ARIS2014 – Tokyo, June 2nd- 6th, 2014

Carlo Barbieri — University of Surrey

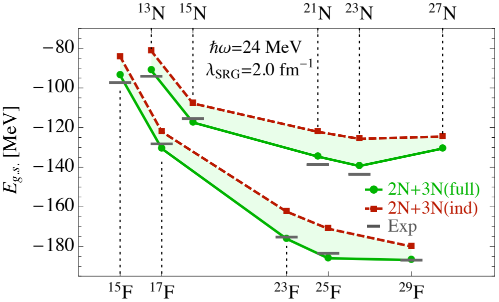
Three-Nucleon Forces in Neutron Rich Isotopes (from O to Ni)

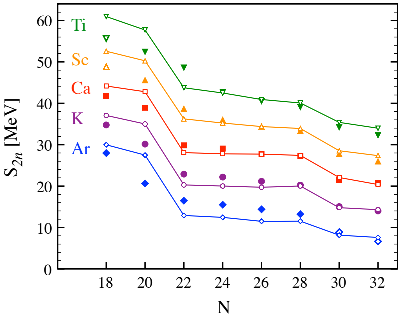
Collaborators:

A. Cipollone, CB, P. Navrátil: *Phys. Rev. Lett.* ***111**, 062501 (2013)*

V. Somà, A. Cipollone, CB, P. Navrátil, T. Duguet: *Phys. Rev. C* ***89**, 061301R (2014)*

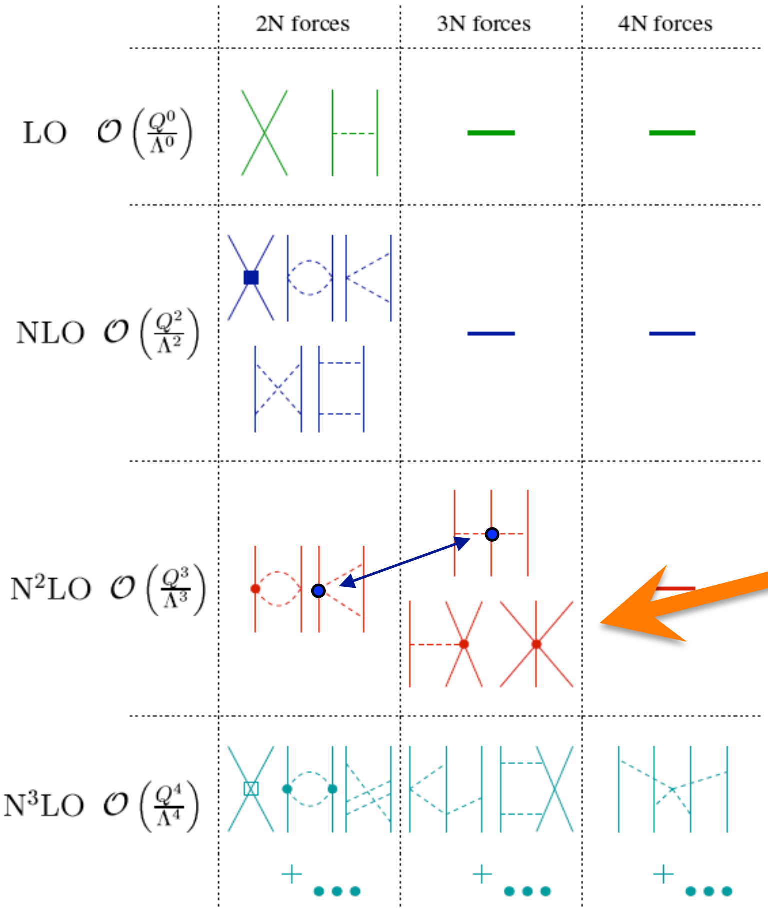
UNIVERSITY OF SURREY





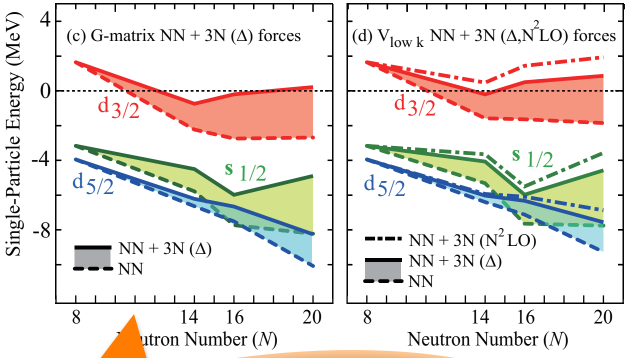
Modern realistic nuclear forces

Chiral EFT for nuclear forces:



