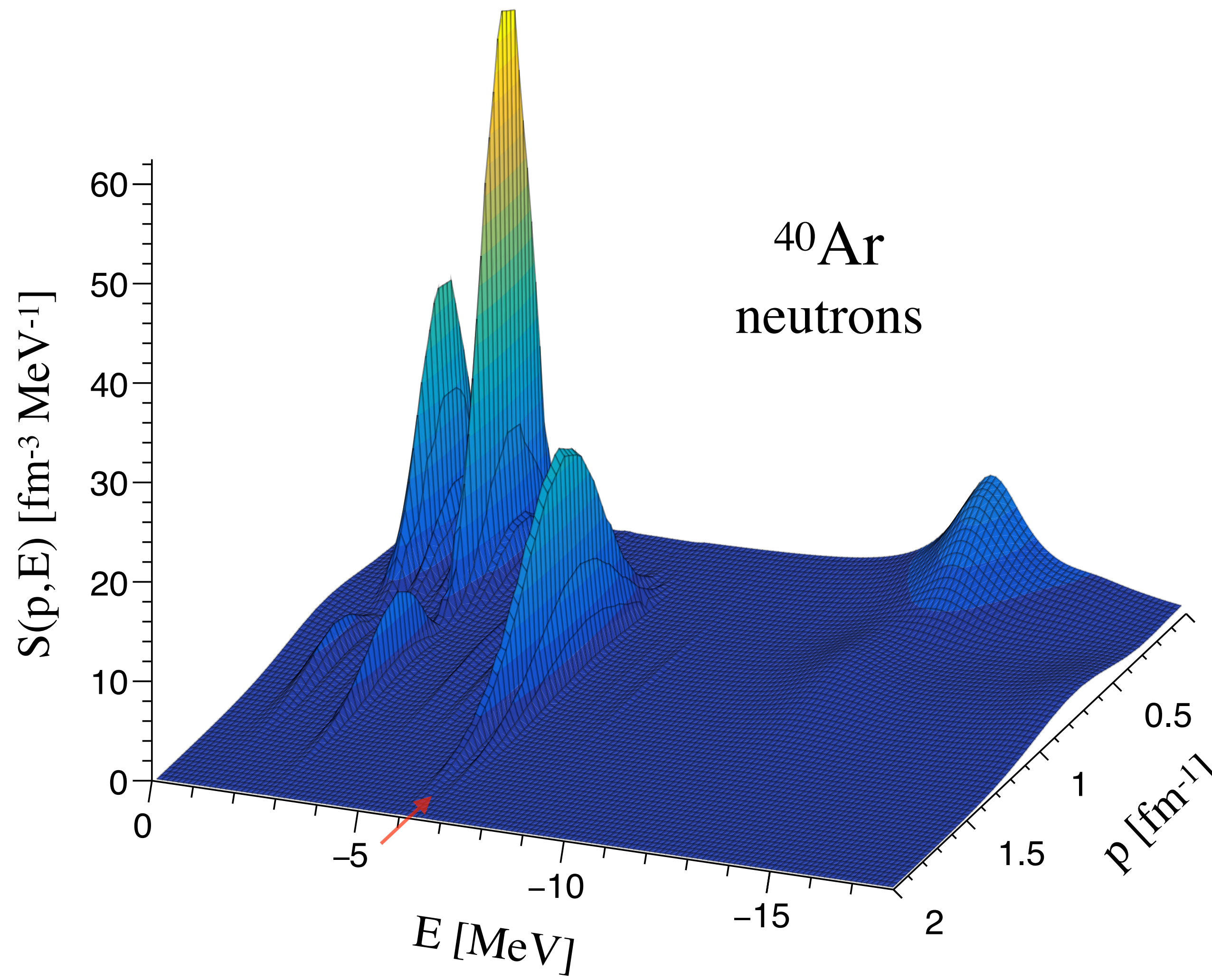
Ab initio description of open-shell nuclei

Vittorio Somà
IRFU, CEA Saclay, France



- VS, Navrátil, Raimondi, Barbieri, Duguet
  arXiv:1907.09790 & *in preparation*
- Barbieri, Rocco, VS
  arXiv:1907.01122

International Nuclear Physics Conference, Glasgow, 29 July 2019

Ab initio approach

A-body Hamiltonian

$$H = T + V^{2\mathrm{N}} + V^{3\mathrm{N}} + \ldots + V^{A\mathrm{N}}$$

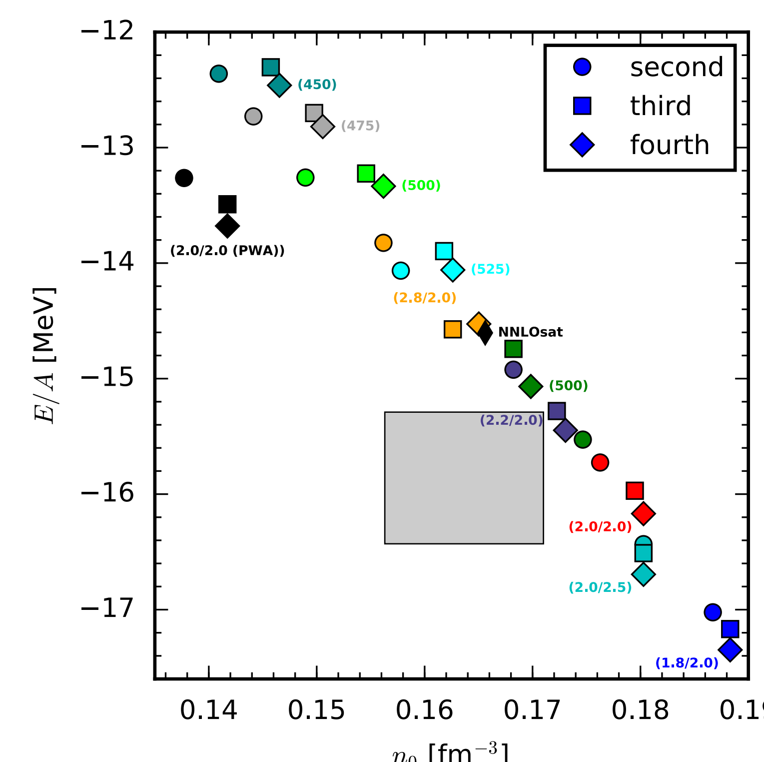
$$\boxed{H|\Psi_k^A\rangle = E_k^A|\Psi_k^A\rangle}$$

A-body wave-function
A-body observables

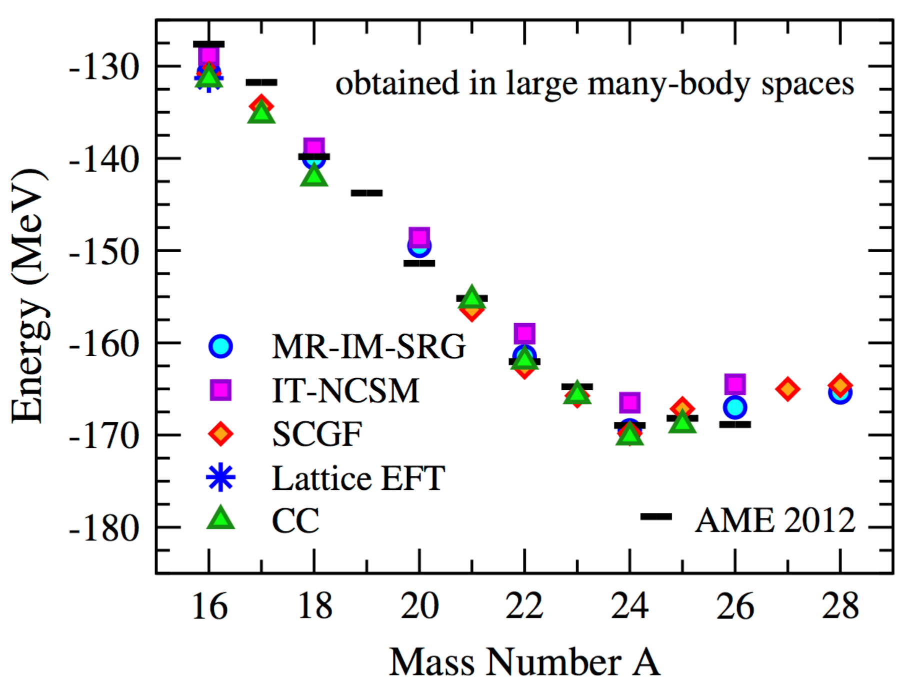
➟ Solve many-body Schrödinger equation in a controlled, systematically improvable way

Hamiltonian

- ○ QCD → Model of inter-nucleon interactions (χEFT)
- ○ Long-term goal: model-independent + uncertainties
- ○ Current situation: **proliferation of models**



[Drischler *et al.* 2019]



[Hebeler *et al.* 2015]

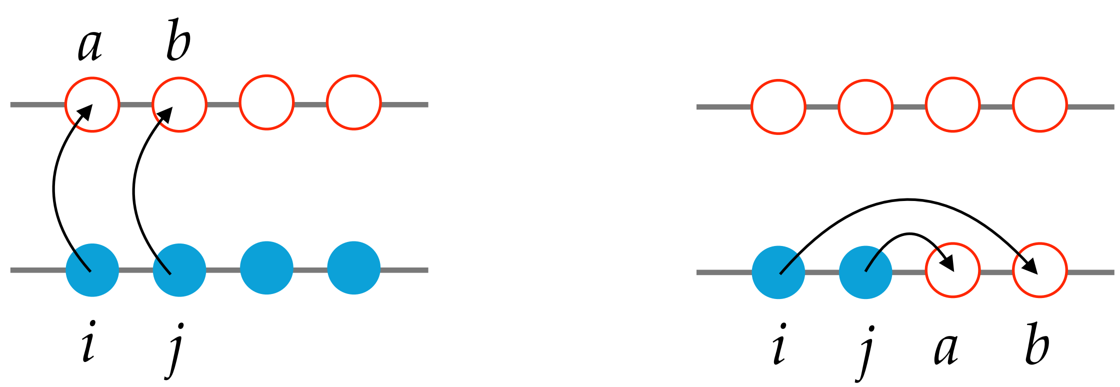
Many-body approaches

- ○ Exact methods limited to light nuclei
- ○ Expansion methods up to mass A ~ 100
- ○ Several complementary methods exist ➟ **benchmarks**

