Saturation with chiral interactions and consequences for finite nuclei

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Outline

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Saturation with chiral interactions and consequences for finite nuclei

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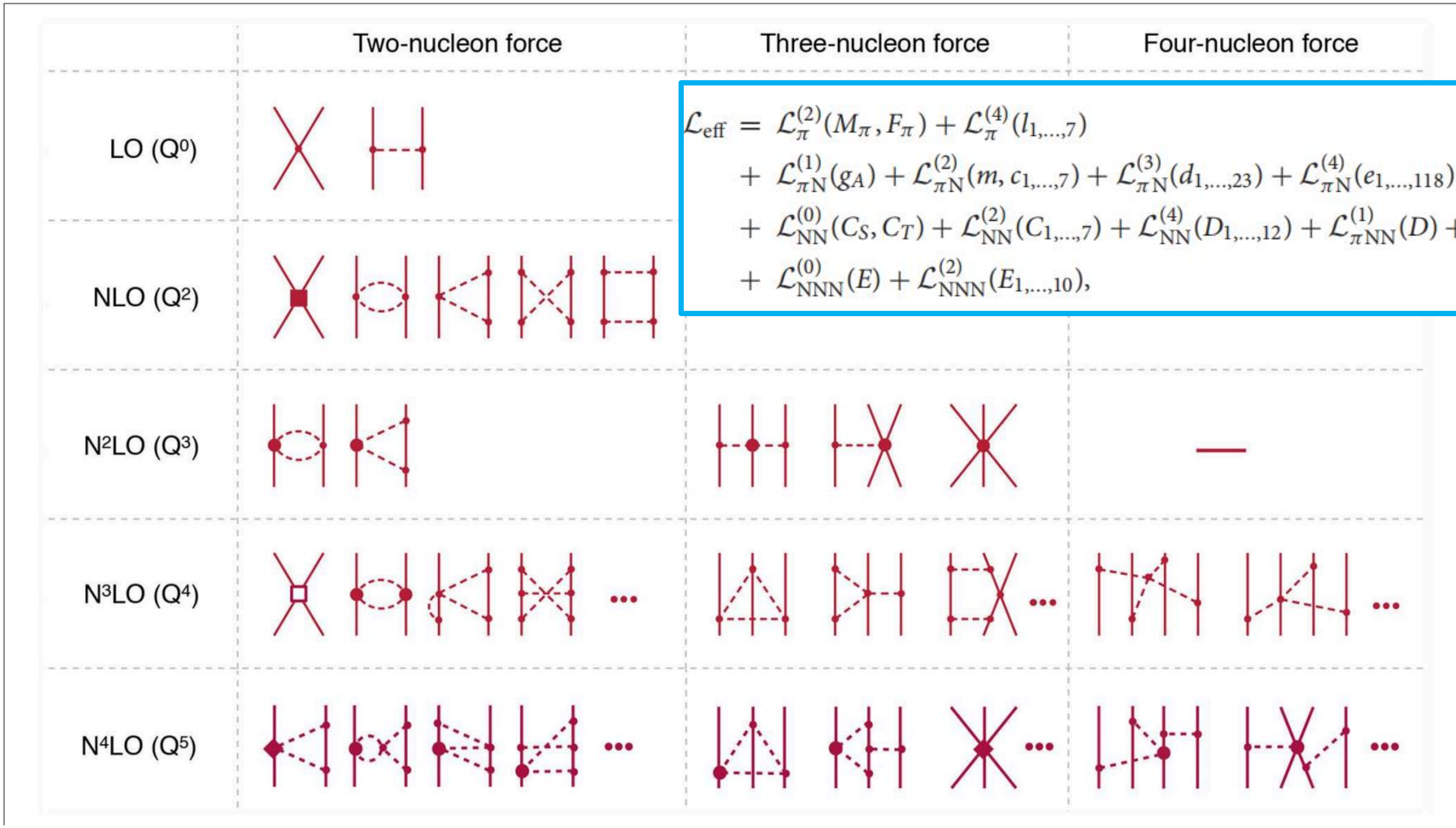
1. **Nuclear forces and many-body theory**
   A. Chiral nuclear force, renormalization group, and nuclear matter
   B. In-medium similarity renormalization group
2. **Results & discussions**
   A. Closed-shell nuclei
   B. Open-shell nuclei
3. **Summary**

Nuclear force, (S)RG & Nuclear matter

Chiral nuclear force



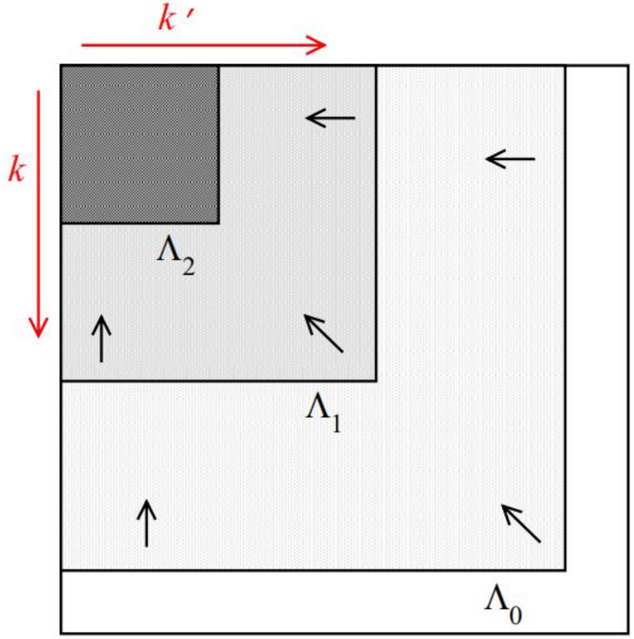
$$
\begin{aligned}
\mathcal{L}_{\text{eff}} = {} & \mathcal{L}_{\pi}^{(2)}(M_\pi, F_\pi) + \mathcal{L}_{\pi}^{(4)}(l_{1,\ldots,7}) \\
& + \mathcal{L}_{\pi N}^{(1)}(g_A) + \mathcal{L}_{\pi N}^{(2)}(m, c_{1,\ldots,7}) + \mathcal{L}_{\pi N}^{(3)}(d_{1,\ldots,23}) + \mathcal{L}_{\pi N}^{(4)}(e_{1,\ldots,118}) \\
& + \mathcal{L}_{NN}^{(0)}(C_S, C_T) + \mathcal{L}_{NN}^{(2)}(C_{1,\ldots,7}) + \mathcal{L}_{NN}^{(4)}(D_{1,\ldots,12}) + \mathcal{L}_{\pi NN}^{(1)}(D) + \\
& + \mathcal{L}_{NNN}^{(0)}(E) + \mathcal{L}_{NNN}^{(2)}(E_{1,\ldots,10}),
\end{aligned}
$$