(3NFs arise naturally at N2LO)

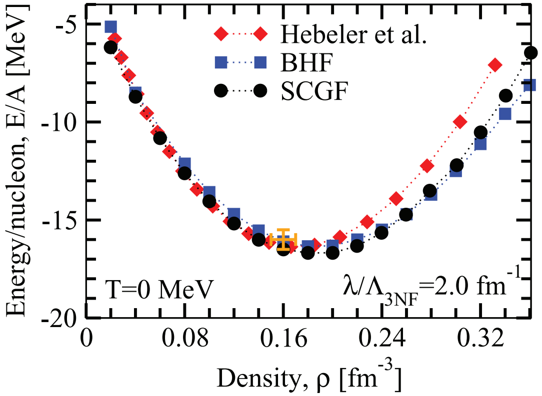
Single particle spectrum at E_{fermi}:



[T. Otsuka et al.,
Phys Rev. Lett **105**,
032501 (2010)]

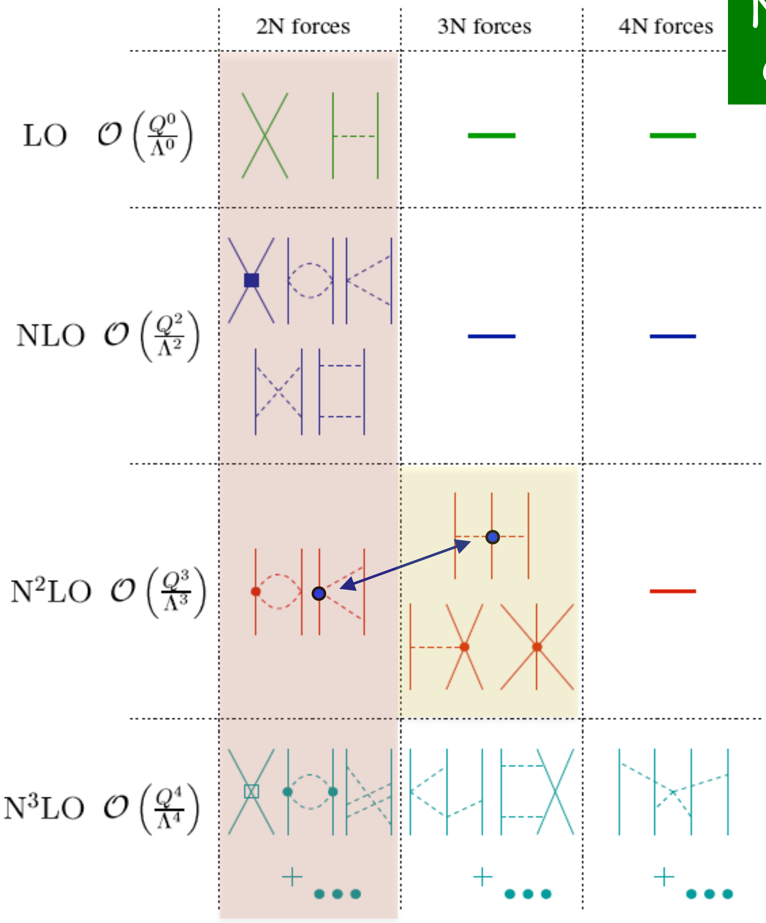
Need at LEAST 3NF!!!
("cannot" do RNB physics without…)

Saturation of nuclear matter:



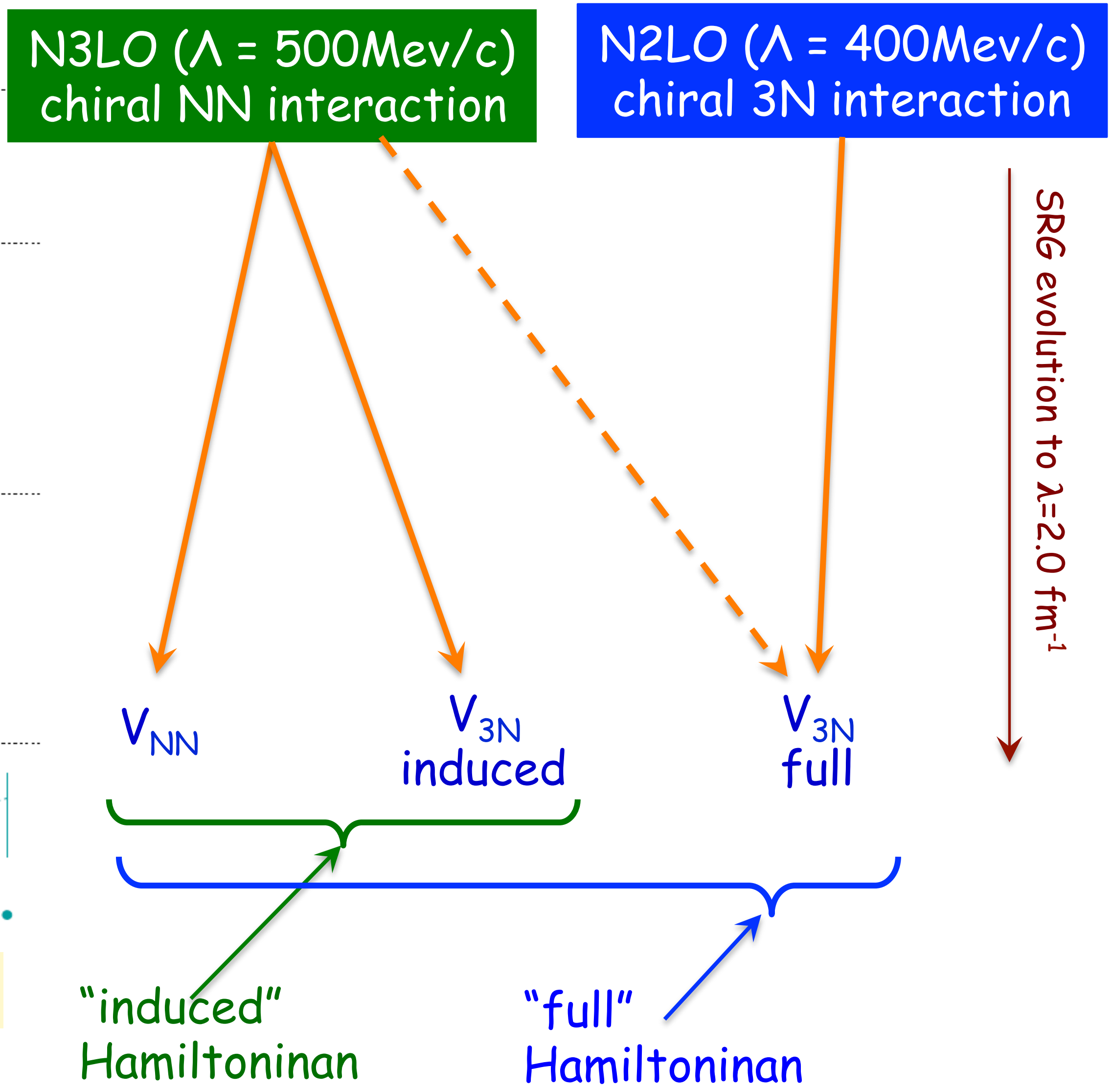
[A. Carbone et al.,
Phy.s Rev. C **88**, 044302 (2013)]

Chiral Nuclear forces - SRG evolved



(3NFs arise naturally at N2LO)

[Jurgenson, Navrátil, Furnstahl,
Phys. Rev. Lett. **103**, 082501 (2009);
Hebeler, Phys. Rev. C 85, 021002 (2012)]