Open-shell nuclei

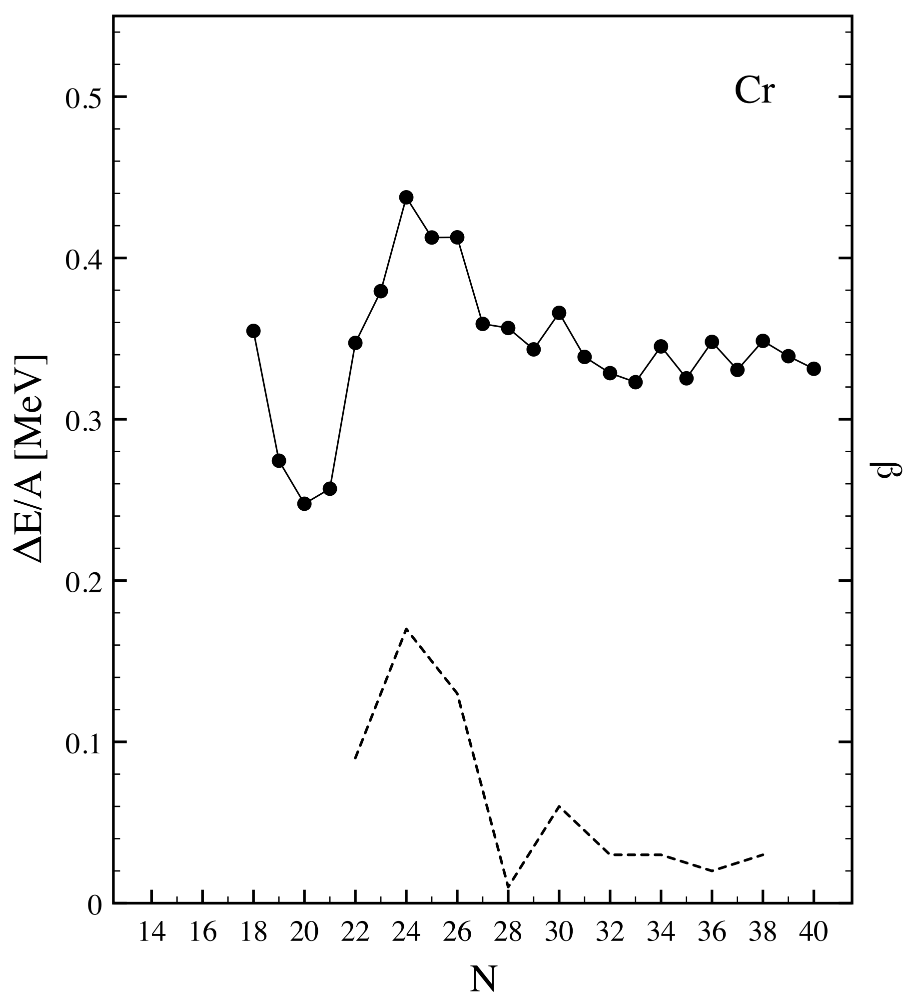
- ⦿ Approximate / truncated methods capture correlations via an expansion in **ph excitations**
  - ○ Reference states respects symmetries of H $\rightarrow$ works well in closed-shell systems
- ⦿ Open-shell nuclei are **(near-)degenerate** with respect to ph excitations

closed-shell



open-shell

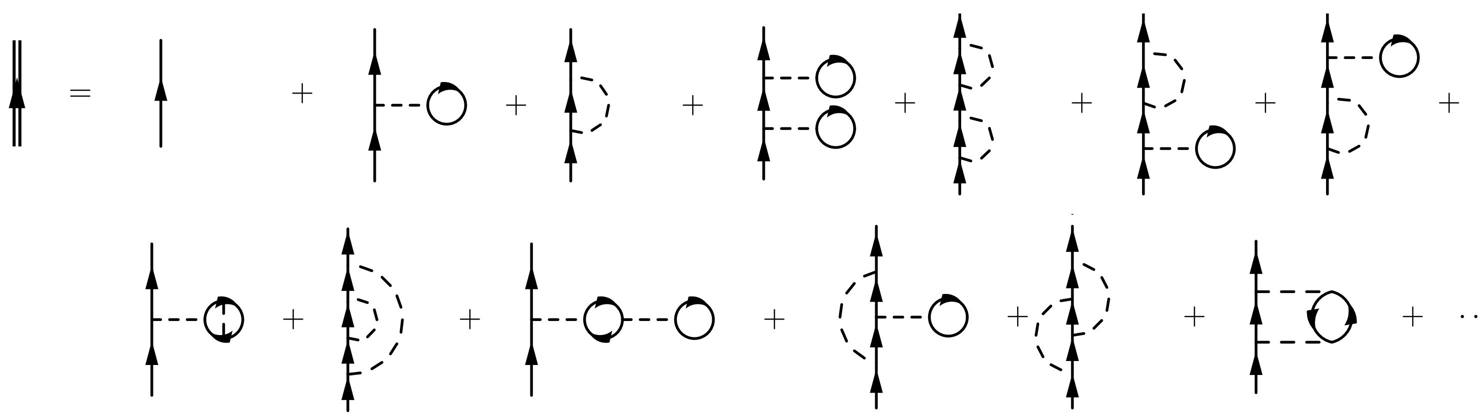
- ⦿ A **symmetry-breaking** reference lifts the degeneracy

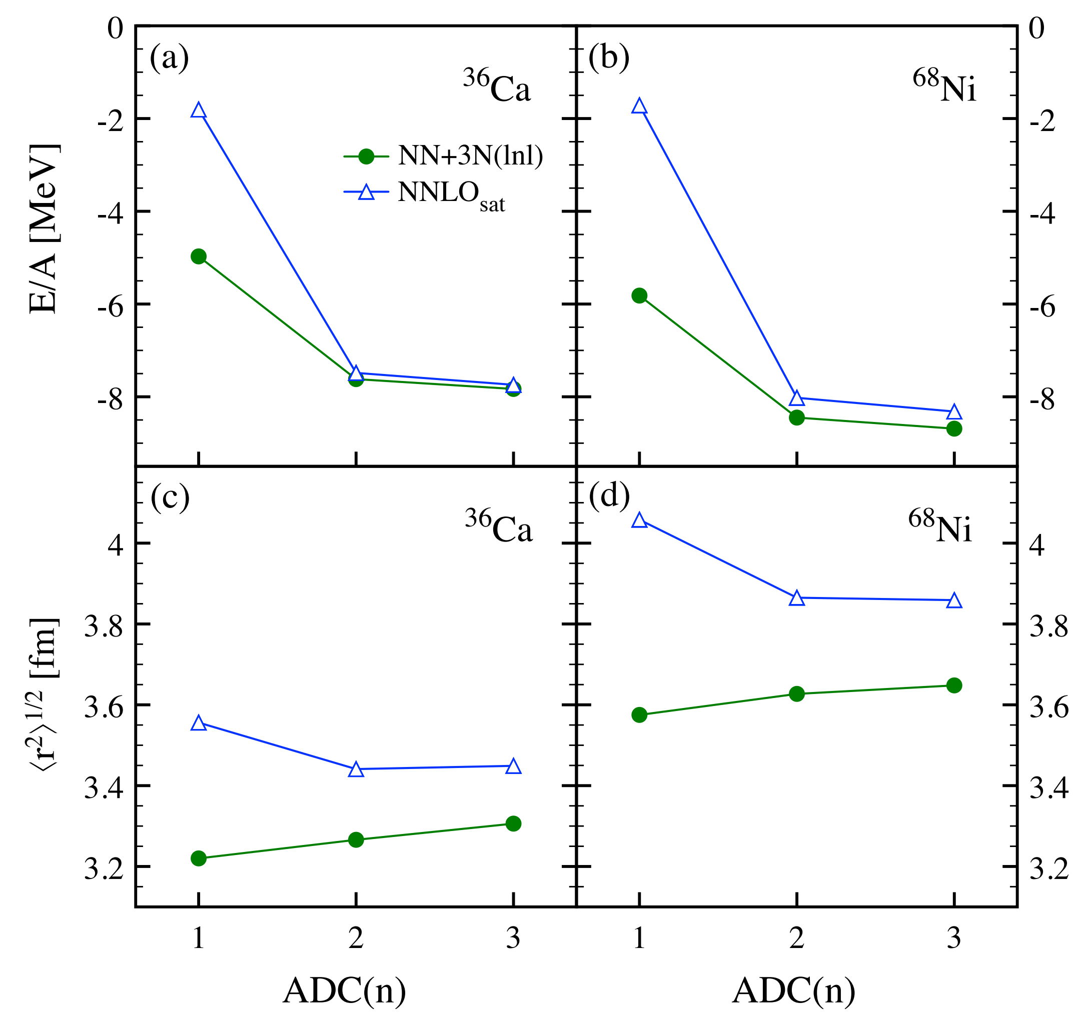


Pairing correlations	Quadrupole correlations
↕	↕
Superfluidity	Deformation
↕	↕
Breaking of U(1)	Breaking of SU(2)
↓	↓
Singly open-shells	**Doubly** open-shells

Set up

- **Many-body approach: Self-Consistent Green's Functions**
  - Generalised to Gorkov scheme [Somà, Duguet, Barbieri 2011]
  - G.s. properties of even-even A + spectra of odd-even
  - Self-energy → Optical potential for NA scattering

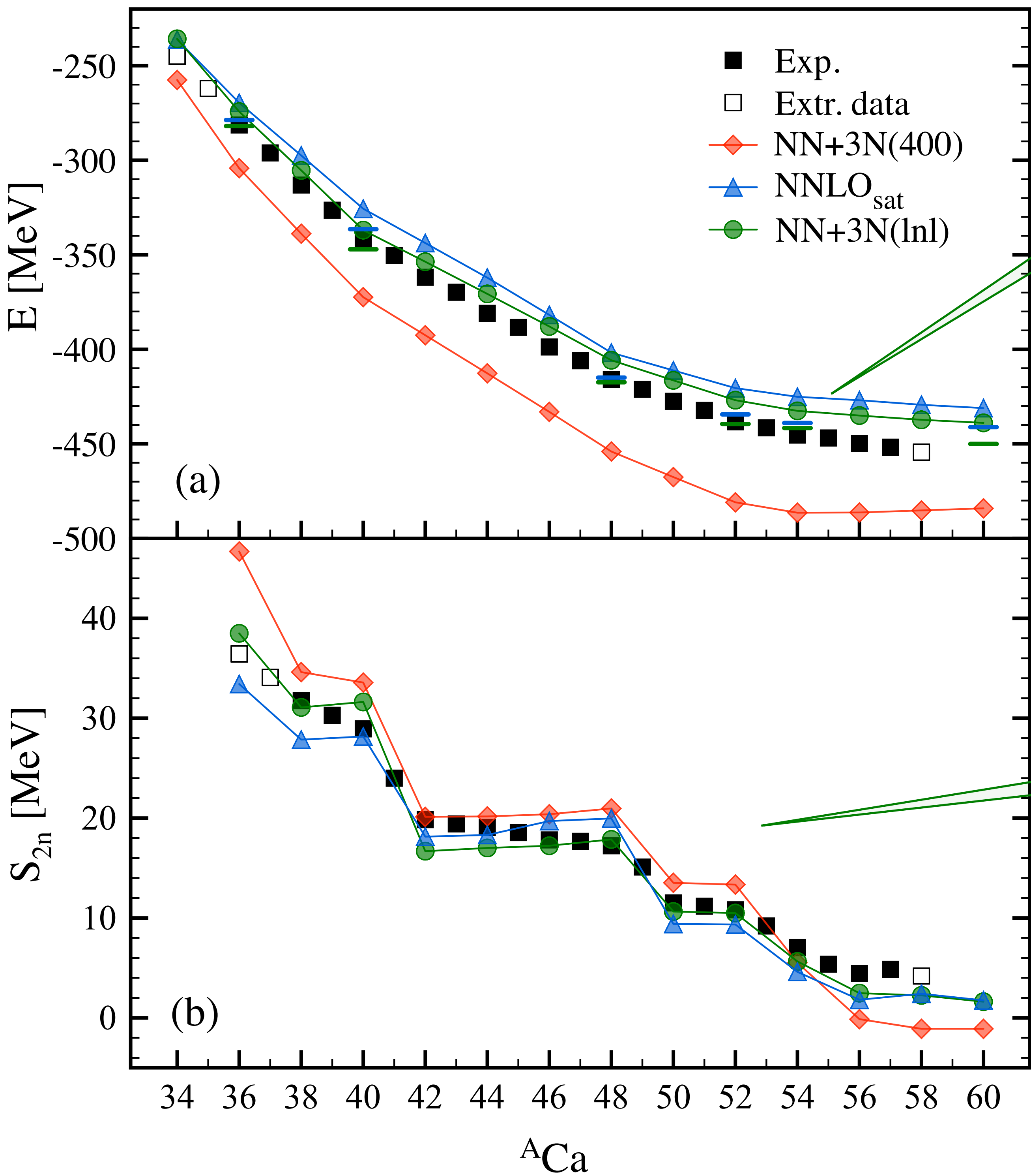




- **Hamiltonians**
  - NN+3N(400) **(~2010)** [Entem & Machleidt 2003, Navrátil 2007, Roth et al. 2012]
  - NNLO$_{sat}$ **(2015)** [Ekström *et al.* 2015]
  - NN+3N(lnl) **(2018)** [Entem & Machleidt 2003, Navrátil 2018]