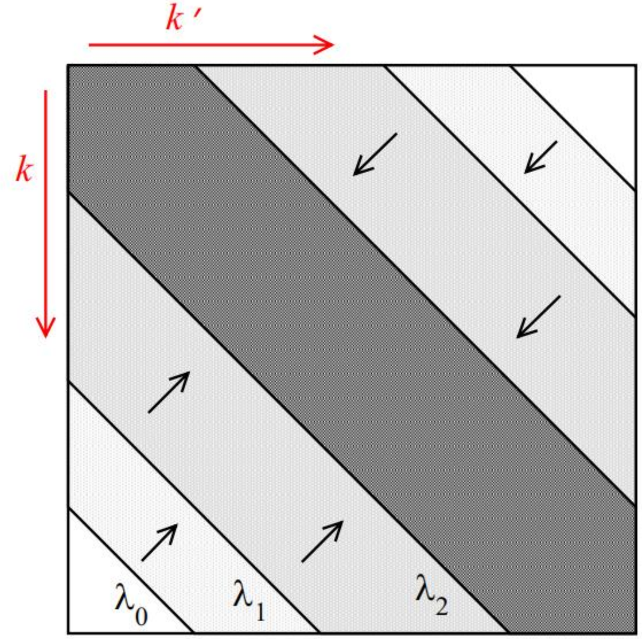
Hierarchy of nuclear forces at increasing orders in chiral expansion in the Weinberg scheme, from [*Epelbaum, Krebs and Reinert, Front. Phys. 8, 98 (2020).*]

Similarity renormalization group

Renormalization group (sharp or smooth cut) $V_{\text{low }k}$

Similarity renormalization group V_{SRG}





$$H_s = U_s H U_s^\dagger \equiv T_{\text{rel}} + V_s$$

$$\frac{dH_s}{ds} = [\eta_s, H_s], \quad \eta_s = \frac{dU_s}{ds} U_s^\dagger = -\eta_s^\dagger.$$

$$\eta_s = [G_s, H_s],$$

$$\frac{dH_s}{ds} = [[G_s, H_s], H_s].$$

Bogner, Furnstahl & Schwenk, Prog. Part. Nucl. Phys. 65 (2010) 94.

In-medium SRG (many-body method)

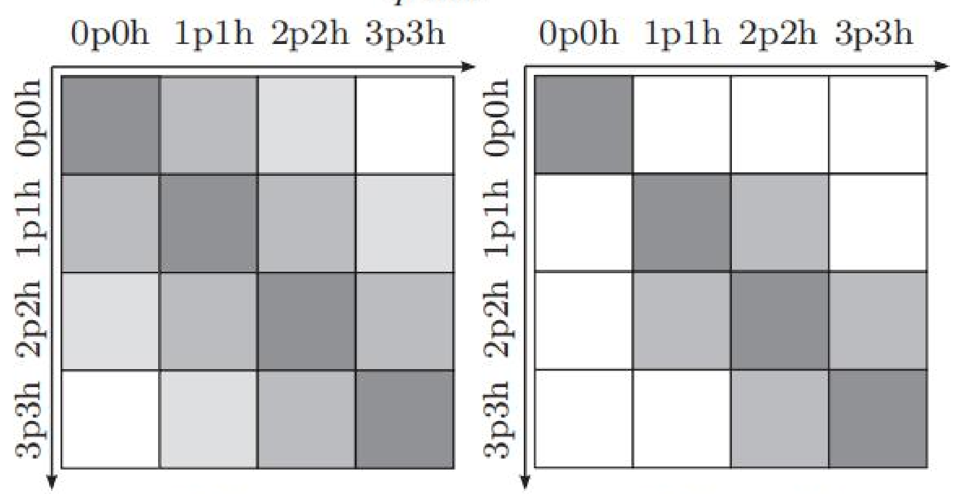
$$\hat{H} = \sum_{qr} T_{qr} a_q^\dagger a_r + \frac{1}{2!^2} \sum_{qrst} V^{(2)}_{qrst} a_q^\dagger a_r^\dagger a_t a_s + \frac{1}{3!^2} \sum_{qrstuv} V^{(3)}_{qrstuv} a_q^\dagger a_r^\dagger a_s^\dagger a_v a_u a_t + \cdots$$

reference state $|\Phi\rangle$

$$H = E + \sum_{qr} f_{qr} : a_q^\dagger a_r : + \frac{1}{4} \sum_{qrst} \Gamma_{qrst} : a_q^\dagger a_r^\dagger a_t a_s + \frac{1}{36} \sum_{qrstuv} W_{qrstuv} : a_q^\dagger a_r^\dagger a_s^\dagger a_v a_u a_t :$$

$$\frac{dH(s)}{ds} = [\eta(s), H(s)]$$

$$\eta = \sum_{ai} \frac{f_{ai}}{f_a - f_i} : a_a^\dagger a_i : + \frac{1}{4} \sum_{abij} \frac{\Gamma_{abij}}{f_a + f_b - f_i - f_j} : a_a^\dagger a_b^\dagger a_j a_i : - \mathrm{H.c.},$$