N3LO (Λ = 500Mev/c)
chiral NN interaction

N2LO (Λ = 400Mev/c)
chiral 3N interaction

SRG evolution to λ=2.0 fm^{-1}

V_{NN}

V_{3N}
induced

V_{3N}
full

"induced"
Hamiltoninan

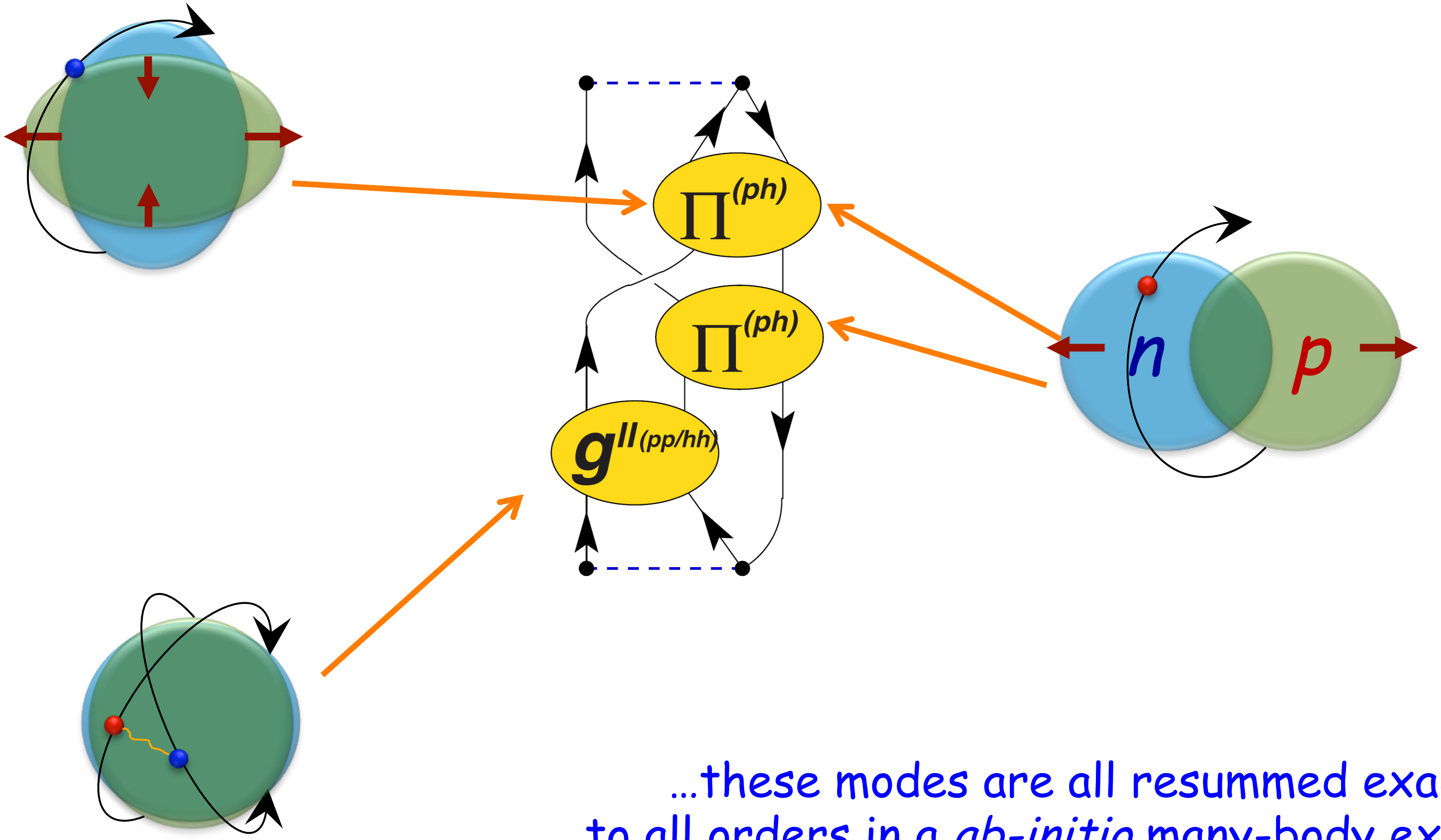
"full"
Hamiltoninan

Faddeev-RPA in two words…

Particle vibration coupling is the main cause driving the distribution of particle strength—a least close to the Fermi surface…

↑ ≡ particle

↓ ≡ hole



…these modes are all resummed exactly and to all orders in a *ab-initio* many-body expansion.