Energy systematics: binding energies

⦿ First objective: ab initio calculations as a **diagnostic tool** for the development of Hamiltonian

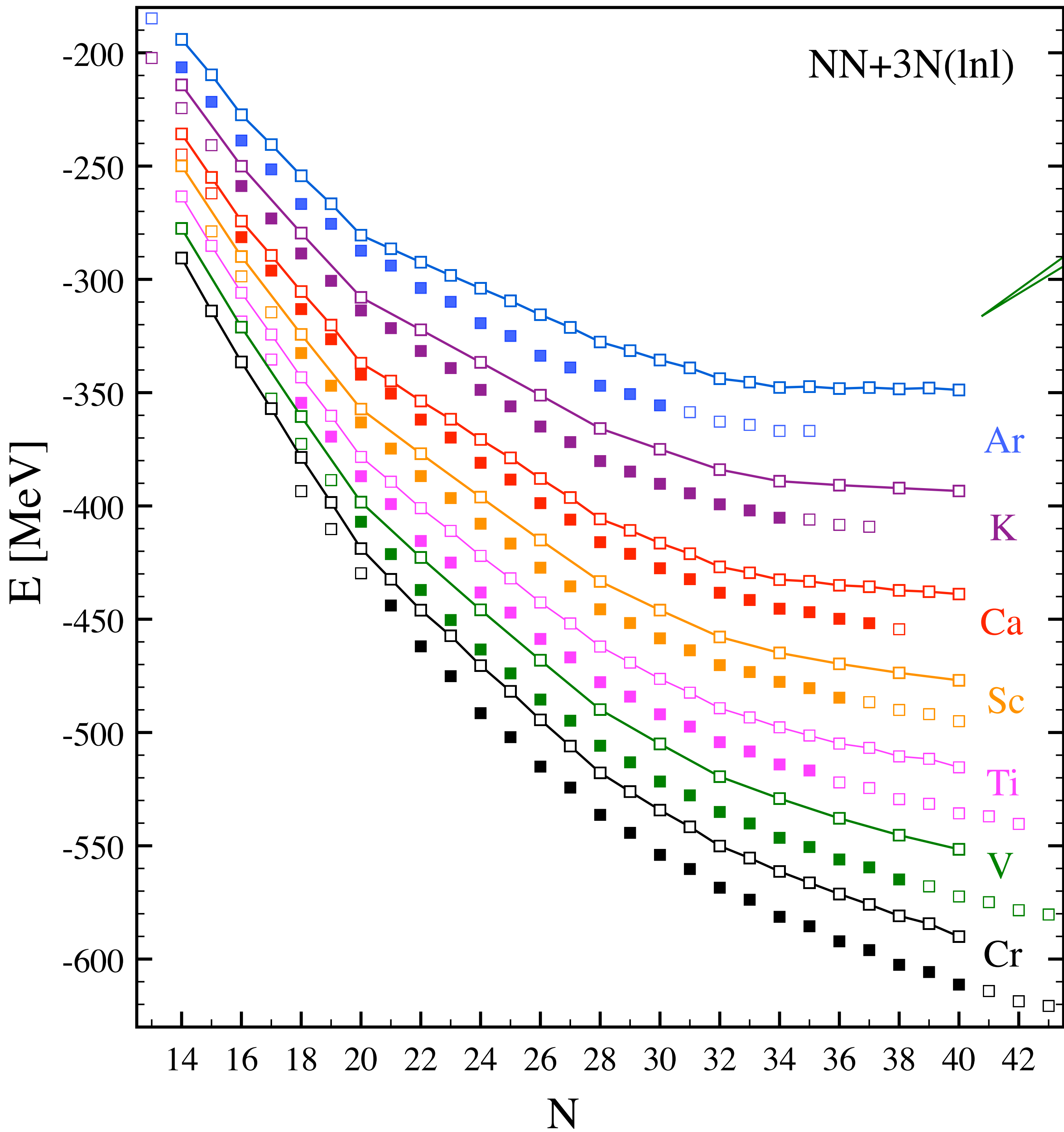


- ○ Novel Hamiltonians correct overbinding
- ○ 3rd-order yields needed correlations

- ○ Very reasonable agreement for S2n
- ○ N=20 gap still overestimated

Energy systematics: binding energies

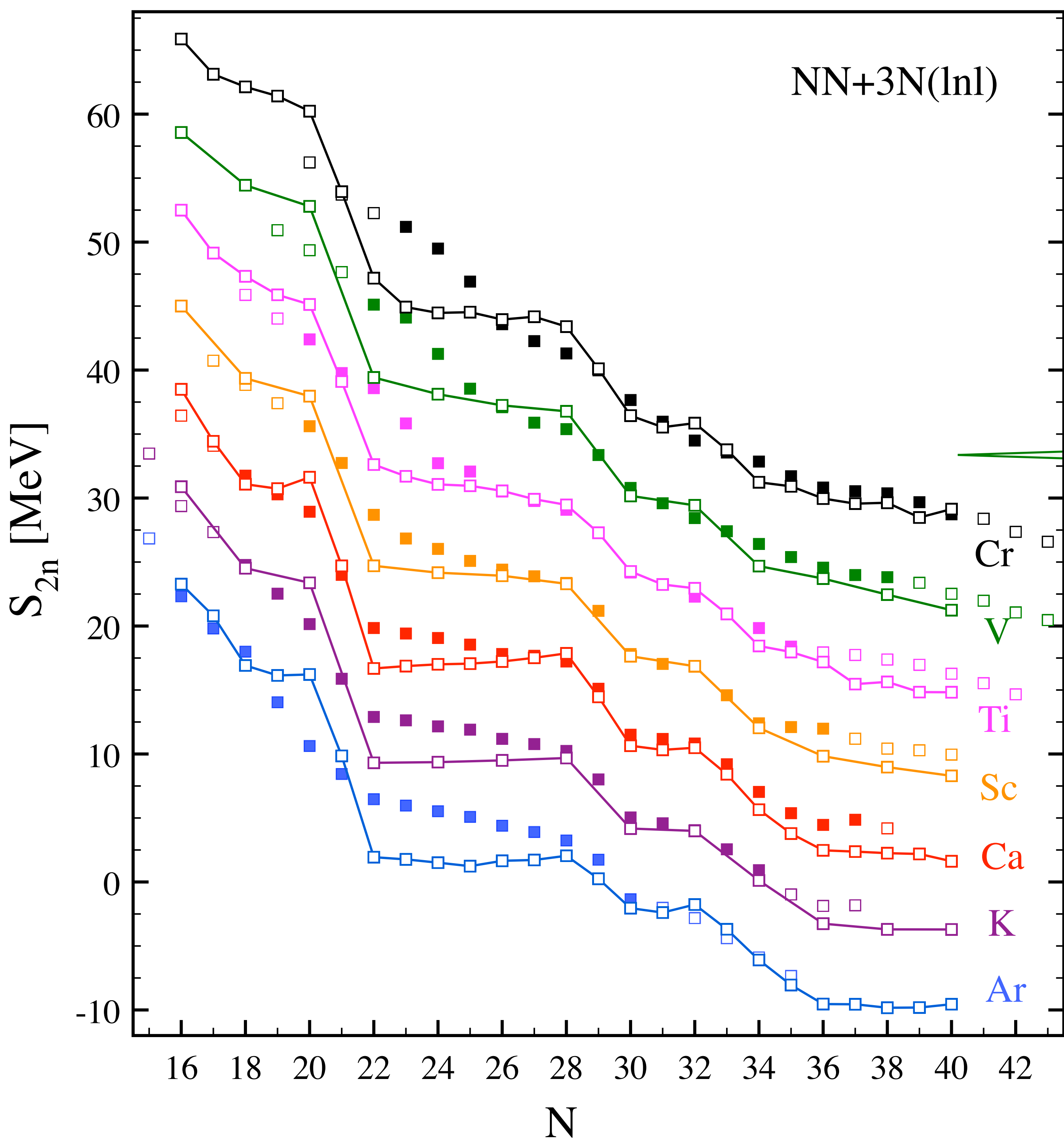
- Total energies $E(N, Z)$



- Several chains, not only semi-magic
- Trend w.r.t. experiment similar for all Z

Energy systematics: S_{2n}

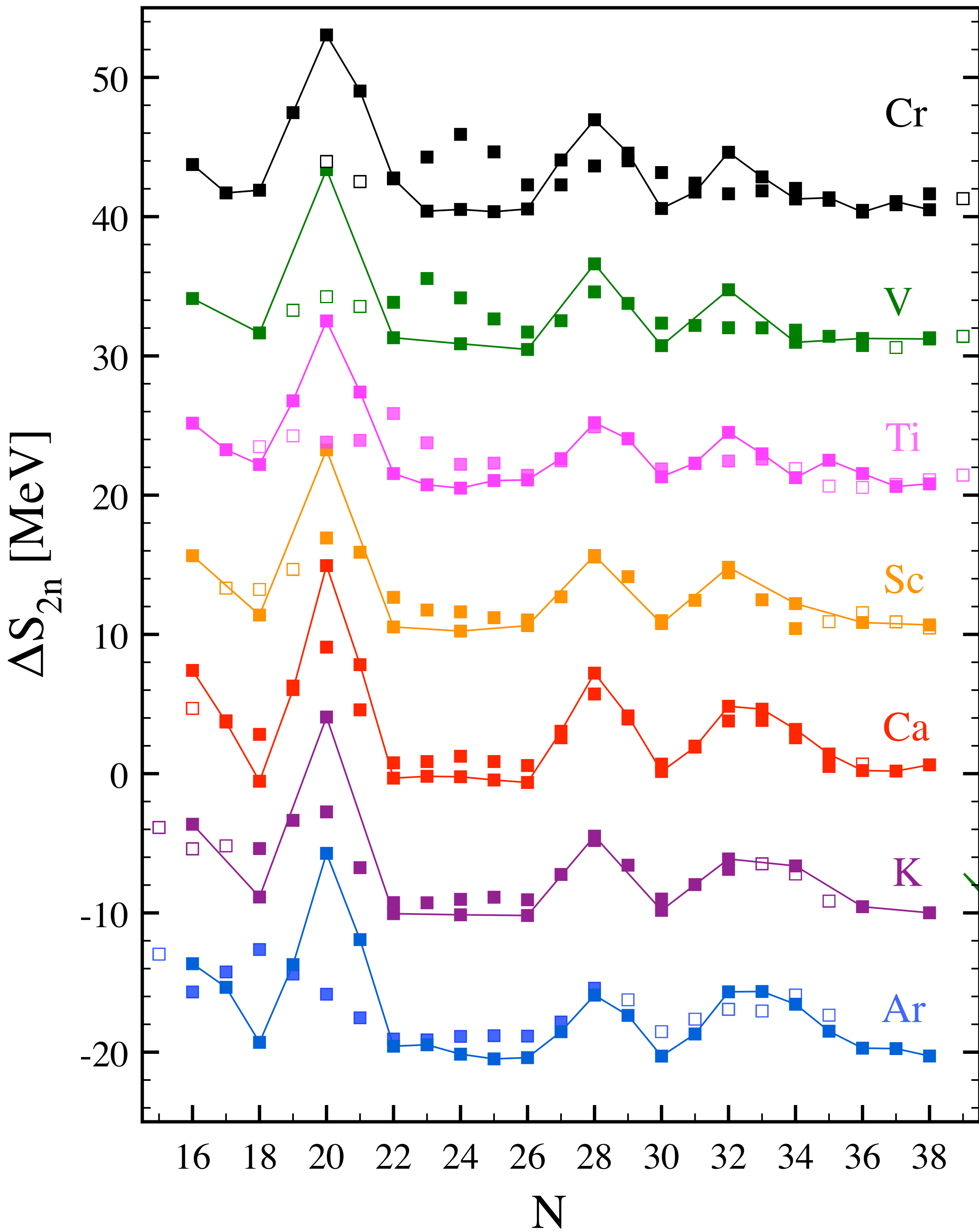
⊙ Two-neutron separation energies $S_{2\mathrm{n}}(N,Z) \equiv |E(N,Z)| - |E(N-2,Z)|$