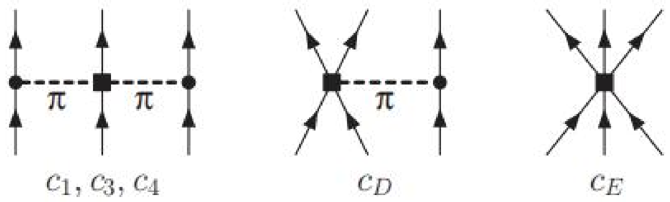


$\langle i|\, H(0)\,|j\rangle$ $\langle i|\, H(\infty)\,|j\rangle$

$$\lim_{s\to\infty} E_0(s) = \langle\Phi|H(s)|\Phi\rangle = E_{\rm gs}\,.$$

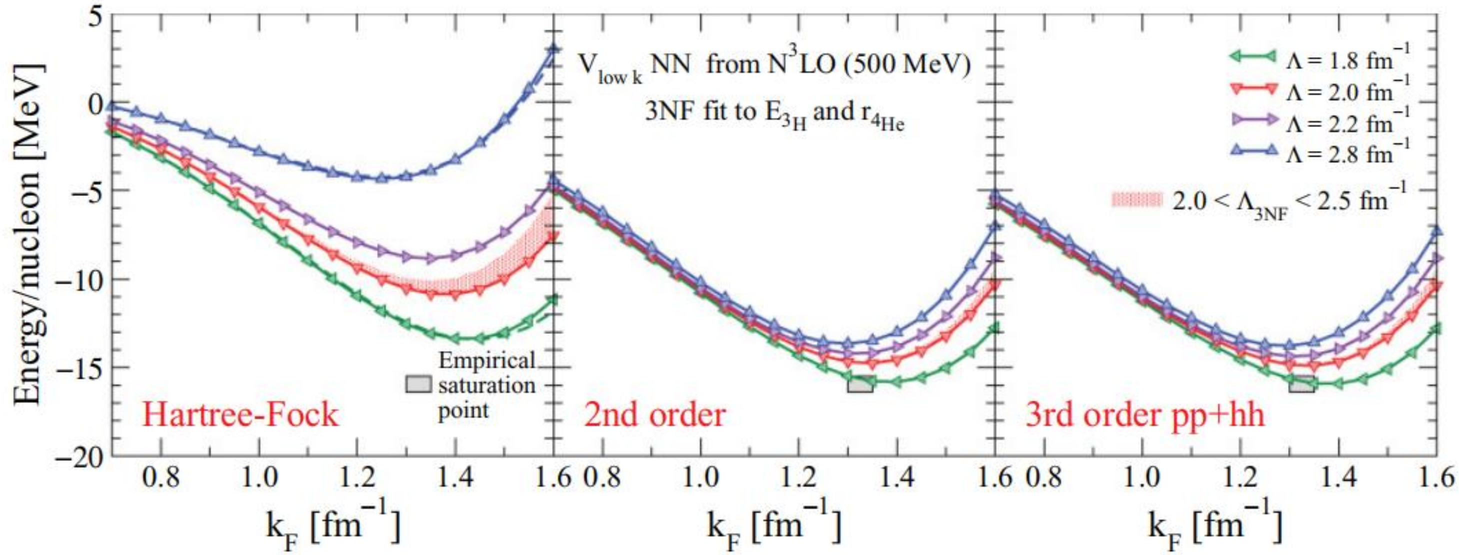
Morris, Parzuchowski & Bogner, Phys. Rev. C 92 034331 (2015).

Nuclear matter



$$\exp\{-[(p^2+3/4q^2)/\Lambda_{3NF}^2]^{n_{\exp}}\}$$

Λ or λ/Λ_{3NF} (fm)	$V_{\text{low } k}$		SRG	
	c_D	c_E	c_D	c_E
1.8/2.0 (EM c_i's)	+1.621	−0.143	+1.264	−0.120
2.0/2.0 (EM c_i's)	+1.705	−0.109	+1.271	−0.131
2.0/2.5 (EM c_i's)	+0.230	−0.538	−0.292	−0.592
2.2/2.0 (EM c_i's)	+1.575	−0.102	+1.214	−0.137
2.8/2.0 (EM c_i's)	+1.463	−0.029	+1.278	−0.078
2.0/2.0 (EGM c_i's)	−4.381	−1.126	−4.828	−1.152
2.0/2.0 (PWA c_i's)	−2.632	−0.677	−3.007	−0.686



NN force: N^{3}LO nucleon-nucleon (NN) potential (Entem & Machleidt, 500 MeV),

from *Hebeler, et al., Phys. Rev. C 83, 031301 (2011).*

Results & discussions: Closed-shell nuclei

Closed-shell nuclei (model space & observables)

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Truncations

NN: single-particle spherical harmonic-oscillator (HO) states with quantum $e = 2n + l \le e_{\max}$

3N: $e_1 + e_2 + e_3 \le E_{3\mathrm{Max}}$

$e_{\mathrm{Max}}/E_{3\mathrm{Max}} = 10/14,\ 12/14,\ 14/14,\ 14/16$, and $14/18$.

Total angular momentum $J \le 9$

IM-SRG(2): normal-ordered two-body approximation, the residual three-body term W is discarded.

