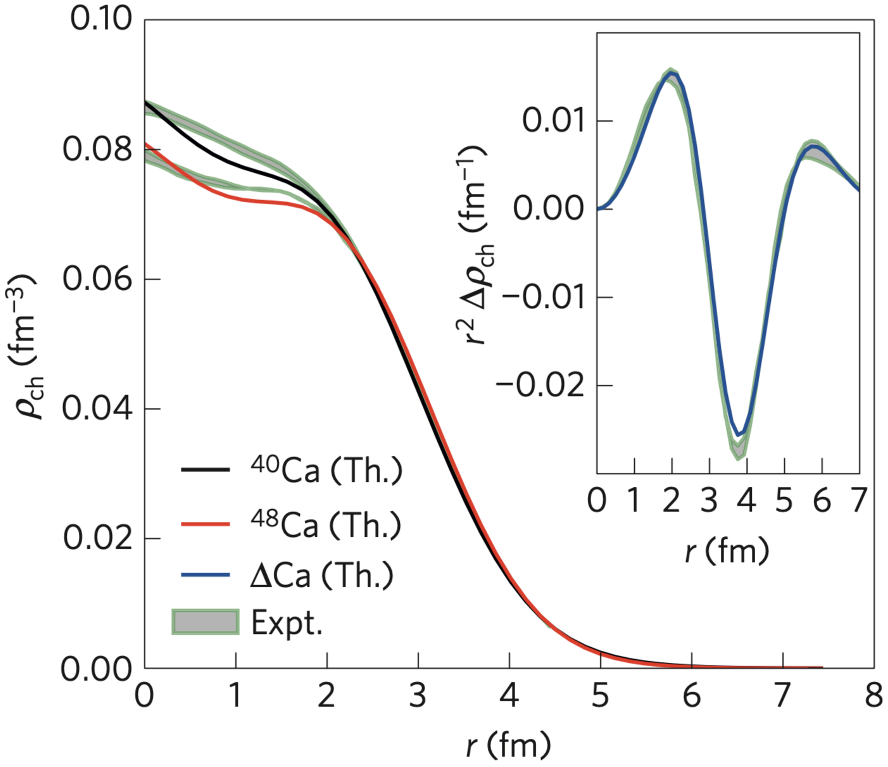
- Most often fitted in the 3N sector
- Bring repulsion necessary for a good qualitative description

A good reproduction of all nuclear properties is hard

Some early ab initio densities with NNLOsat

Charge densities of ^{40}Ca and ^{48}Ca

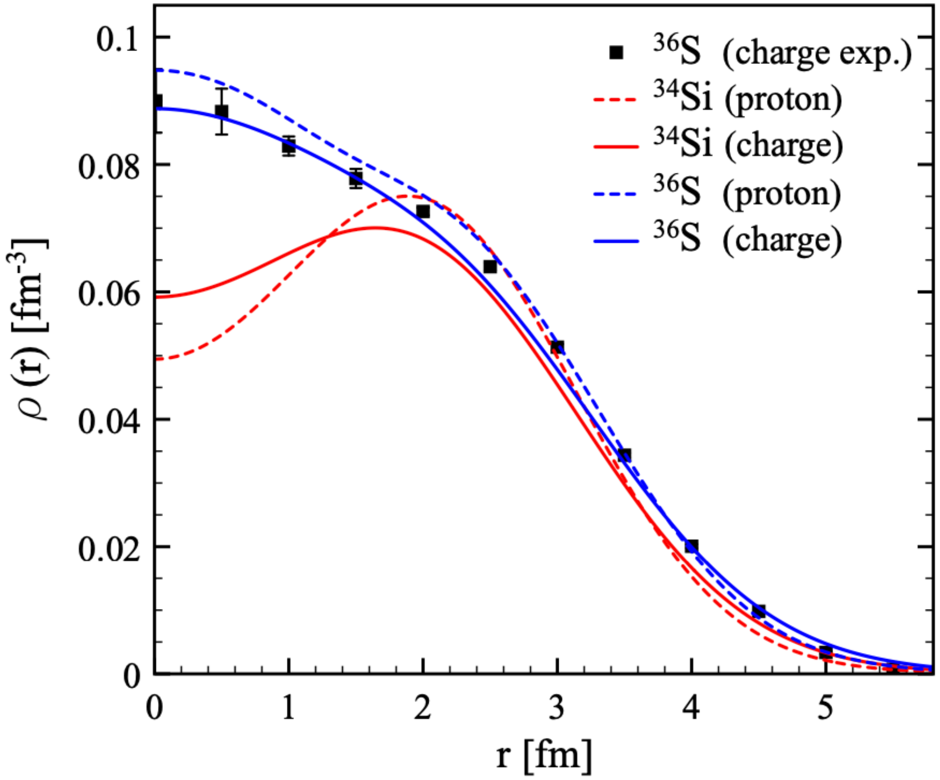
- First established NNLOsat as accurate interaction for ρ
- Connection to weak charge radius, R_{skin} and α_D



[Hagen *et al.*, *Nat. Phys.* **12** (2015)]

Study of candidate bubble nucleus ^{34}Si

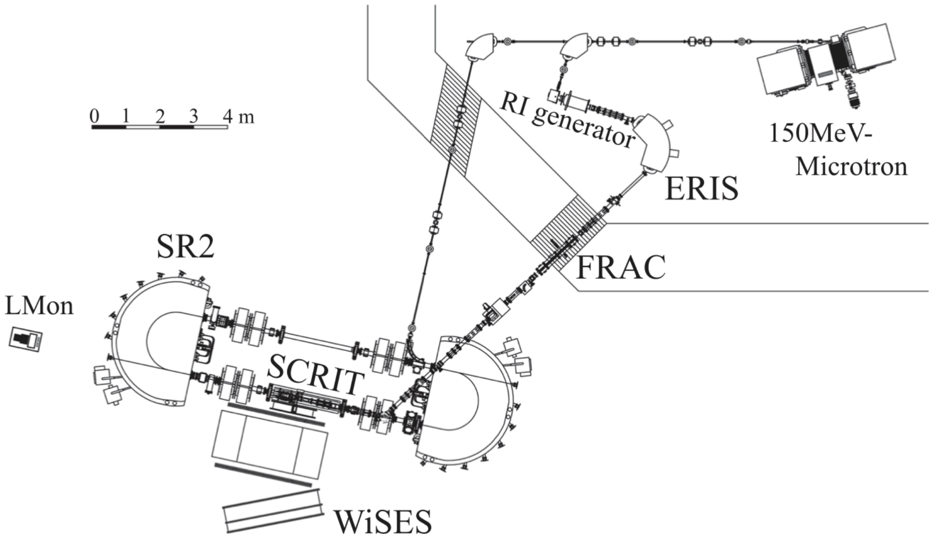
- Investigation of the central depletion in ^{34}Si
- Link to details of the interaction and s.p. structure