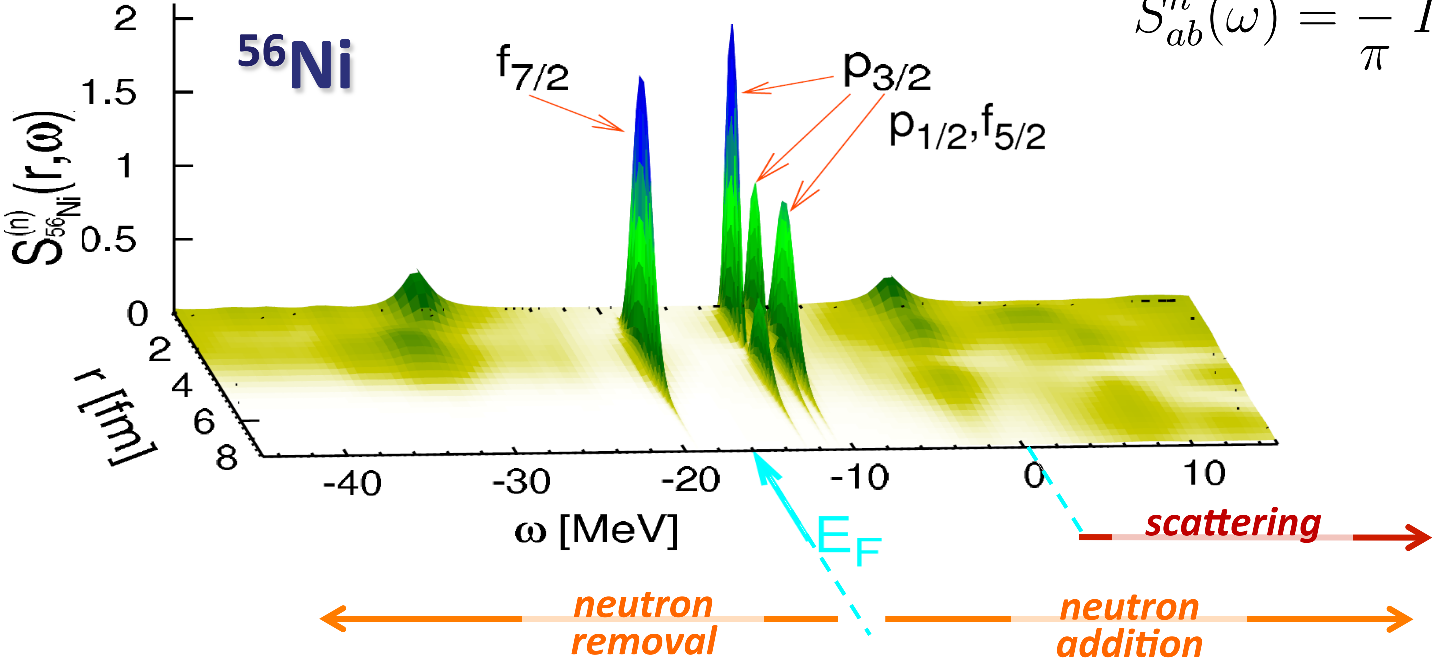
Green's functions in many-body theory

One-body Green's function (or propagator) describes the motion of quasi-particles and holes:

$$g_{\alpha\beta}(E) = \sum_n \frac{\langle\Psi_0^A|c_\alpha|\Psi_n^{A+1}\rangle\langle\Psi_n^{A+1}|c_\beta^\dagger|\Psi_0^A\rangle}{E-(E_n^{A+1}-E_0^A)+i\eta} + \sum_k \frac{\langle\Psi_0^A|c_\beta^\dagger|\Psi_k^{A-1}\rangle\langle\Psi_k^{A-1}|c_\alpha|\Psi_0^A\rangle}{E-(E_0^A-E_k^{A-1})-i\eta}$$

…this *contains all the structure information* probed by nucleon transfer (spectral function):