Charge radius

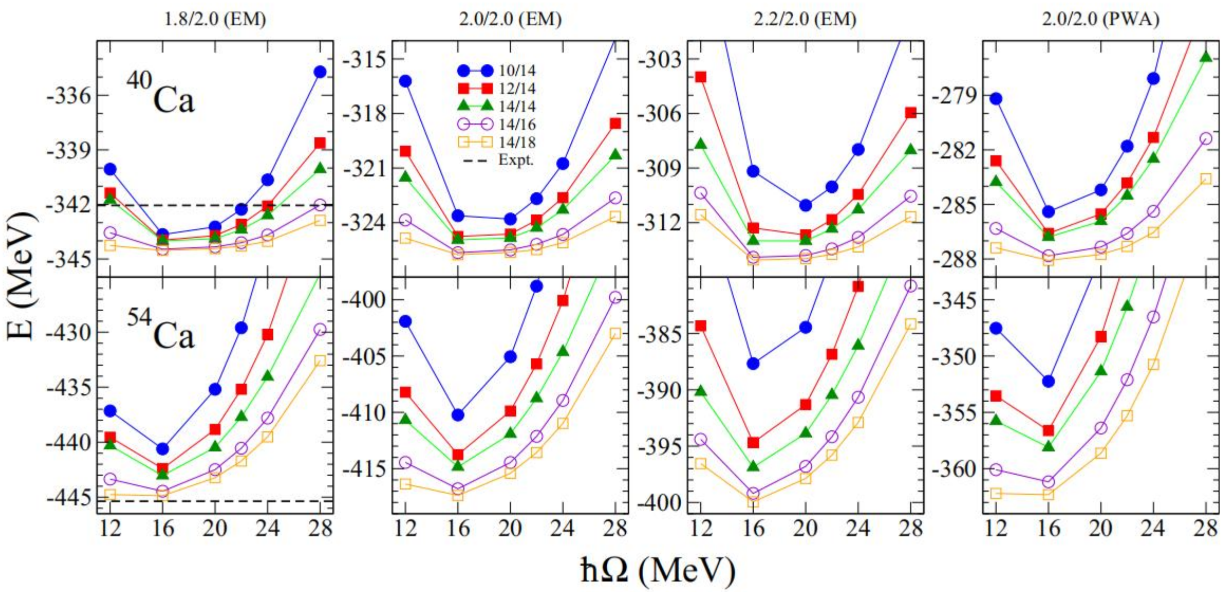
$$R_{\mathrm{ch}} = \sqrt{R_p^2 + \langle r_p^2\rangle + \frac{N}{Z}\langle r_n^2\rangle + \frac{3}{4M_p^2c^4} + \langle r^2\rangle_{\mathrm{so}}},$$

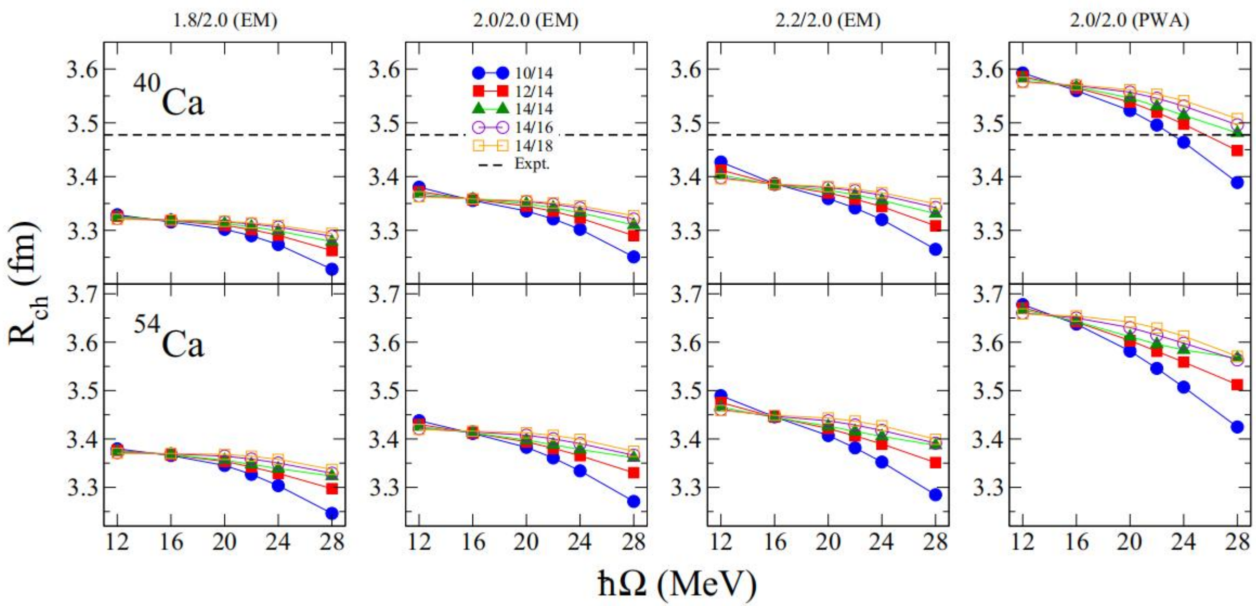
$$\langle r^2\rangle_{\mathrm{so}} = \frac{1}{Z}\sum_{i=1}^{A}\langle r_i^2\rangle_{\mathrm{so}} = -\frac{1}{Z}\sum_i \frac{\mu_i}{M^2}(\kappa_i + 1),$$