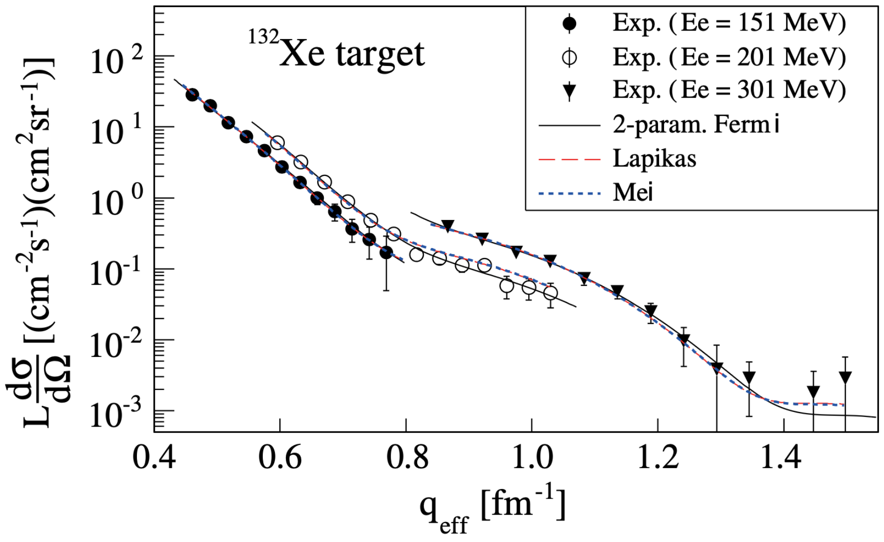


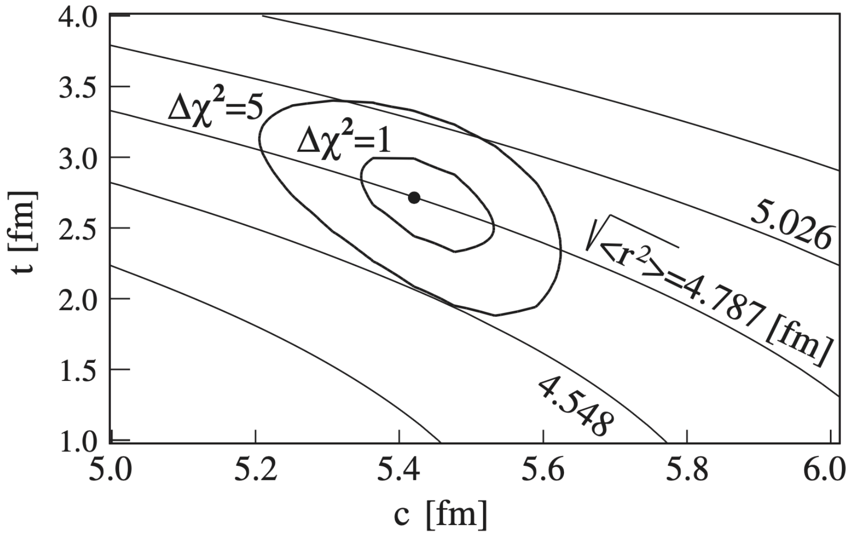
[Duguet *et al.*, *PRC* **95** (2017)]

2017: First SCRIT results

[Tsukada, Enokizono, Ohnishi, *et al.*, *PRL* **118** (2017)]







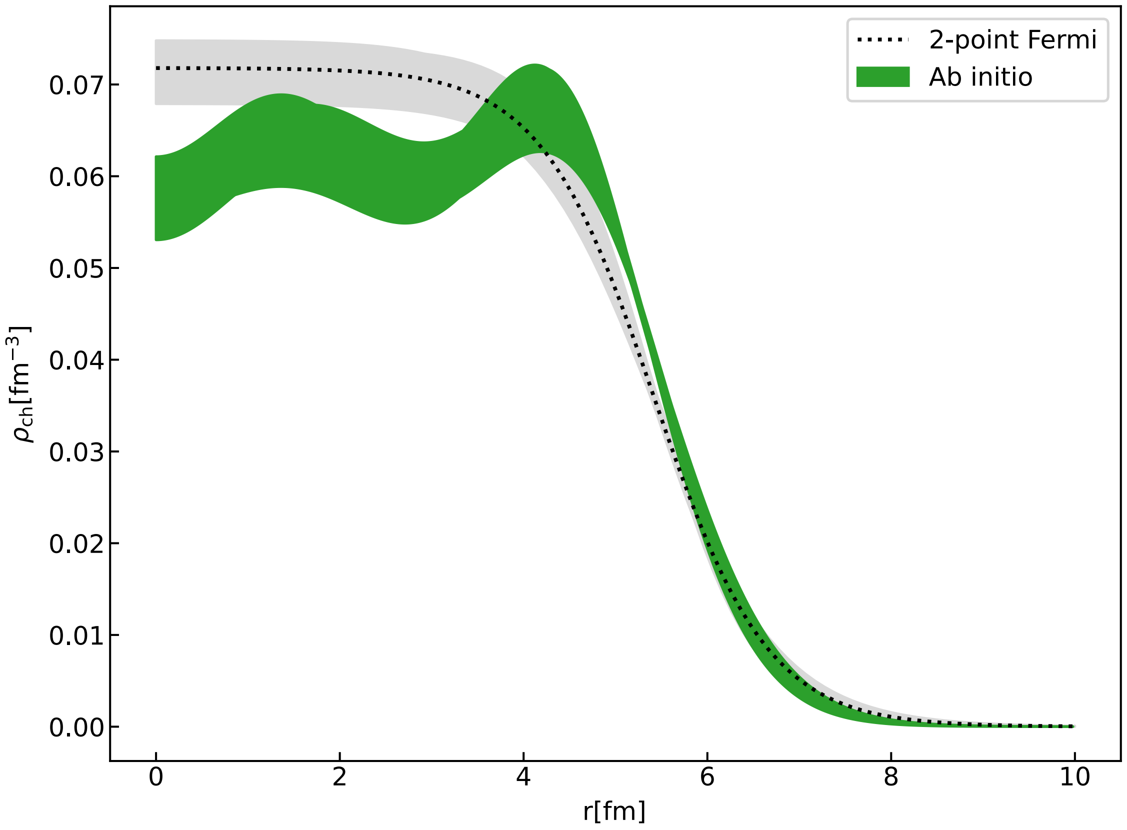
Scattering off ^{132}Xe

- Strong motivation to try and push our reach towards higher masses
- Radius and two-point Fermi extracted from the experiment

Charge density distributions

^{132}Xe charge density distribution with NNLOsat

- Radius compatible with experiment: 4.824 ± 0.124 fm
  [Tsukada *et al.*, *PRL* **118** (2017)]: $4.79^{+0.12}_{-0.10}$ fm
- NN+3N(lnl) severely underpredicts: 4.070 ± 0.045 fm
- 2-point Fermi distribution insufficient to describe expected behaviour