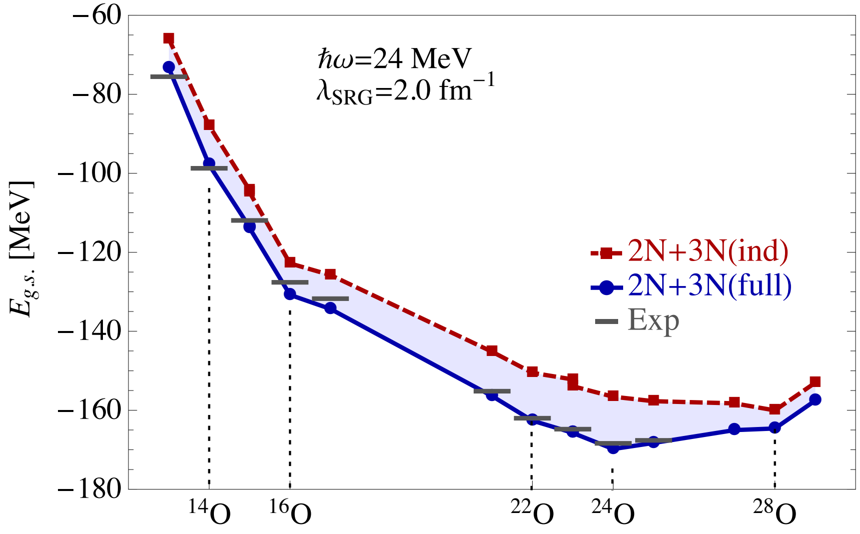
$$S^h_{ab}(\omega) = \frac{1}{\pi}\, Im\, g_{ab}(\omega)$$

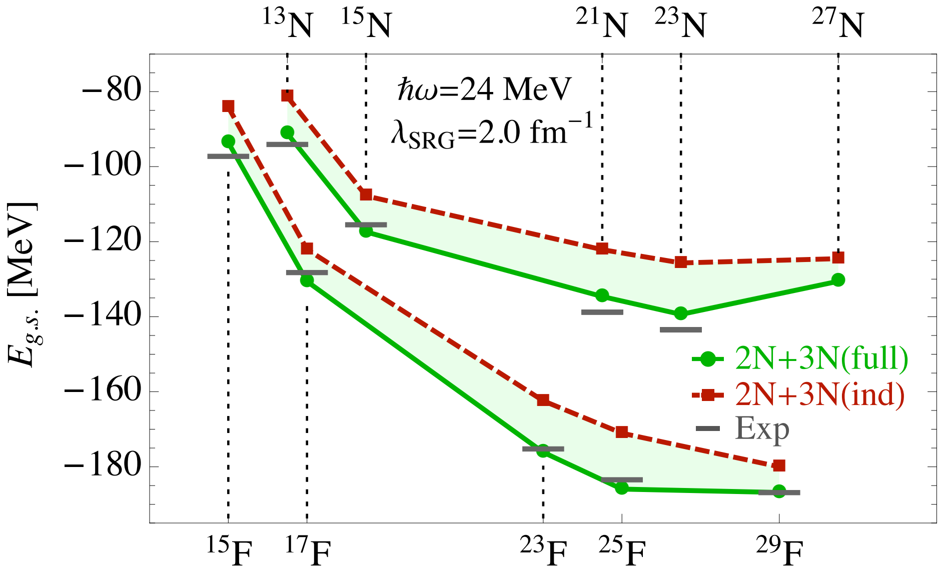


[CB, M.Hjorth-Jensen, Pys. Rev. C**79**, 064313 (2009); CB, Phys. Rev. Lett. **103**, 202502 (2009)]

Results for the N-O-F chains

A. Cipollone, CB, P. Navrátil, Phys. Rev. Lett. **111**, 062501 (2013)





→ 3NF crucial for reproducing binding energies and driplines around oxygen

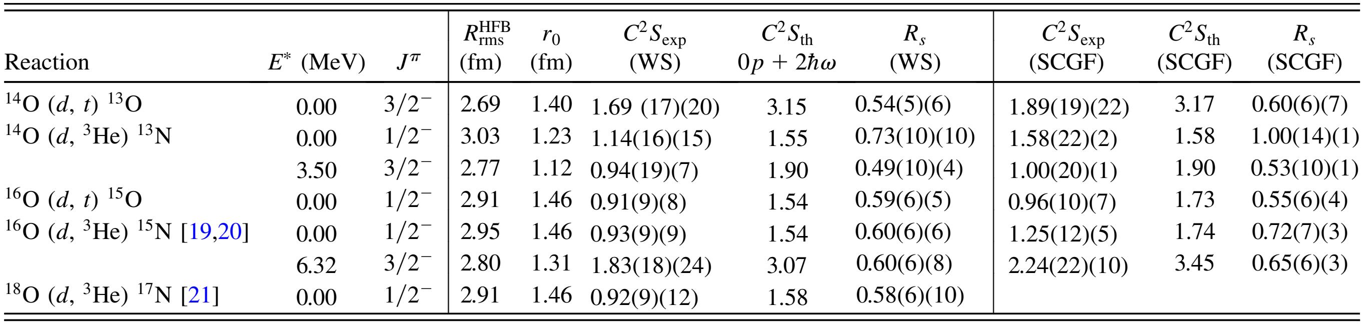
→ cf. microscopic shell model [Otsuka et al, PRL**105**, 032501 (2010).]