$$R_p^2 = \frac{1}{Z}\sum^{Z}(\vec{r}_i - \vec{R})^2,$$

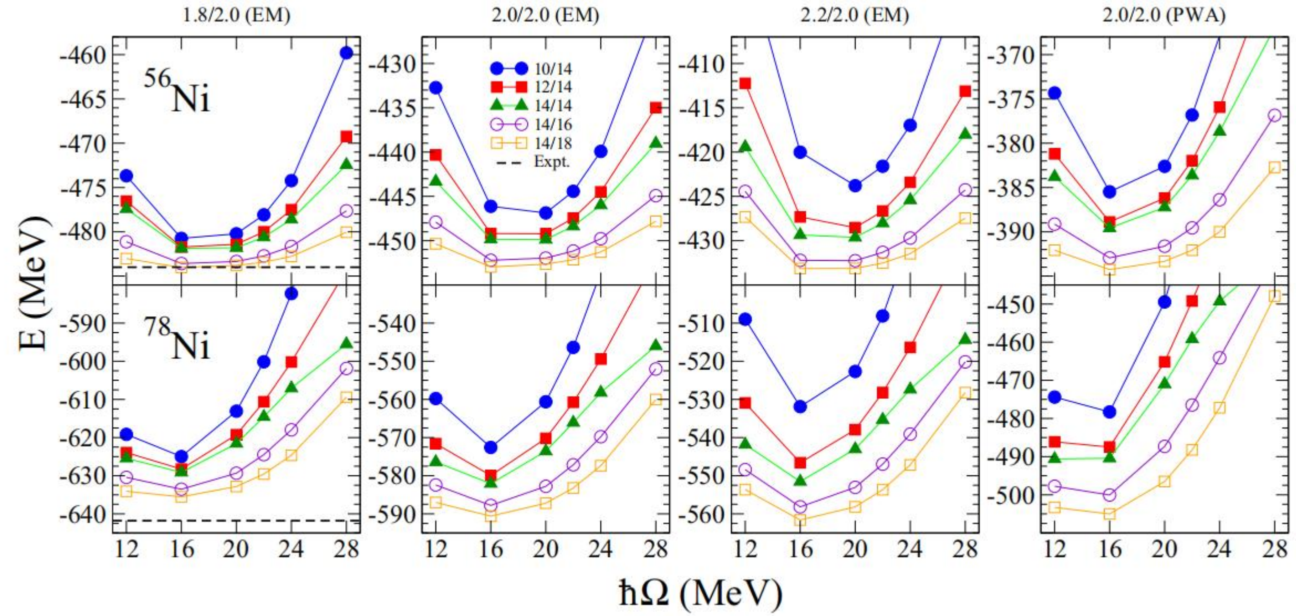
$$\kappa = \begin{cases} l, & j = l - \frac{1}{2} \\ -(l+1), & j = l + \frac{1}{2}. \end{cases}$$

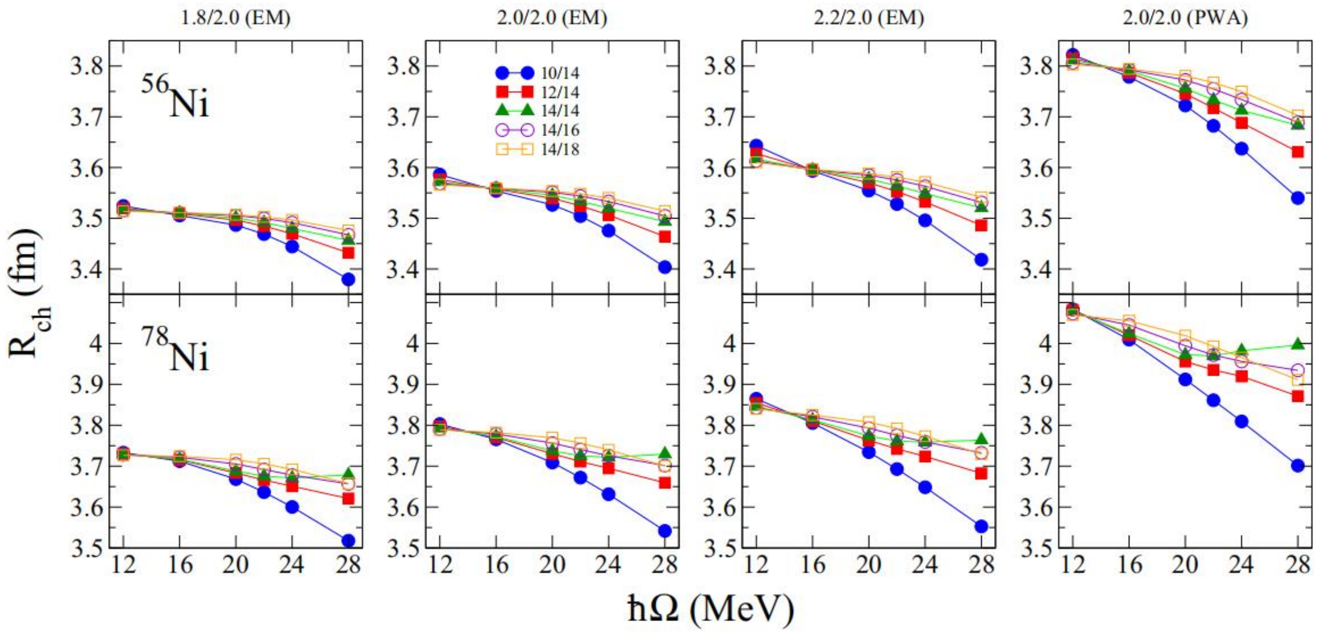
Closed-shell nuclei (Ca)