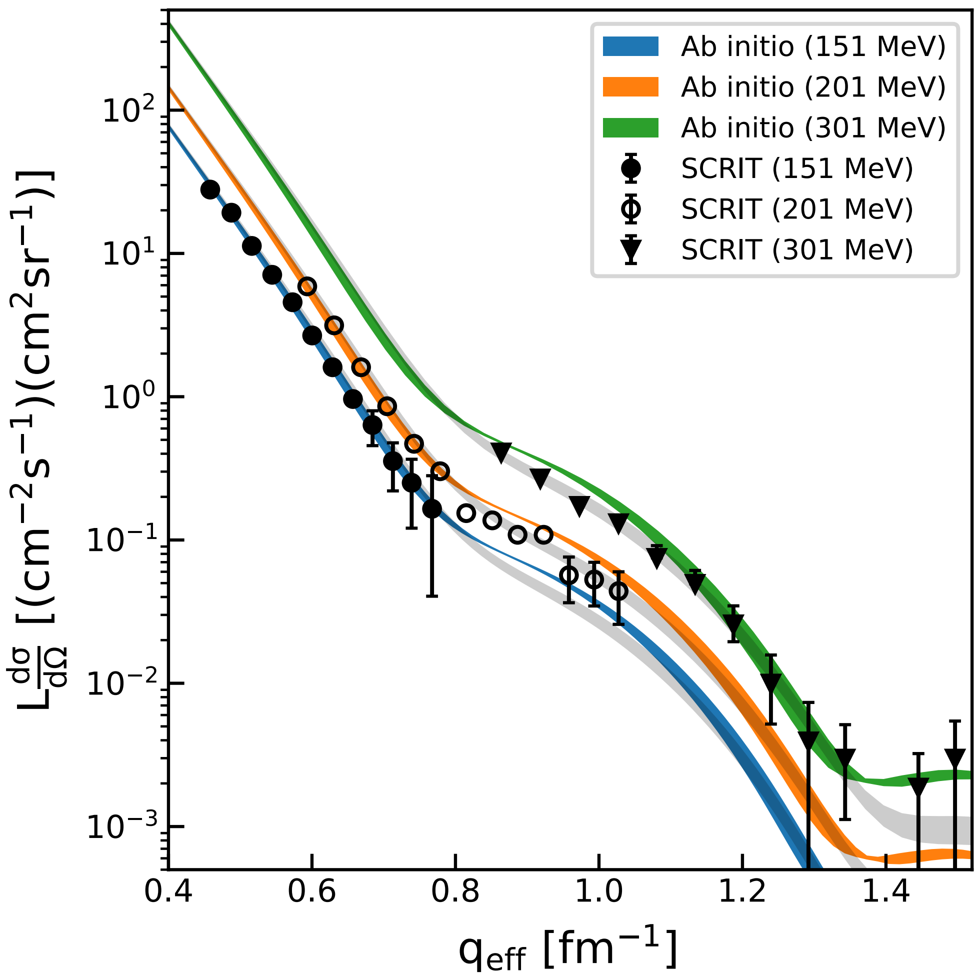


Uncertainty band

- Mainly model-space convergence uncertainty (truncated 3NF)
- Many-body method basically converged
- Not included: Chiral EFT uncertainty

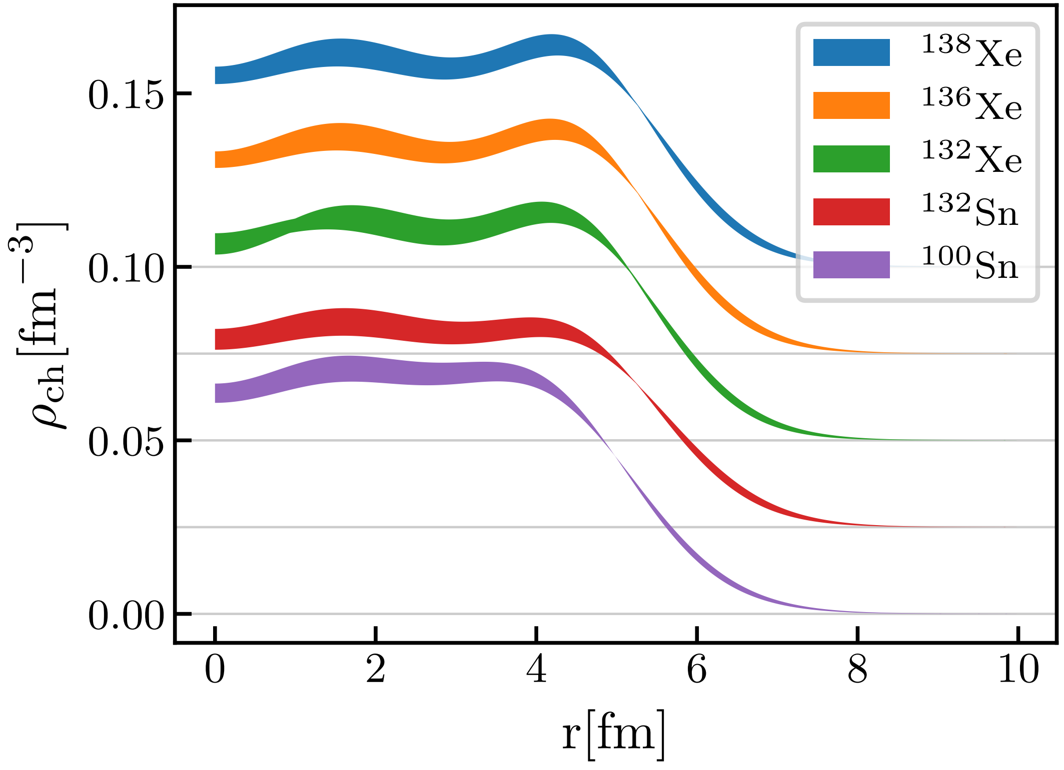
Electron scattering on ^{132}Xe at SCRIT