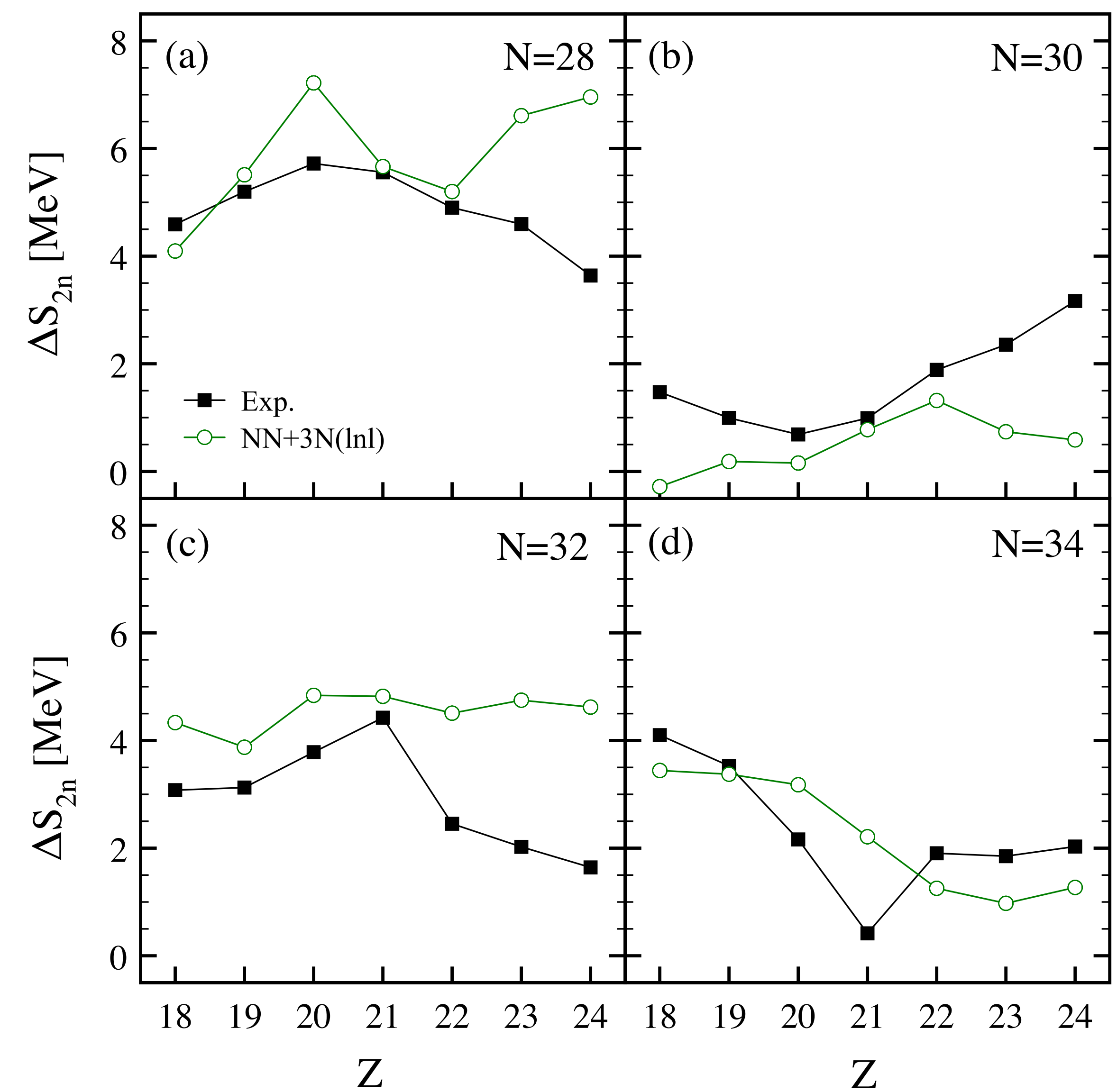


- ○ High-order corrections ~ cancel out
- ○ Overall good agreement with data
- ○ N=20 gap overestimated
- ○ Excellent reproduction for N>28