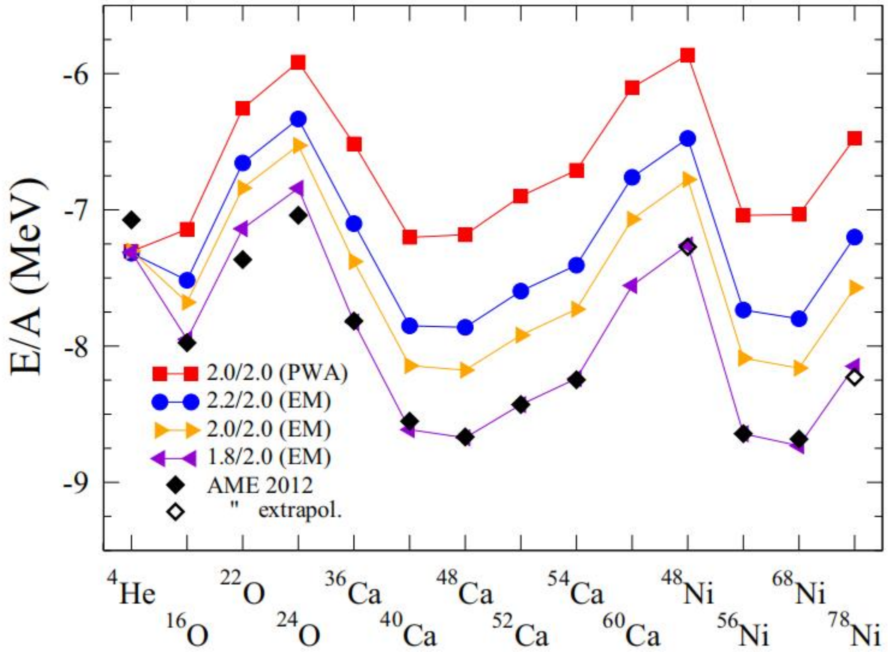


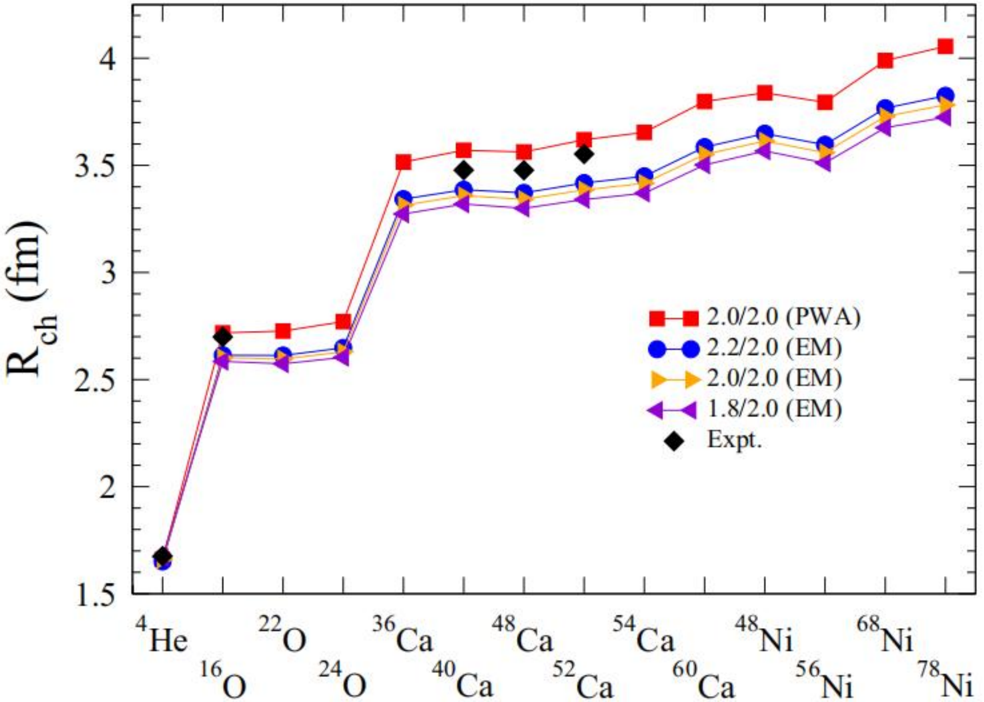
Closed-shell nuclei (Ni)