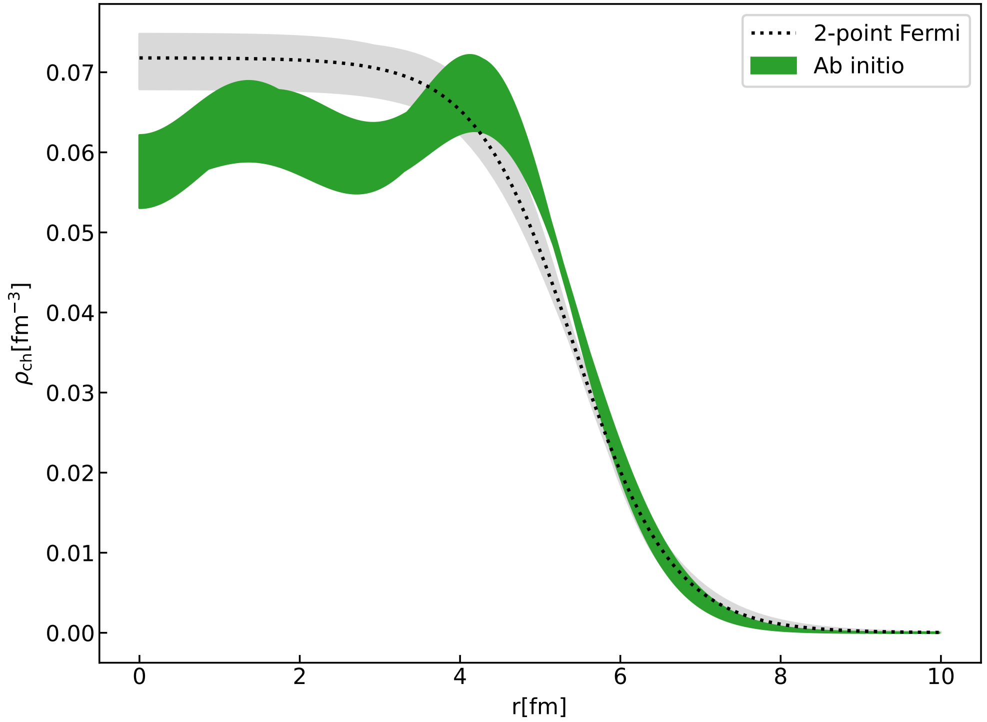
[Arthuis, Barbieri, Vorabbi, Finelli, *PRL* **125** (2020)]

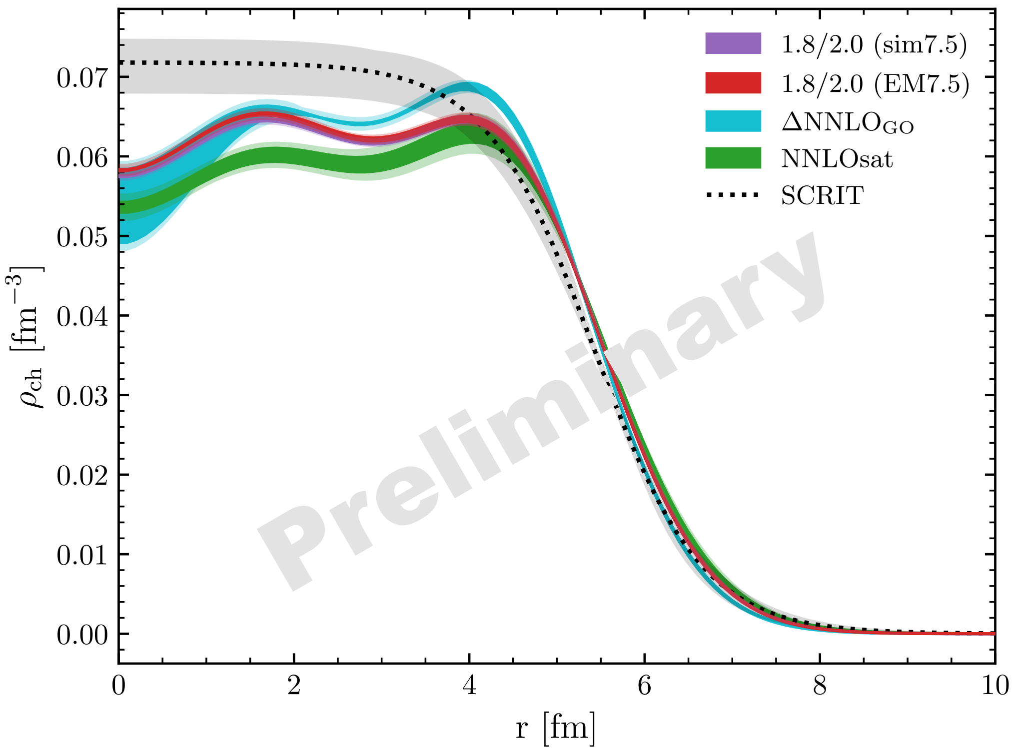


First *ab initio* calculation past the Sn isotopic line

- Reproduce experimental electron scattering results
- Results meaningful for exp. despite moderate convergence

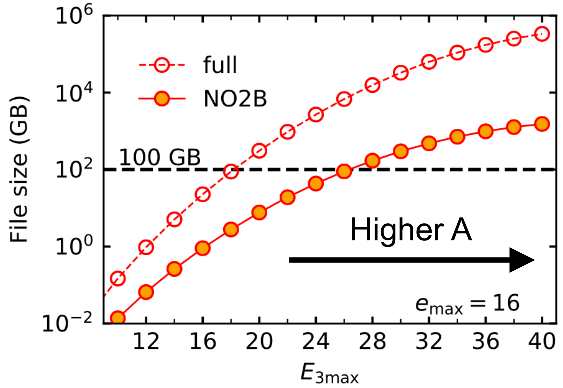






Reduced uncertainties

- Better storage method for the 3NF [Miyagi *et al.*, *PRC* **105** (2022)]
- Truncation on 3NF ME partially lifted
- New Xe densities provided to SCRIT group



Why new low-resolution interactions?

Need for good reproduction of radii and densities

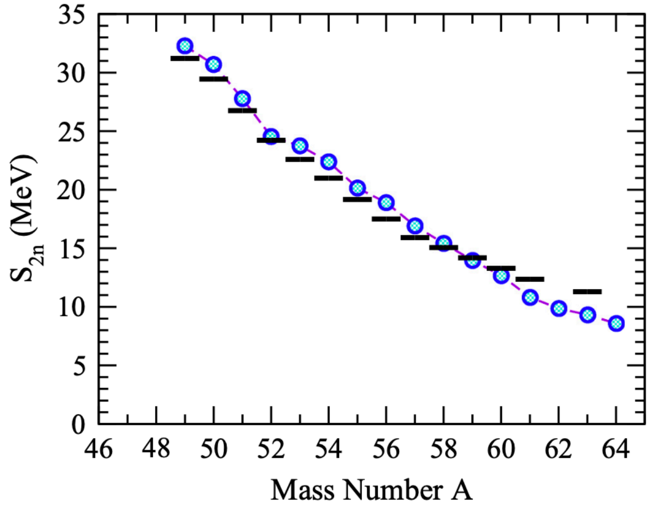
- NNLOsat very successful with radii
- But underbinds and too hard for heavy nuclei
- Other interactions that scale well underbind radii

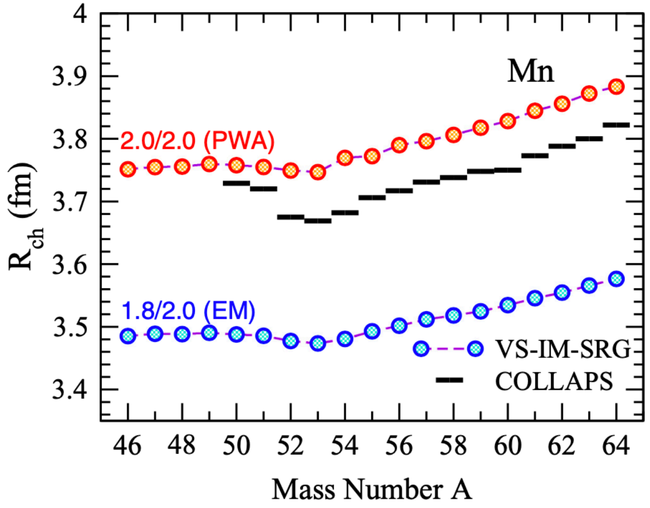
Sufficient to describe bulk properties of nuclei