Energy systematics: gaps & magic numbers

- Neutron gaps $\Delta_{2n}(N,Z) \equiv S_{2n}(N,Z) - S_{2n}(N+2,Z)$

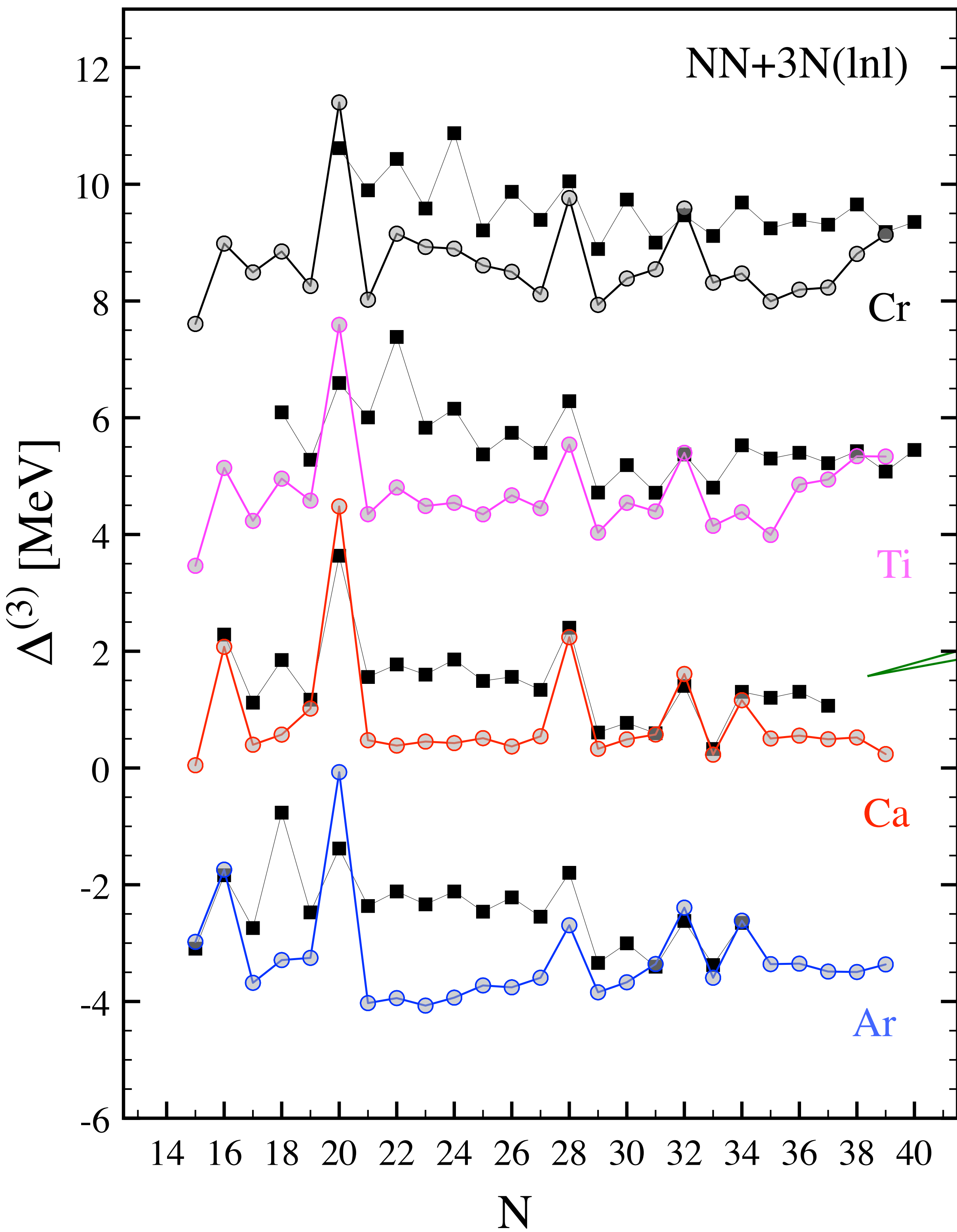




- Magic numbers emerge "ab initio"
- Evolution with Z captured

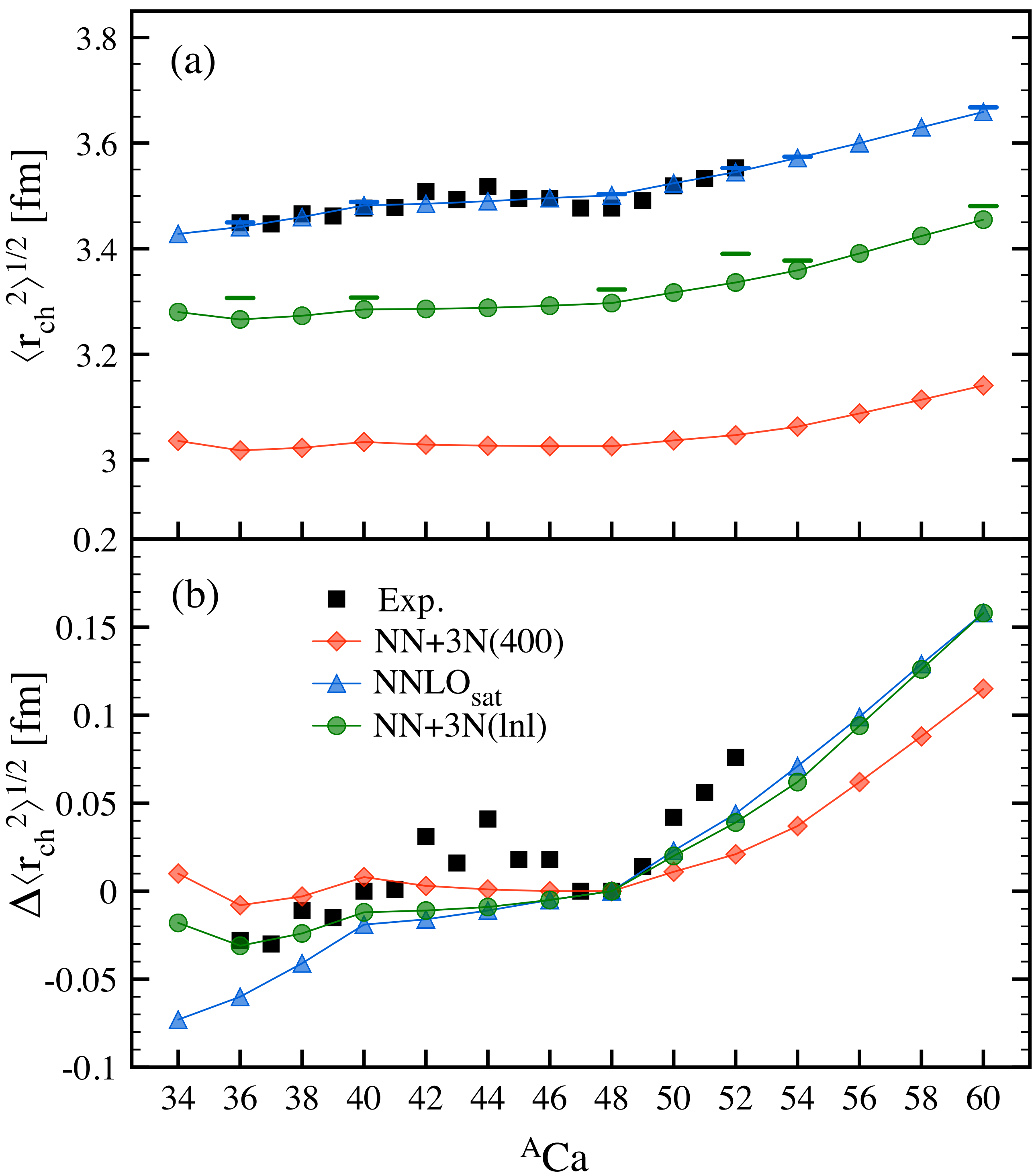
Energy systematics: pairing gaps

⦿ Three-point mass differences $\Delta^{(3)}(N,Z) \equiv \frac{(-1)^N}{2}[E(N-1,Z) - 2E(N,Z) + E(N+1,Z)]$

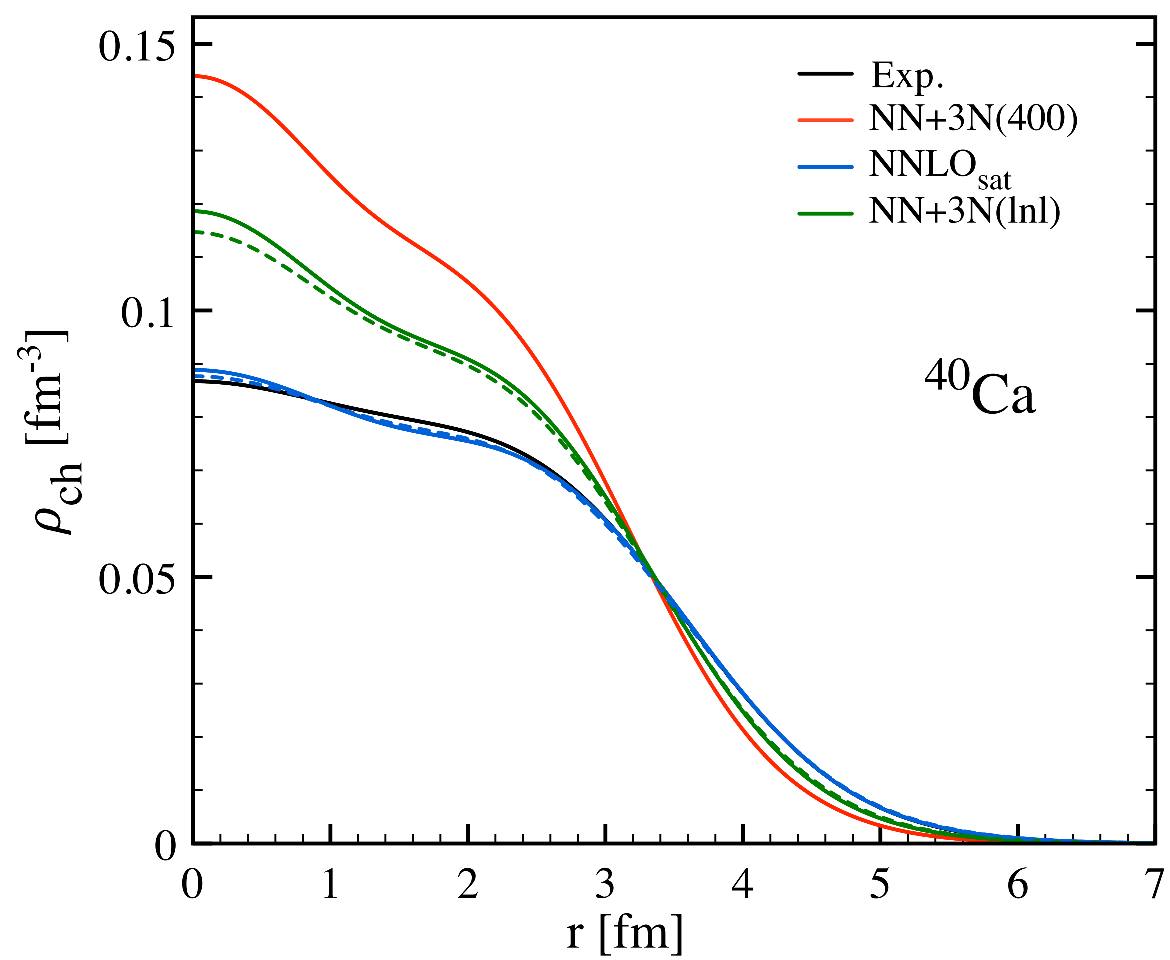


- ○ Magic peaks nicely visible
- ○ Pairing too weak
- ○ Dynamic contributions beyond second order?
- ○ Interaction?