N3LO (Λ = 500Mev/c) chiral NN interaction evolved to 2N + 3N forces (2.0fm^{-1})
N2LO (Λ = 400Mev/c) chiral 3N interaction evolved (2.0fm^{-1})

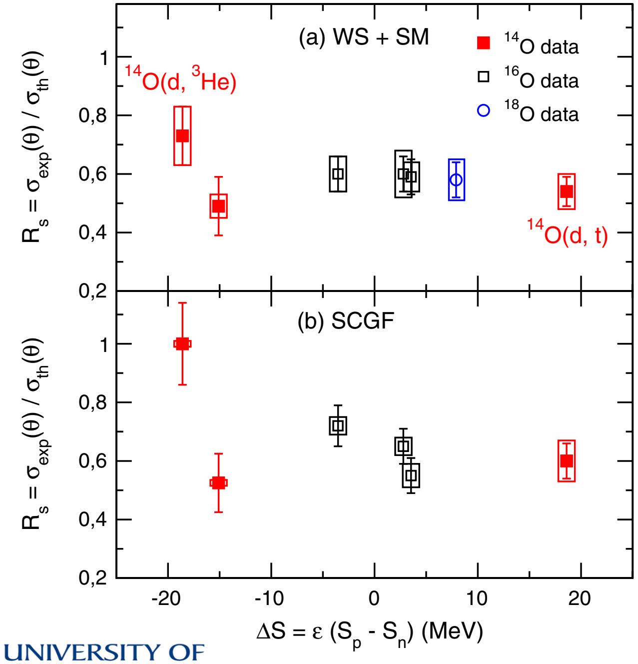
Single nucleon transfer in the oxygen chain

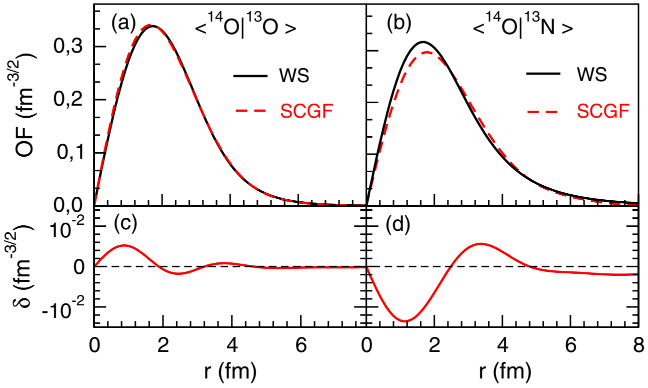
[F. Flavigny et al, PRL**110**, 122503 (2013)]

→ Analysis of ^{14}O(d,t)^{13}O and ^{14}O(d,^{3}He)^{13}N transfer reactions @ SPIRAL



Reaction	E^* (MeV)	J^π	$R_{\rm rms}^{\rm HFB}$ (fm)	r_0 (fm)	$C^2S_{\rm exp}$ (WS)	$C^2S_{\rm th}$ $0p + 2\hbar\omega$	R_s (WS)	$C^2S_{\rm exp}$ (SCGF)	$C^2S_{\rm th}$ (SCGF)	R_s (SCGF)
^{14}O (d, t) ^{13}O	0.00	$3/2^-$	2.69	1.40	1.69 (17)(20)	3.15	0.54(5)(6)	1.89(19)(22)	3.17	0.60(6)(7)
^{14}O $(d, {}^3$He$)$ ^{13}N	0.00	$1/2^-$	3.03	1.23	1.14(16)(15)	1.55	0.73(10)(10)	1.58(22)(2)	1.58	1.00(14)(1)
	3.50	$3/2^-$	2.77	1.12	0.94(19)(7)	1.90	0.49(10)(4)	1.00(20)(1)	1.90	0.53(10)(1)
^{16}O (d, t) ^{15}O	0.00	$1/2^-$	2.91	1.46	0.91(9)(8)	1.54	0.59(6)(5)	0.96(10)(7)	1.73	0.55(6)(4)
^{16}O $(d, {}^3$He$)$ ^{15}N [19,20]	0.00	$1/2^-$	2.95	1.46	0.93(9)(9)	1.54	0.60(6)(6)	1.25(12)(5)	1.74	0.72(7)(3)
	6.32	$3/2^-$	2.80	1.31	1.83(18)(24)	3.07	0.60(6)(8)	2.24(22)(10)	3.45	0.65(6)(3)
^{18}O $(d, {}^3$He$)$ ^{17}N [21]	0.00	$1/2^-$	2.91	1.46	0.92(9)(12)	1.58	0.58(6)(10)			