- 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}

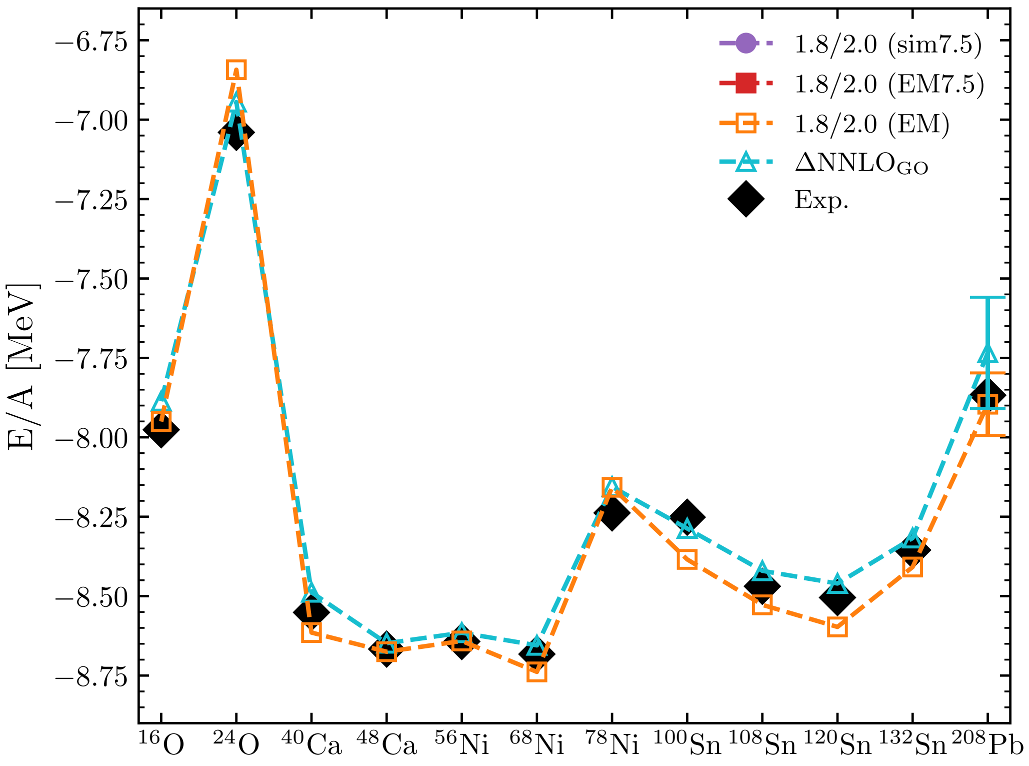


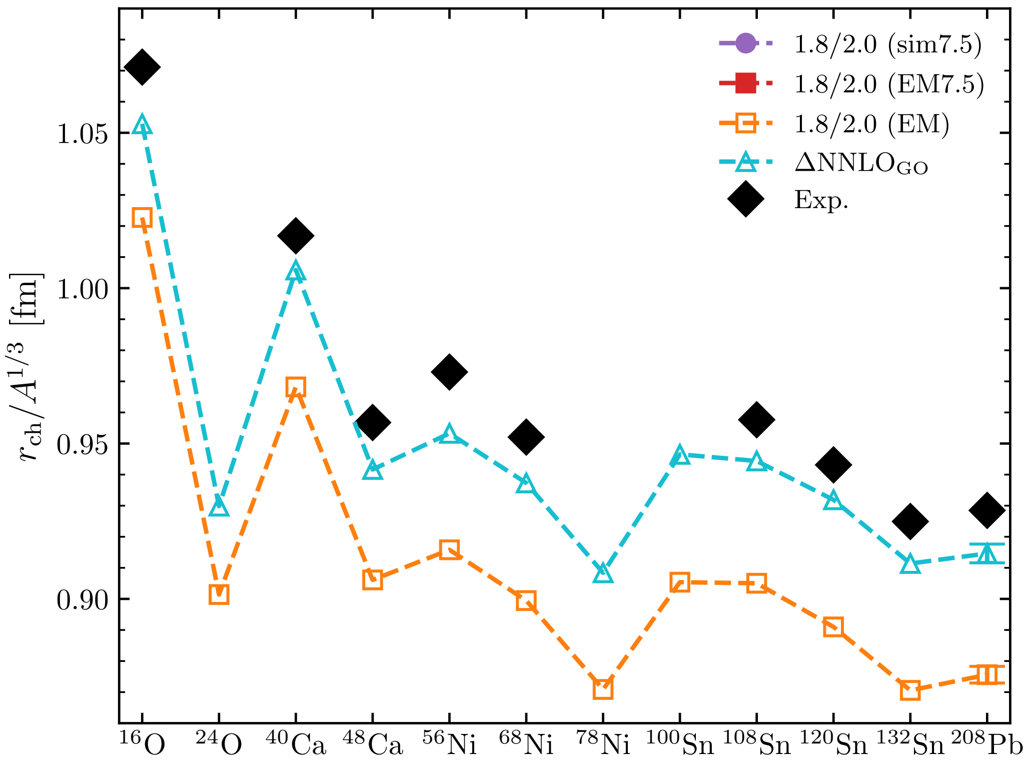


[Simonis *et al.*, *PRC* **96** (2017)]

Ground-state accuracy towards heavy systems

[Arthuis, Hebeler, Schwenk, arxiv:2401.06675]