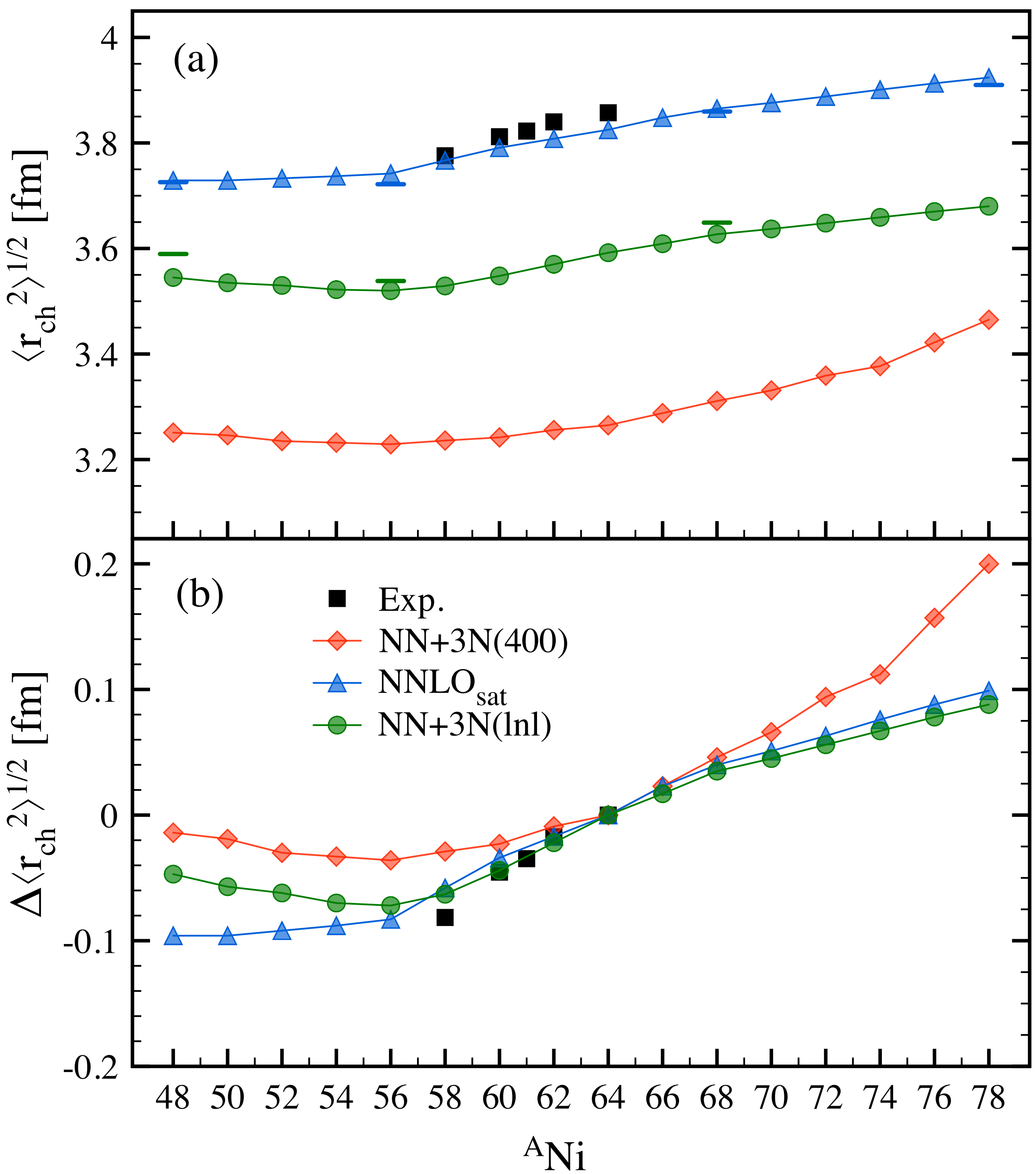
Charge radii & density distributions



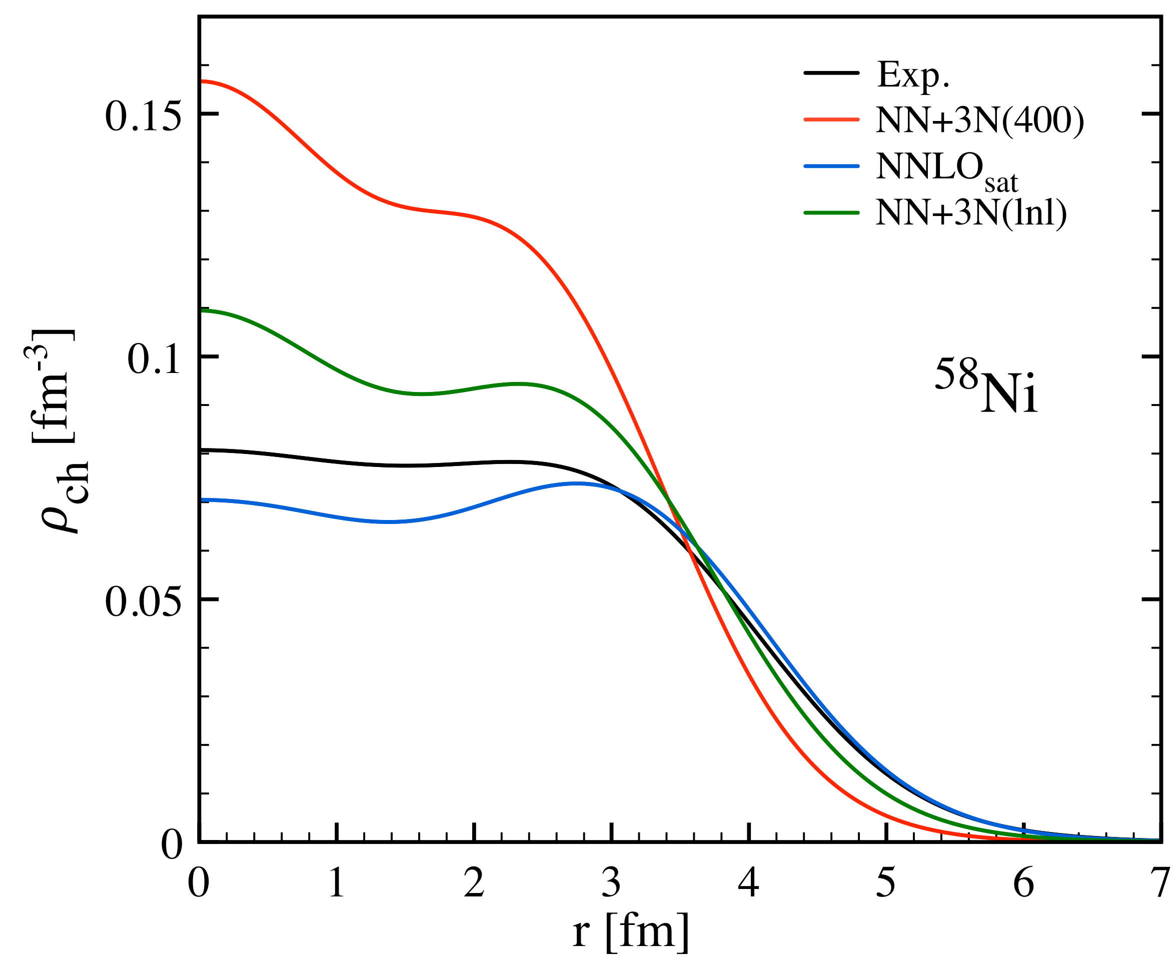
- ○ NNLO$_{sat}$ successful for absolute r_{ch}
- ○ Different behaviours for small N
- ○ All interactions struggle after N=28
- ○ Excellent reproduction of ρ_{ch}



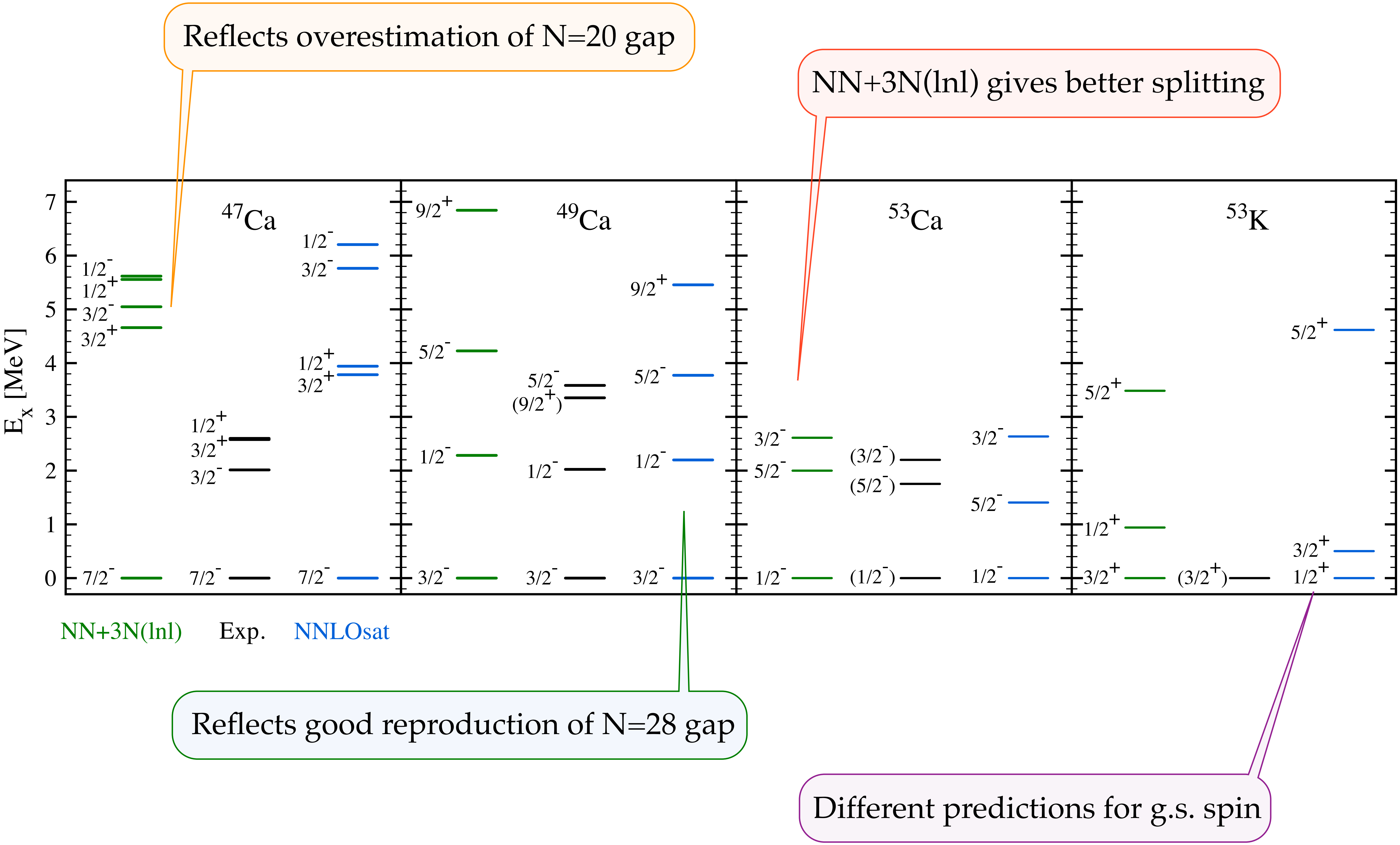
Charge radii & density distributions



- NNLO$_{sat}$ successful for absolute r_{ch}
- Different behaviours for small N
- Good agreement for differential r_{ch}
- Reproduction of ρ_{ch} slightly deteriorates



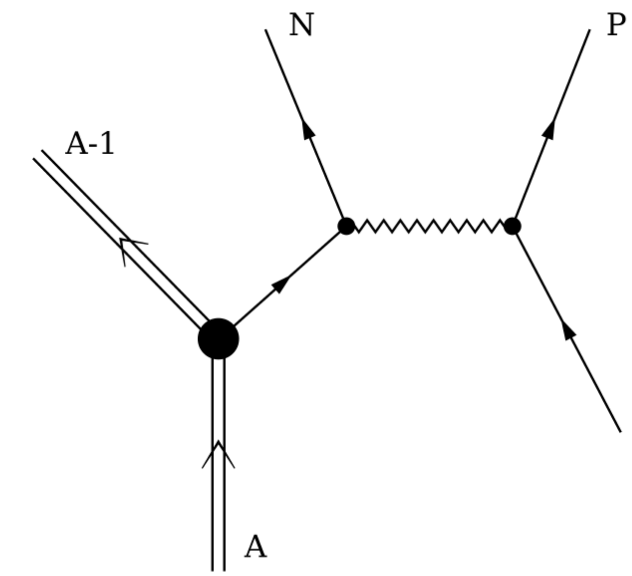
One-nucleon addition / removal spectra



Quasi-free knockout cross sections

- Distorted-wave impulse approximation (DWIA)

$$\left(\frac{d\sigma}{d^3Q}\right)_{\mathrm{DWIA}} = \mathrm{SF}_N \times \left\langle \frac{d\sigma_{pN}}{d\Omega} \right\rangle \times \left\langle S_{pA} S_{p(A-1)} S_{N(A-1)} \Psi_N \right\rangle$$

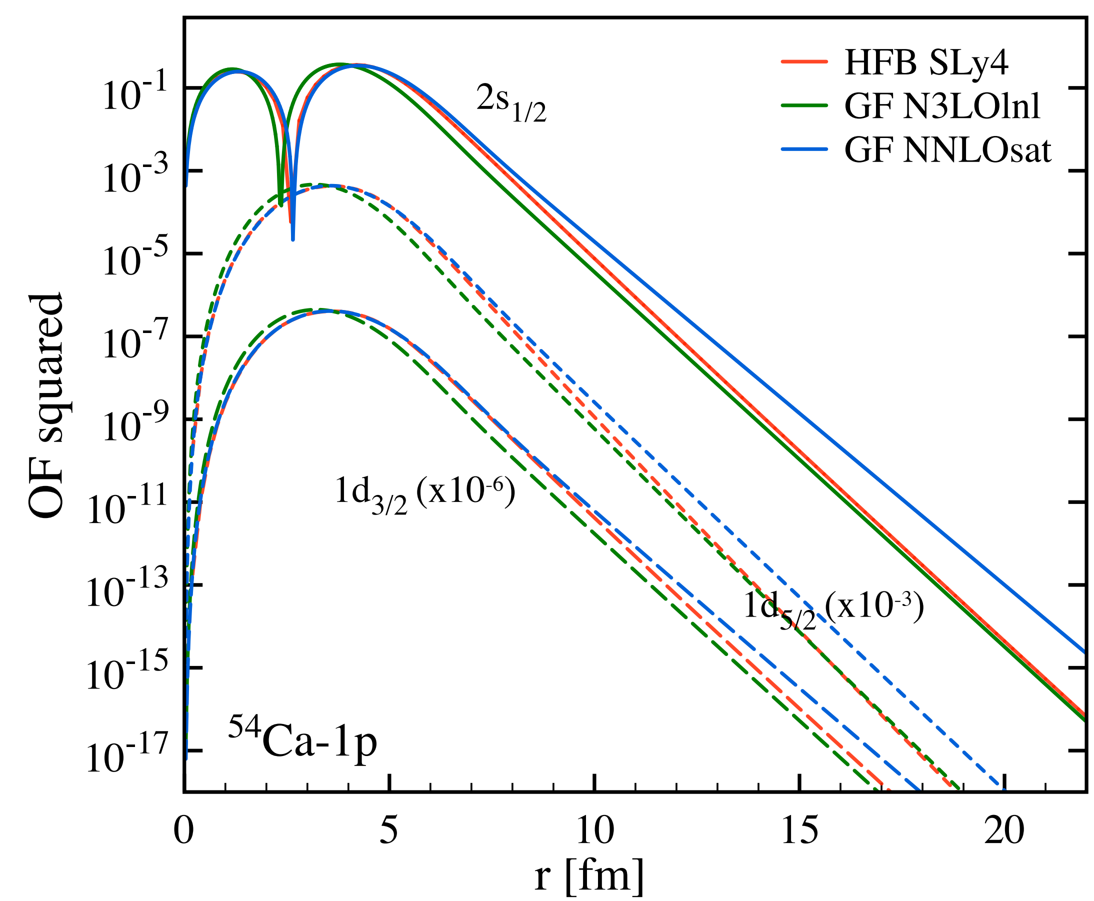


Spectroscopic factor

NN cross section

Scattering matrices for effective d.o.f.
(One-body overlaps + optical potentials)

σ [mb]		Exp.	GF	SM
^{52}Ca(*p*,2*p*)^{51}K	3/2$^+$	5.2(4)	3.56	4.55
	1/2$^+$	1.7(2)	1.87	2.34
^{54}Ca(*p*,2*p*)^{53}K	3/2$^+$	3.8(3)	3.25	4.16
	1/2$^+$	1.5(2)	1.71	2.09
^{54}Ca(*p*,*pn*)^{53}Ca	1/2$^-$	15.9(17)	11.6	13.2
	3/2$^-$	19.1(12)	17.0	22.2