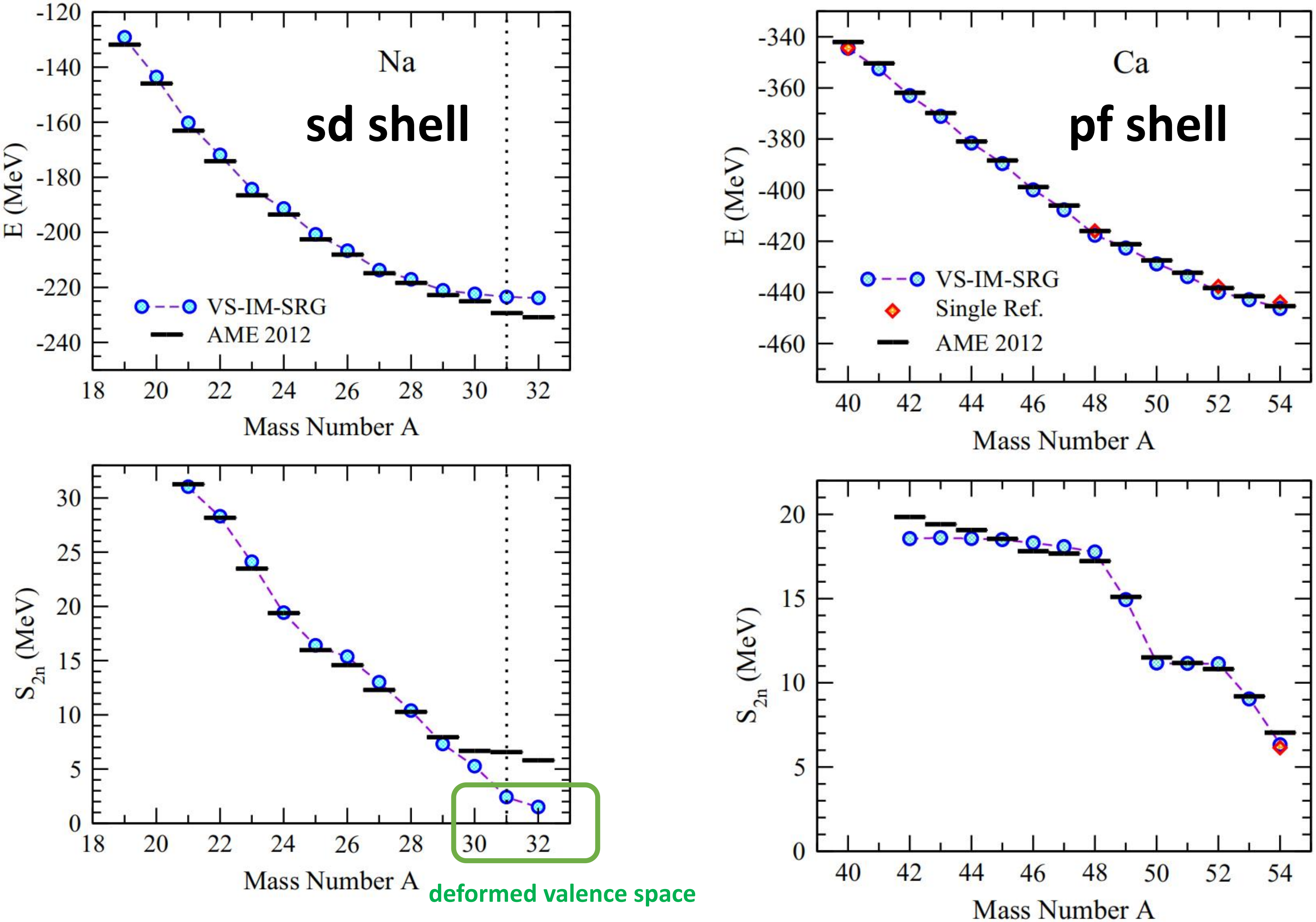


Closed-shell nuclei (overlooking)

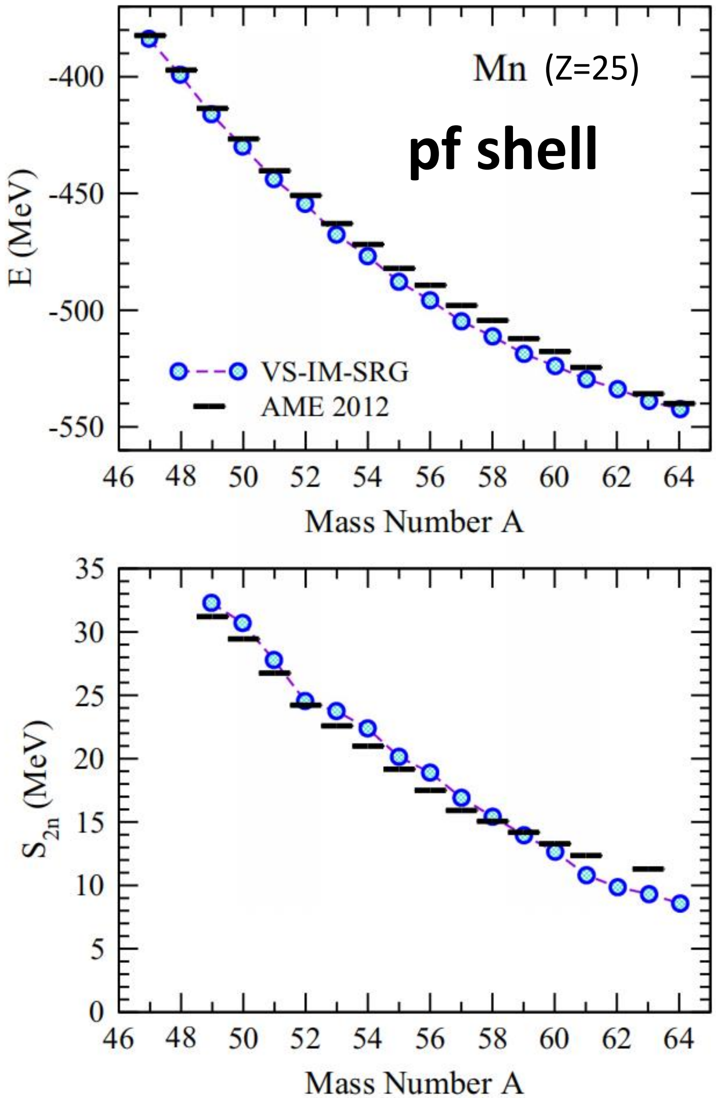


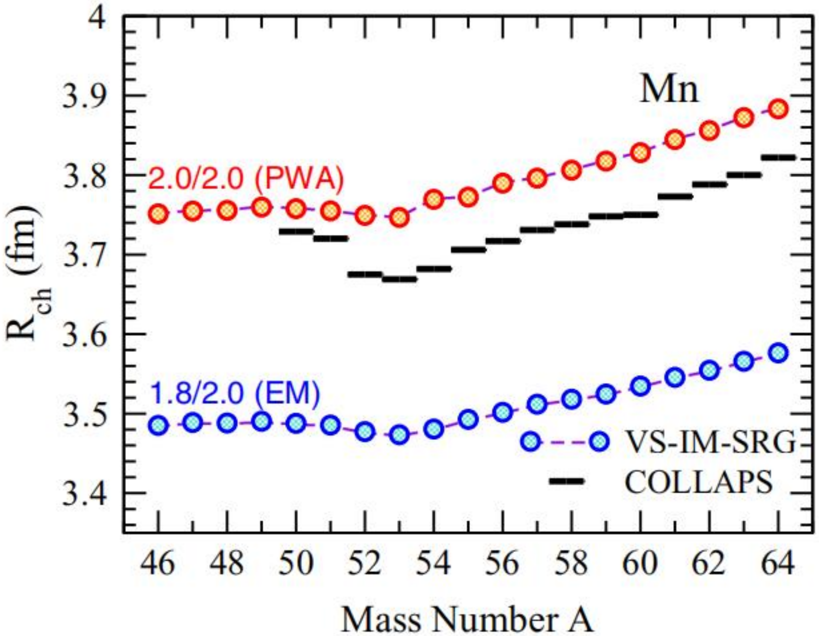


Open-shell nuclei (sd and pf shell nuclei)