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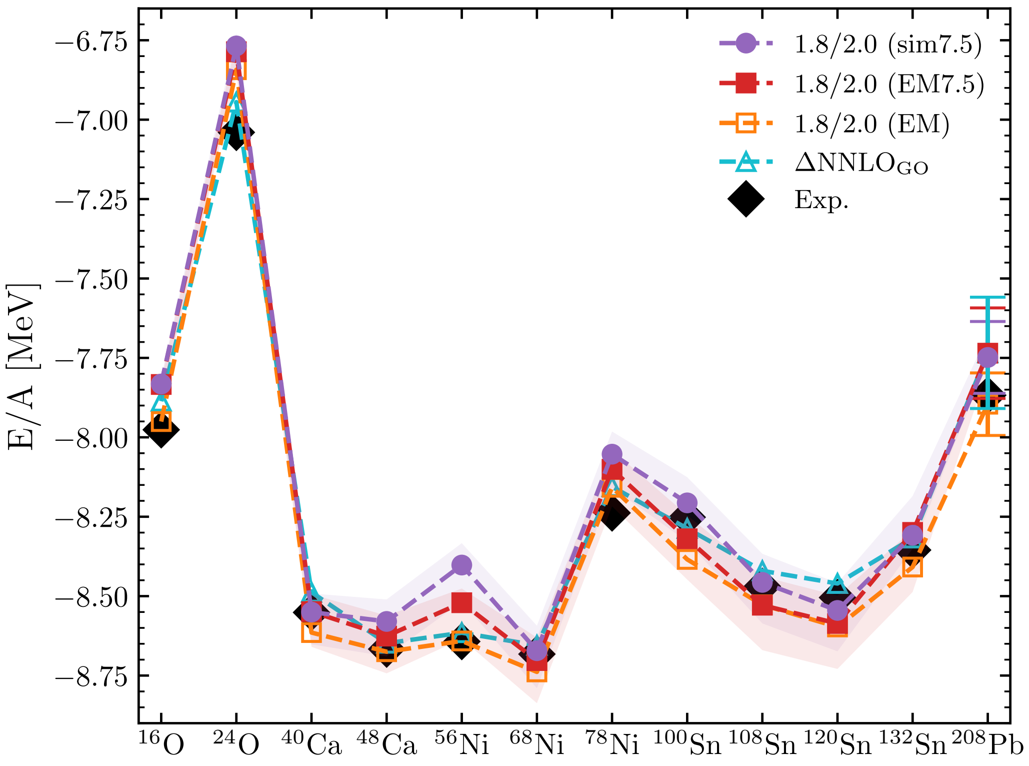
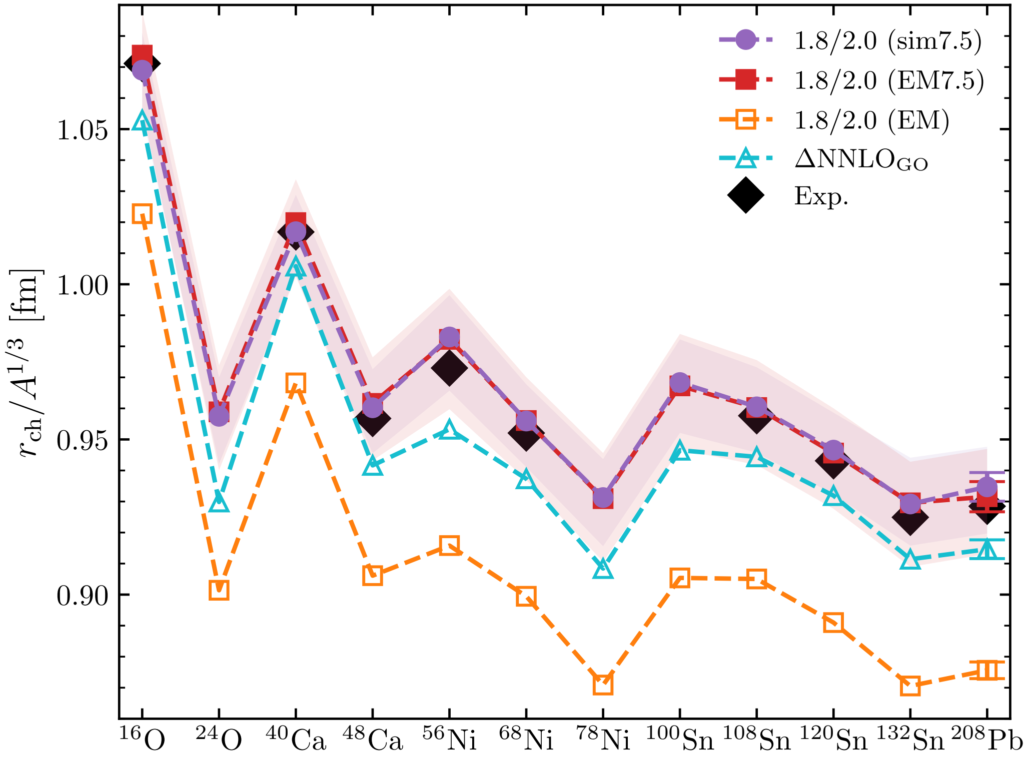