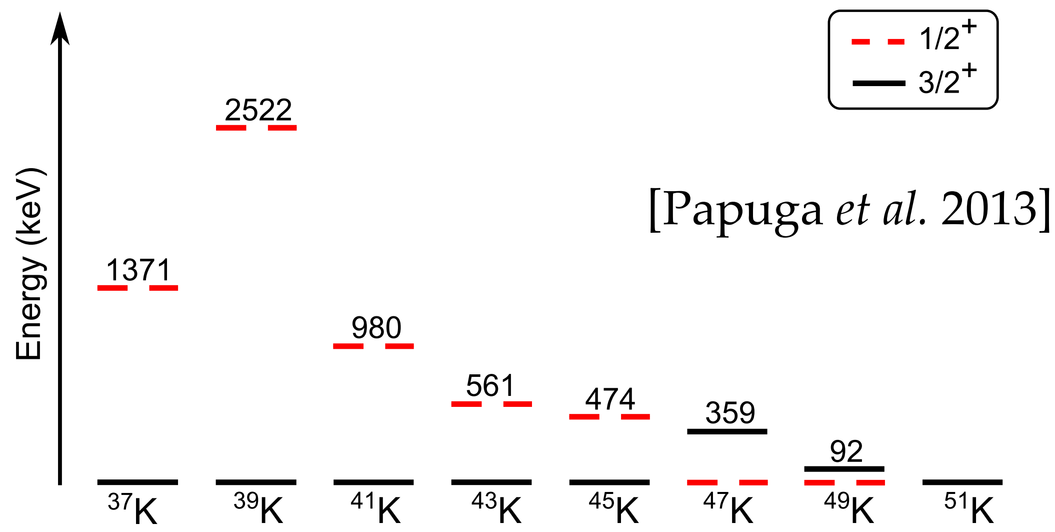


[Sun *et al.*, submitted, 2019 & Chen *et al.*, submitted, 2019]

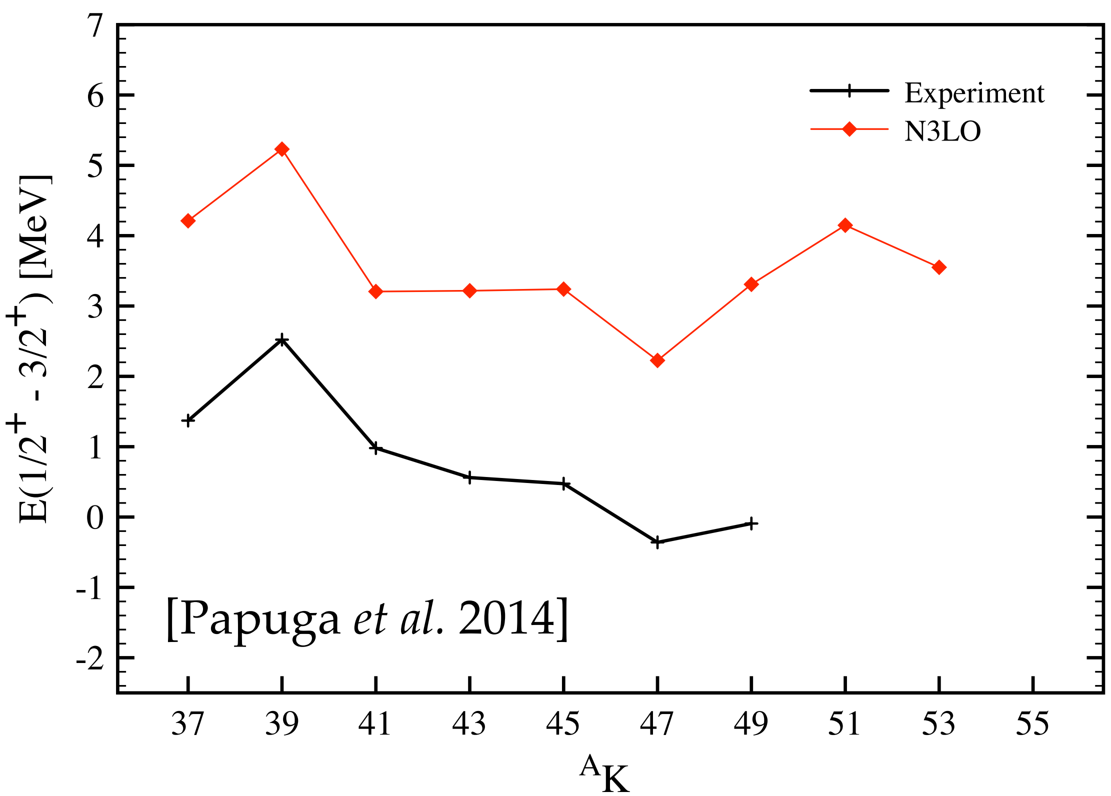
Spectra of K isotopes

- Interesting g.s. spin inversion and re-inversion in K spectra

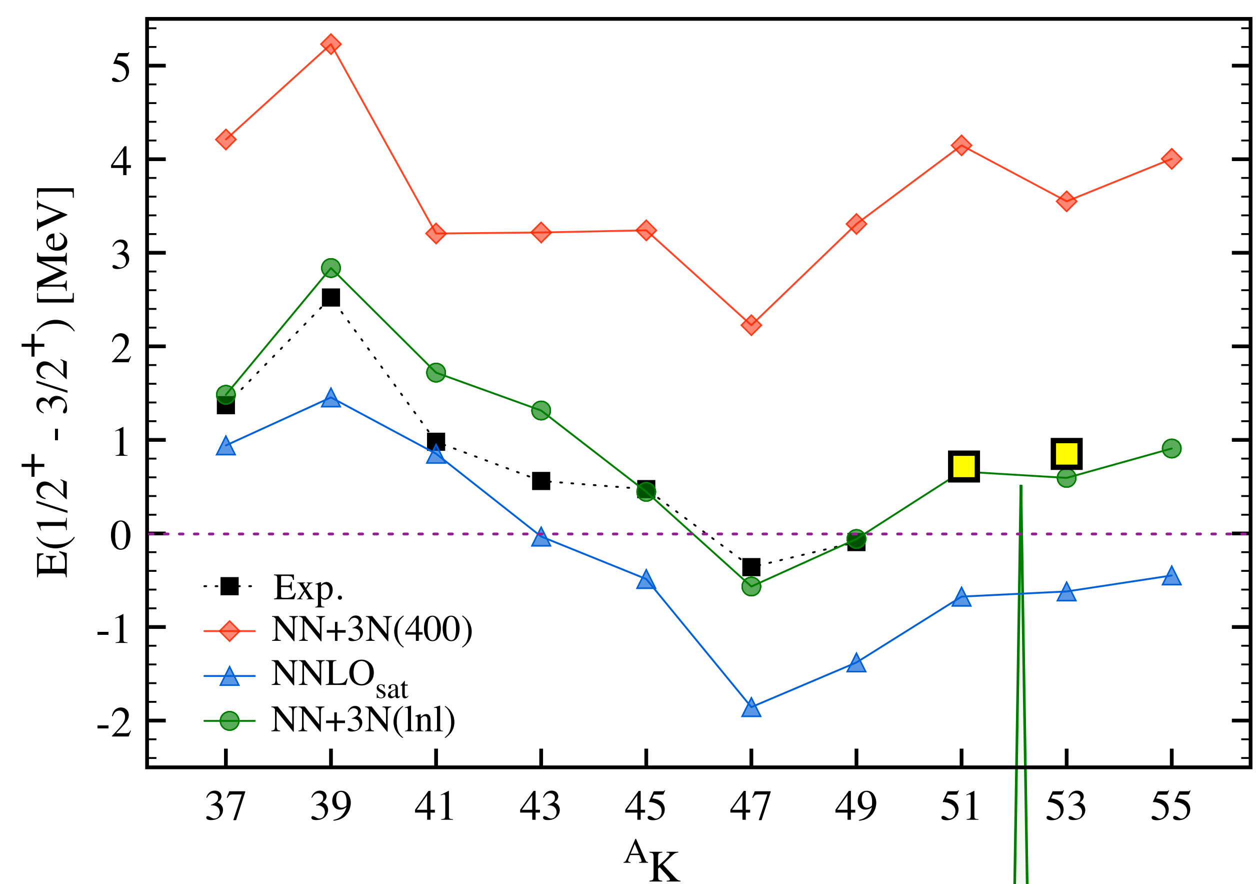
Laser spectroscopy COLLAPS @ ISOLDE



[Papuga *et al.* 2013]



[Papuga *et al.* 2014]