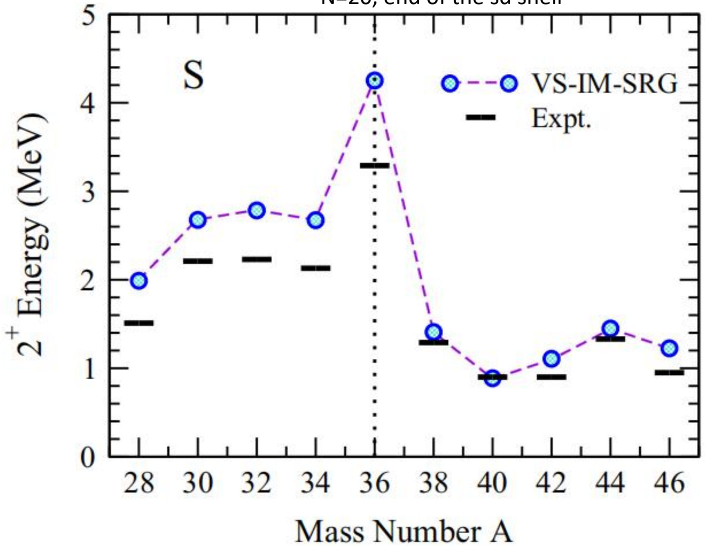
Open-shell nuclei (Mn isotope chain)

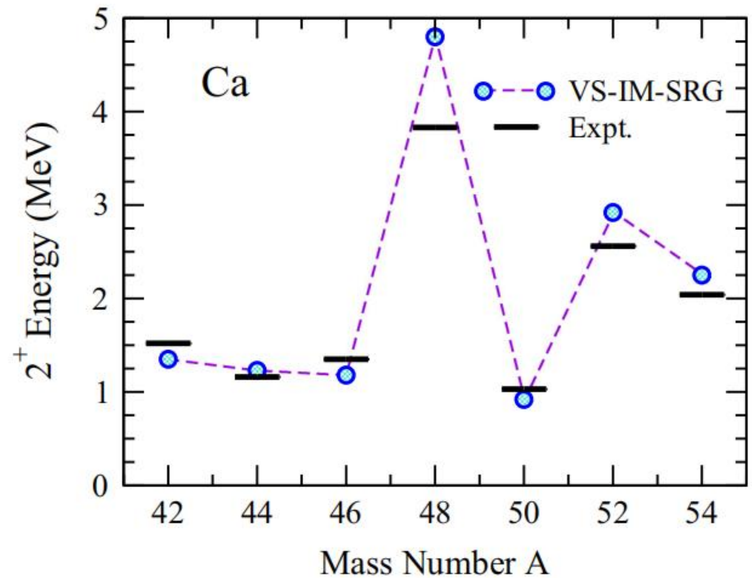


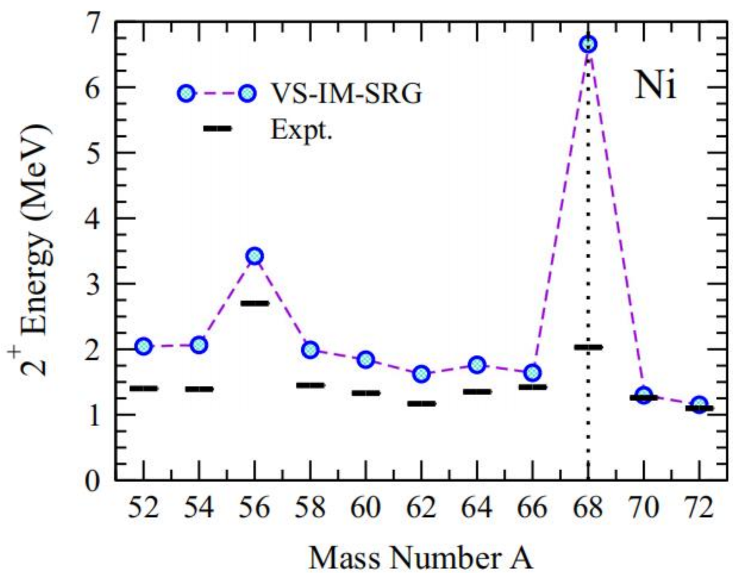


Open-shell nuclei (first-excitation states)

dotted line:
N=20, end of the sd shell







Peaks appear since shell closure.

Results & discussions: Open-shell Nuclei

Summary & Outlook

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- A set of chiral low-resolution NN + 3N interactions that predict realistic saturation properties are employed to calculations of ground-state energies and charge radii of a broad range of closed- and open-shell nuclei with $A \leq 78$.

- The systematics of ground-state energies and radii indicates that the difference is dominantly due to their different nuclear matter saturation properties.

- One particular interaction yields energies in good agreement with experiment from light nuclei up to $A \leq 78$, which appears to be accidental. But it suggests two conclusions:
  First, operator structures contained in these chiral interactions (NN at N^3LO and 3N at N^2LO) are sufficient to describe many of the features of the energies of light- and medium-mass nuclei
  Second, saturation properties are essential for this accurate descriptions.

Thank you for your attention