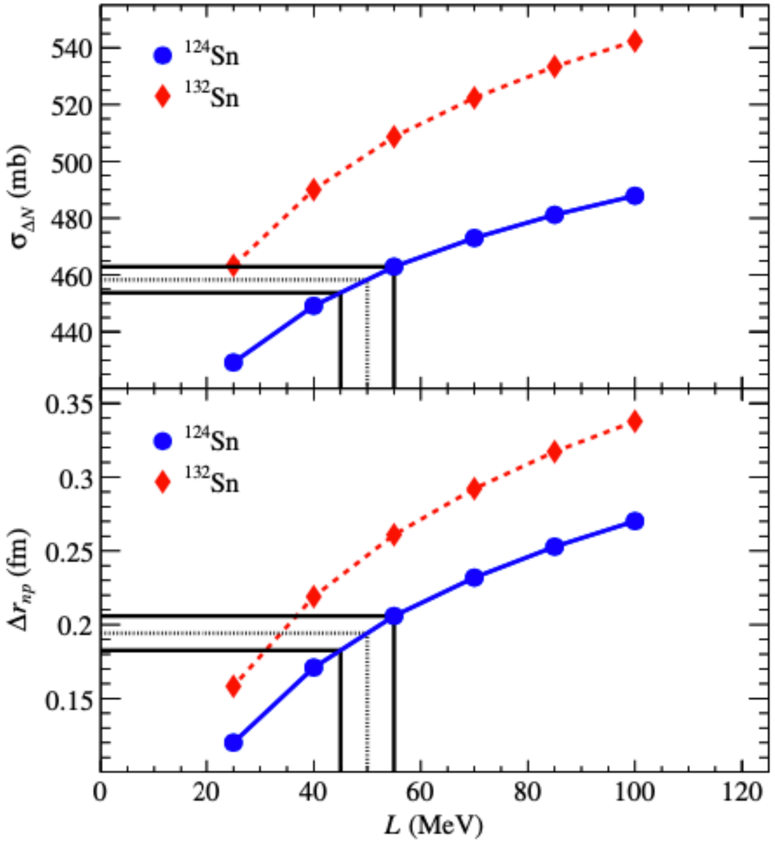
Binding energy

- 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

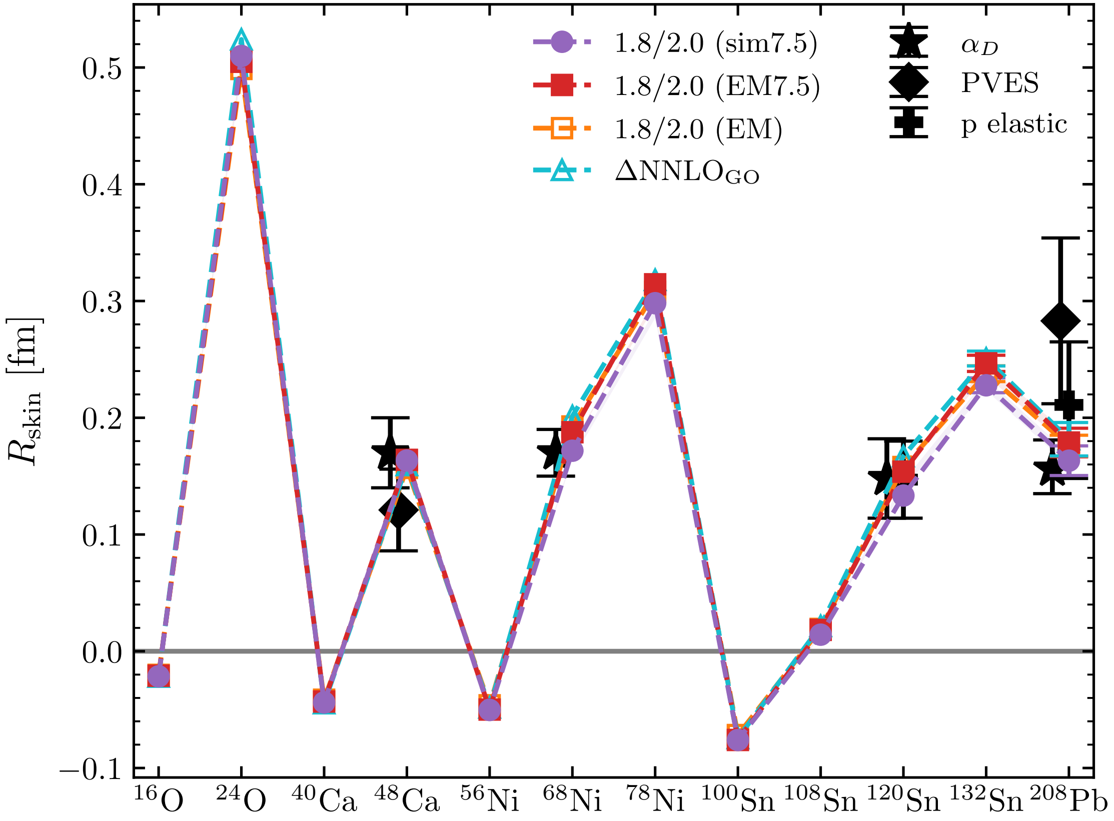
[Arthuis, Hebeler, Schwenk, arxiv:2401.06675]



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

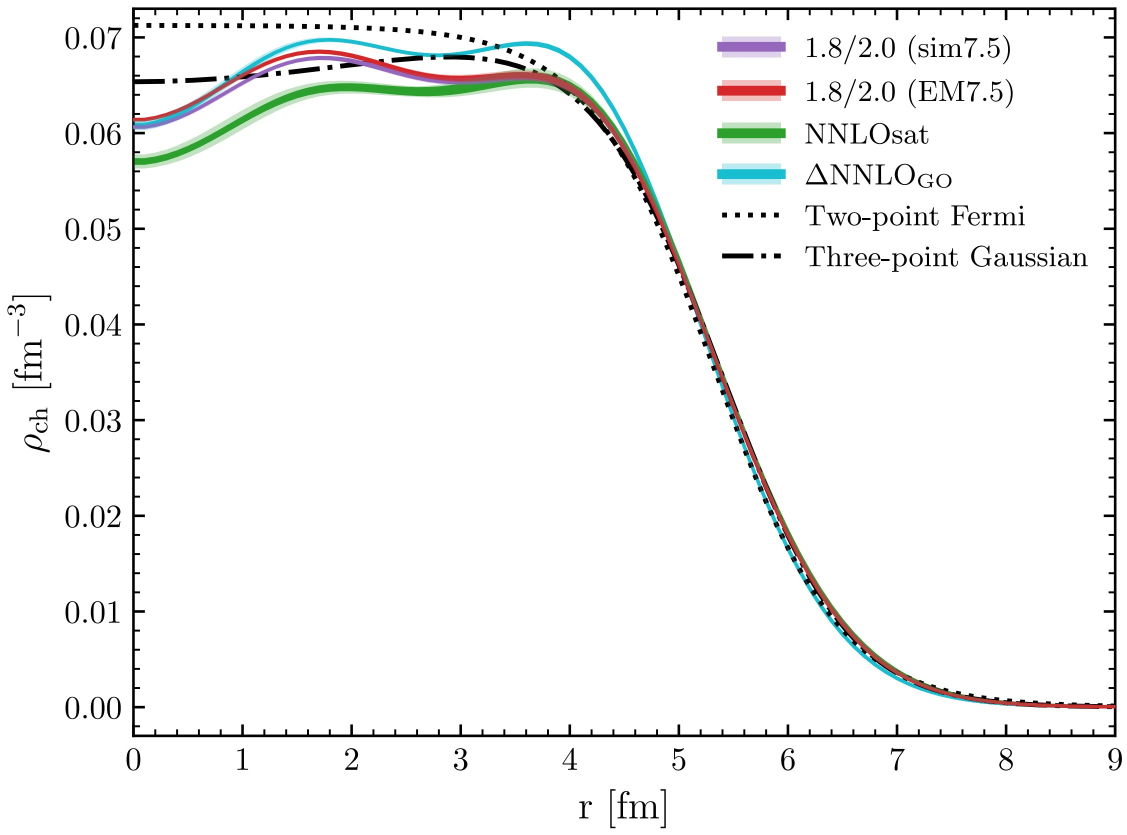
Neutron removal off Sn isotopes @ R3B/GSI