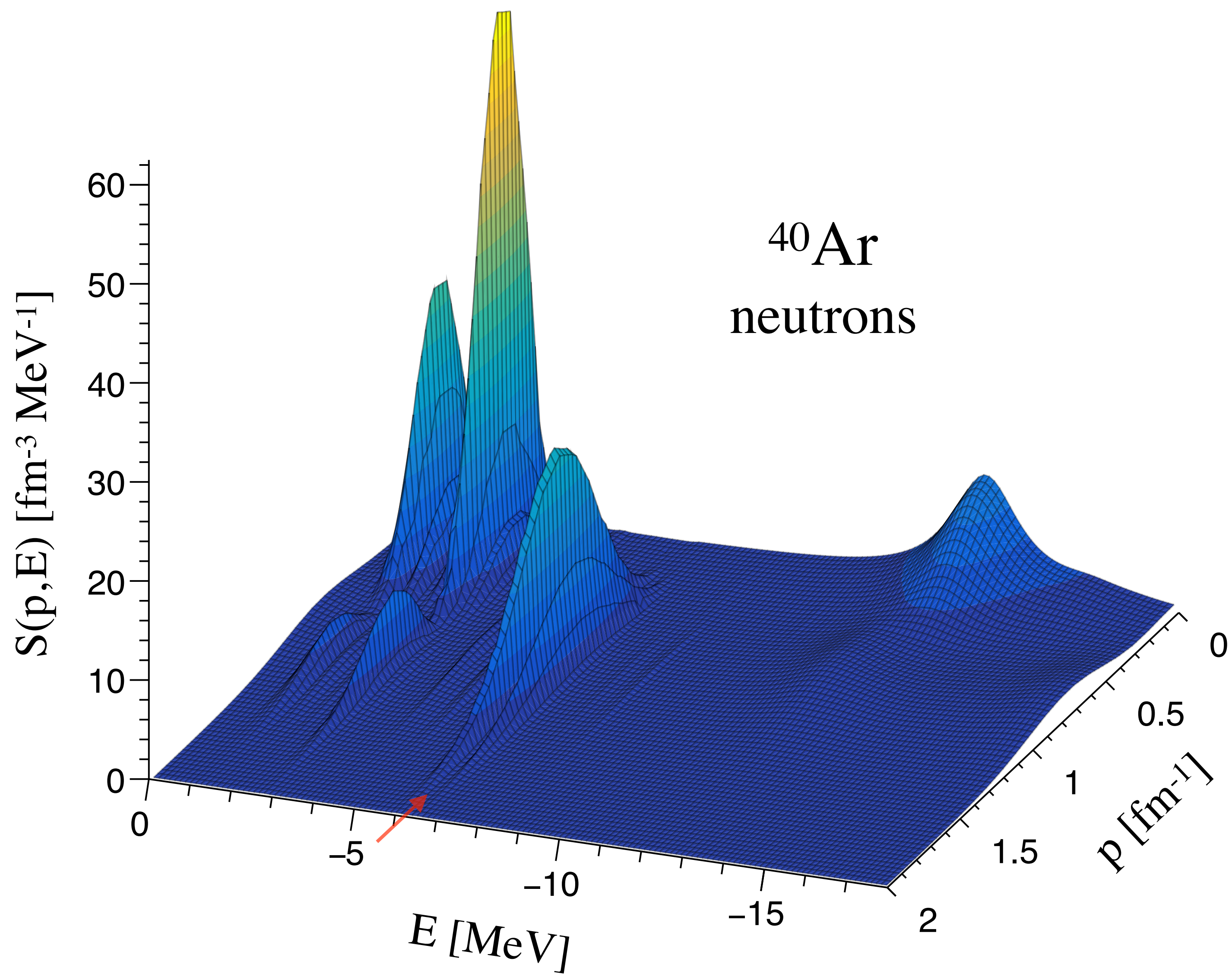


Recent experiment confirms
NN+3N(lnl) prediction for ^{51}K and ^{53}K

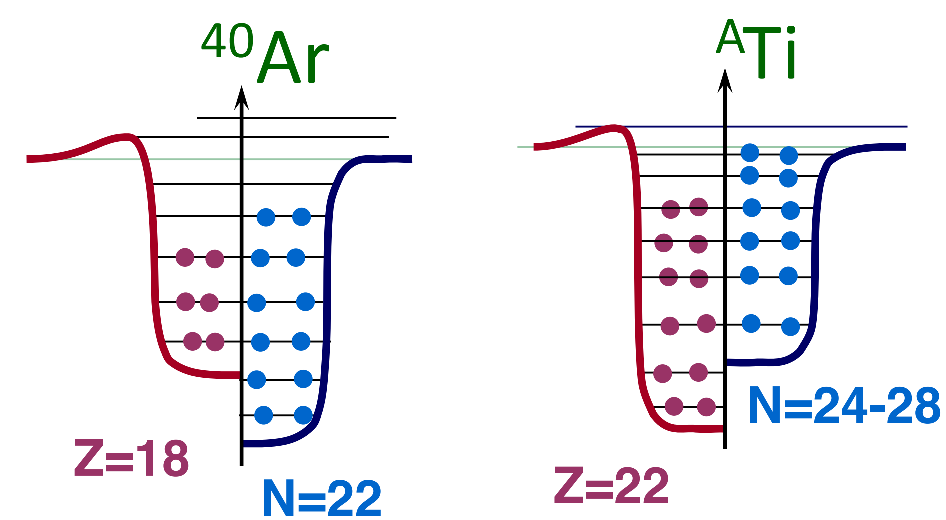
[Sun *et al.* submitted, 2019]

Electron and neutrino scattering

- Next-generation neutrino experiments (e.g. DUNE) make use of liquid-argon TPCs
  - Modelling **neutrino-^{40}Ar cross section** crucial
  - Impulse approximation ➞ nuclear structure effects encoded in the spectral function

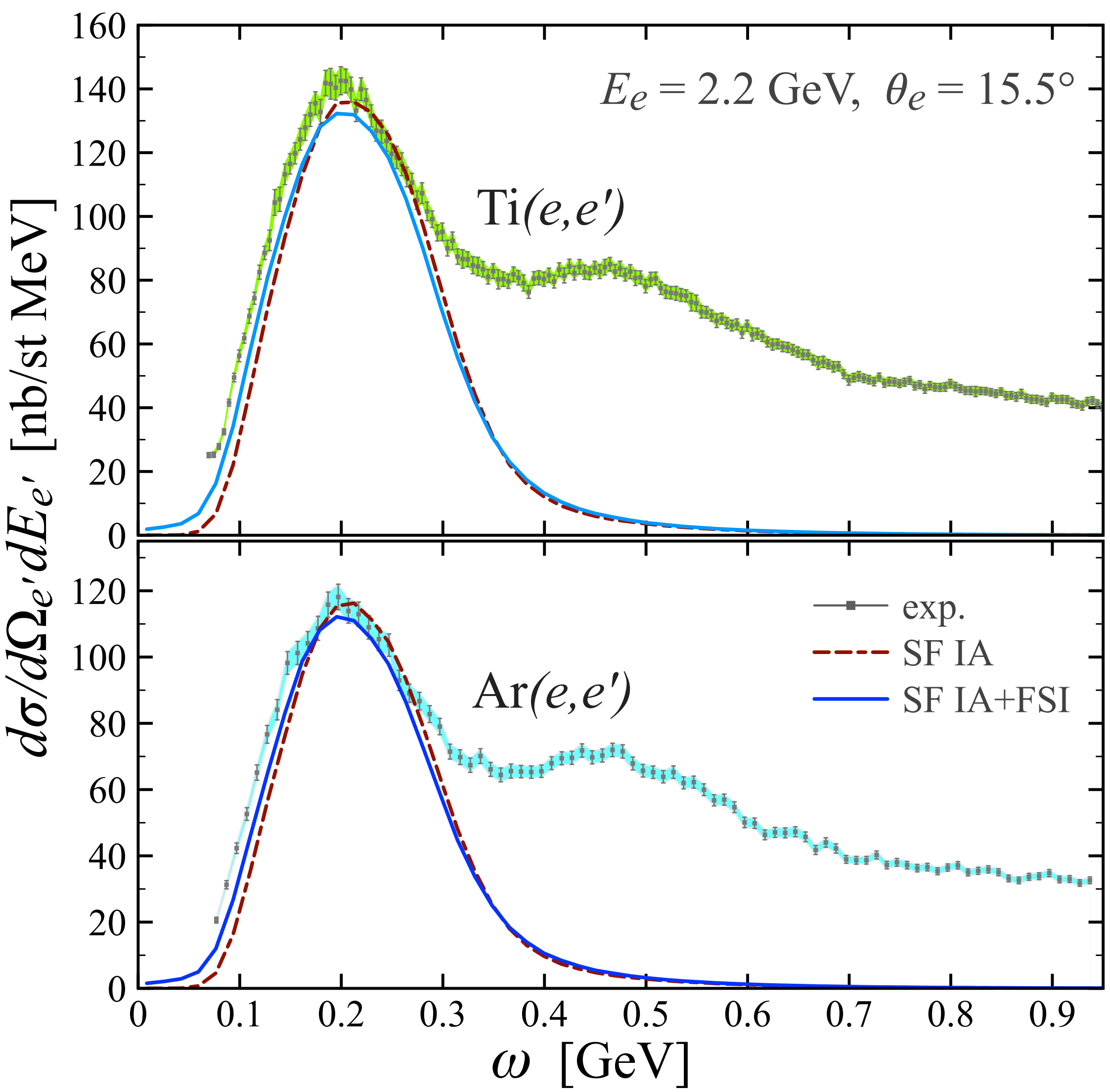


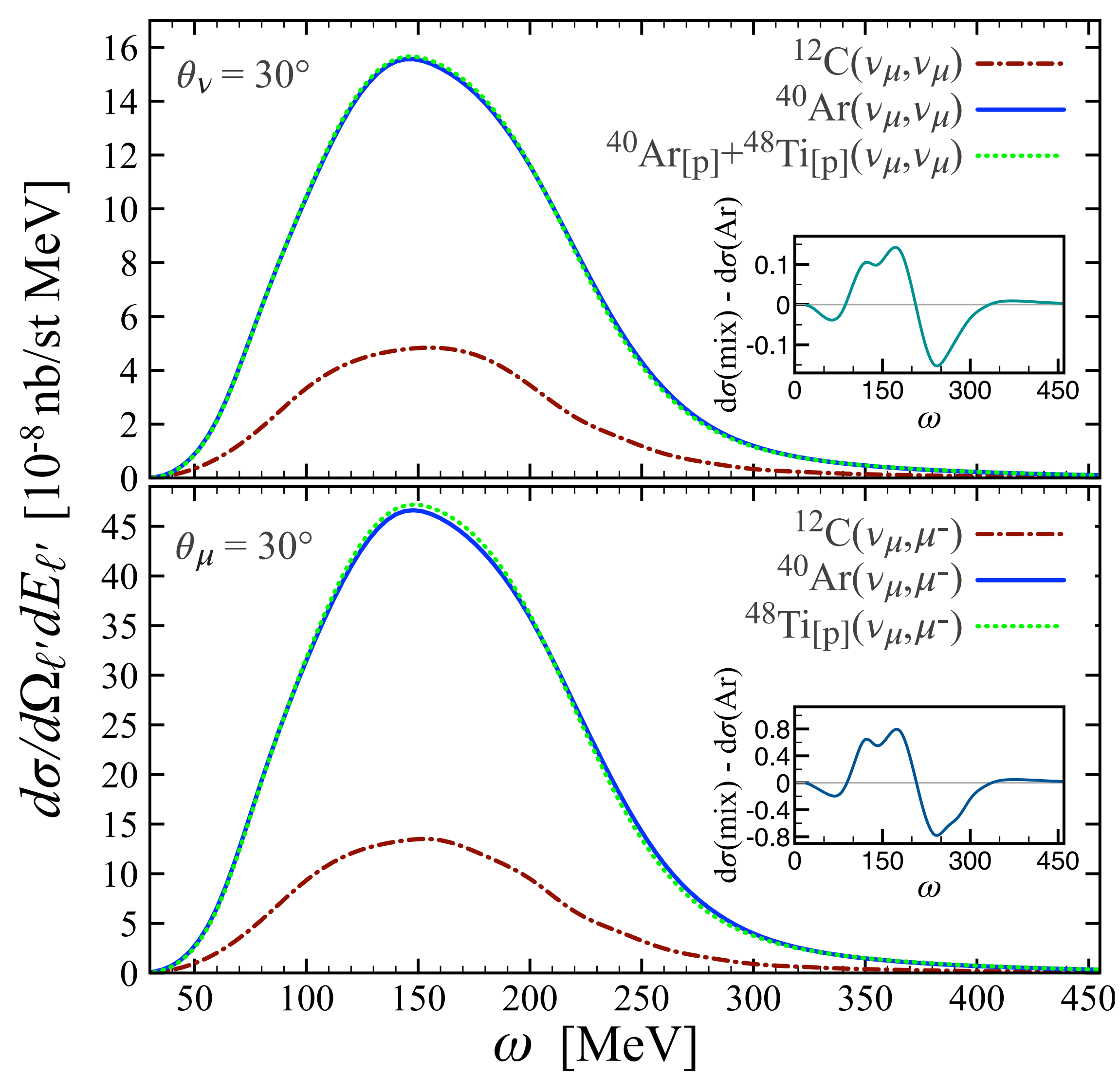
Motivated e-scattering experiments @JLAB



Electron and neutrino scattering

⦿ Application to **electron and neutrino scattering**





○ Good reproduction of JLAB data

○ Approximation ^{40}Ar$_{[n]} \longleftrightarrow$ ^{48}Ti$_{[p]}$ validated

[Dai *et al.* 2018 & 2019]

○ Small contribution from final-state interactions

○ To be included next: 2B currents

Conclusions

⦿ Considerable progress in ab initio calculations of (open-shell) mid-mass nuclei

⦿ **Many-body approaches**

- ○ Complementary methods ➞ benchmarks
- ○ Systematic calculations up to $A \sim 100$
- ○ Frontiers: doubly open-shell & heavy nuclei

⦿ **Hamiltonians**

- ○ Good quality, but not for all observables
- ○ Strong activity ongoing, new developments
- ○ Long-term: full assessment of uncertainties