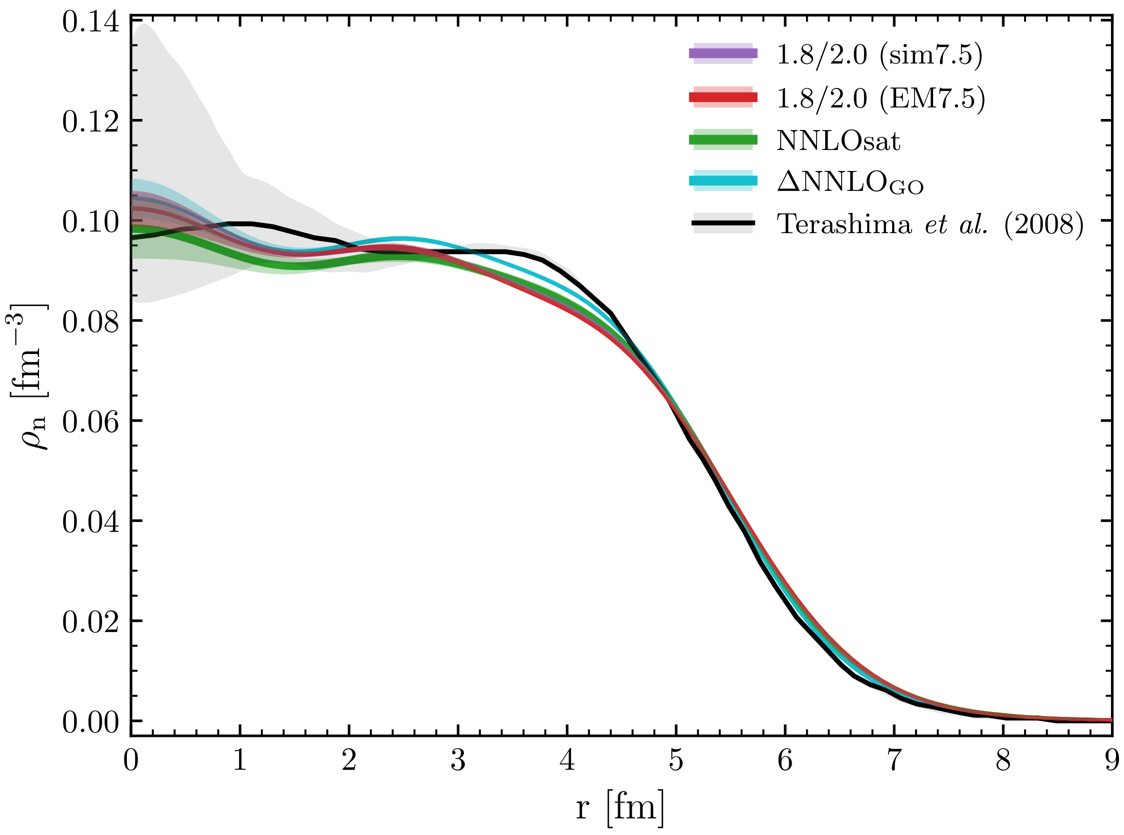
- Access L through the cross-section, need for theory input
- L correlated to neutron skin too: Great test case



Ab initio densities for heavy systems: ^{120}Sn

[Arthuis, Hebeler, Schwenk, arxiv:2401.06675]



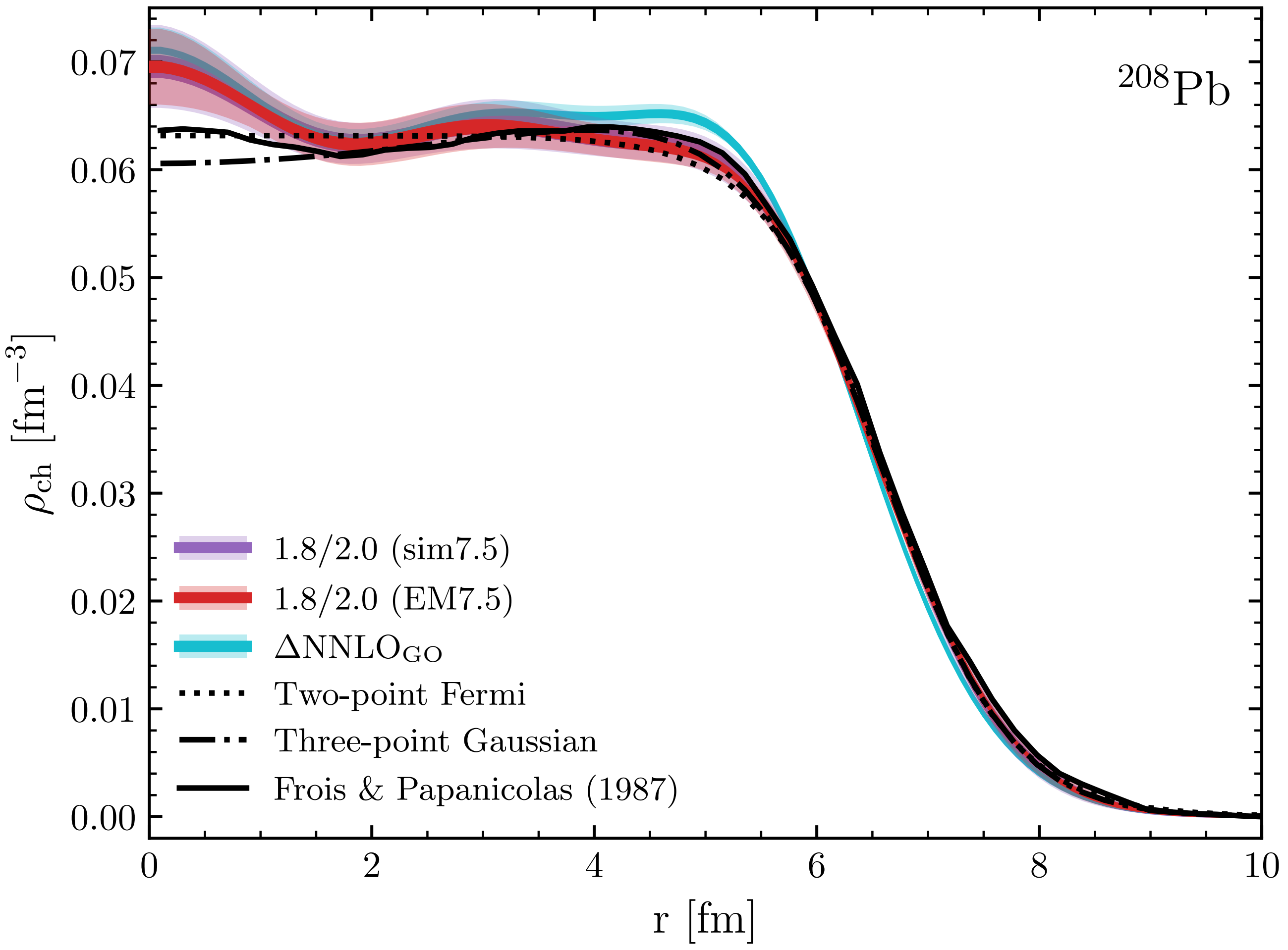


Excellent reproduction of ^{120}Sn densities

- Consistent picture over the different interactions
- Very moderate uncertainties

Ab initio densities for heavier systems: ^{208}Pb

[Arthuis, Hebeler, Schwenk, arxiv:2401.06675]



Charge density for ^{208}Pb

- Consistent picture over the different interactions
- 1.8/2.0s give excellent surface profile
- Inner density not fully converged yet

New interactions consistent over the nuclear chart

Conclusion and outlook

Ab initio methods now mature

- Reach up to the Pb isotopic chain
- Systematically improvable many-body method and interaction
- Diversity of nuclear properties reproduced

Ab initio radii and densities

- Novel interactions with good convergence properties
- Consistent results over the whole nuclear chart
- Meaningful input for experimental collaborations (SCRIT, R3B, …)

Future plans

- Investigation of Ar isotopes: experiment-theory back-and-forth
- Densities as meaningful checks for interaction developments
- Looking forward to new experimental results

See V. Lapoux' talk

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European Commission
Marie Skłodowska-Curie Actions

Thank your for your attention!

V. Lapoux
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