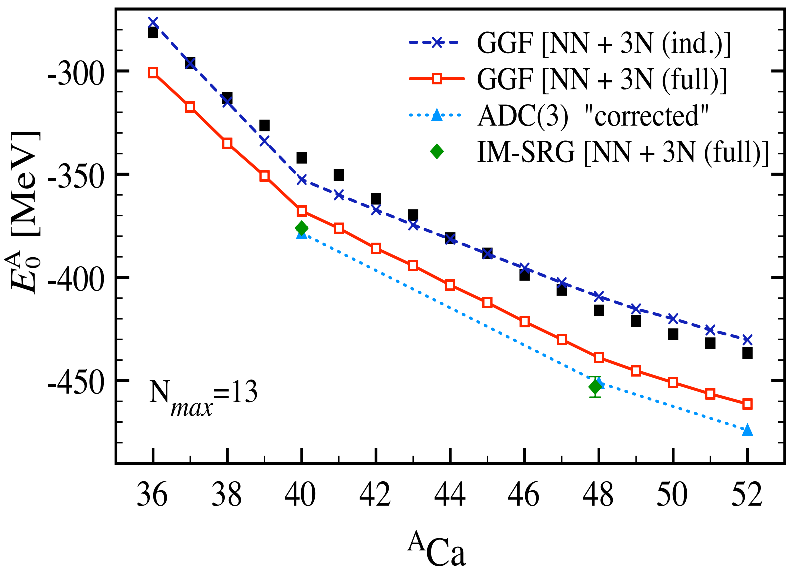


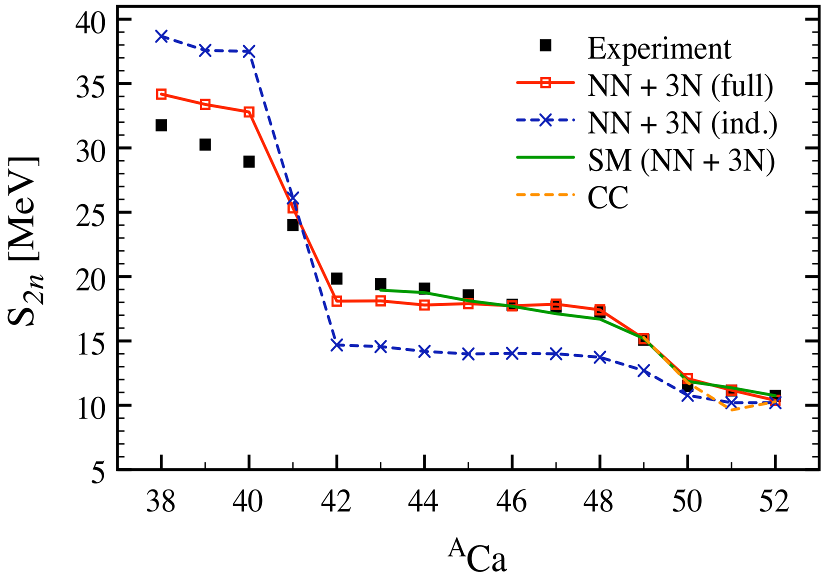
- Overlap functions and strengths from GF

- Rs independent of asymmetry

Calcium isotopic chain

Ab-initio calculation of the whole Ca: *induced* and full3NF investigated





→ *induced* and full3NF investigated

→ genuine (N2LO) 3NF needed to reproduce the energy curvature and S_{2n}

→ N=20 and Z=20 gaps overestimated!

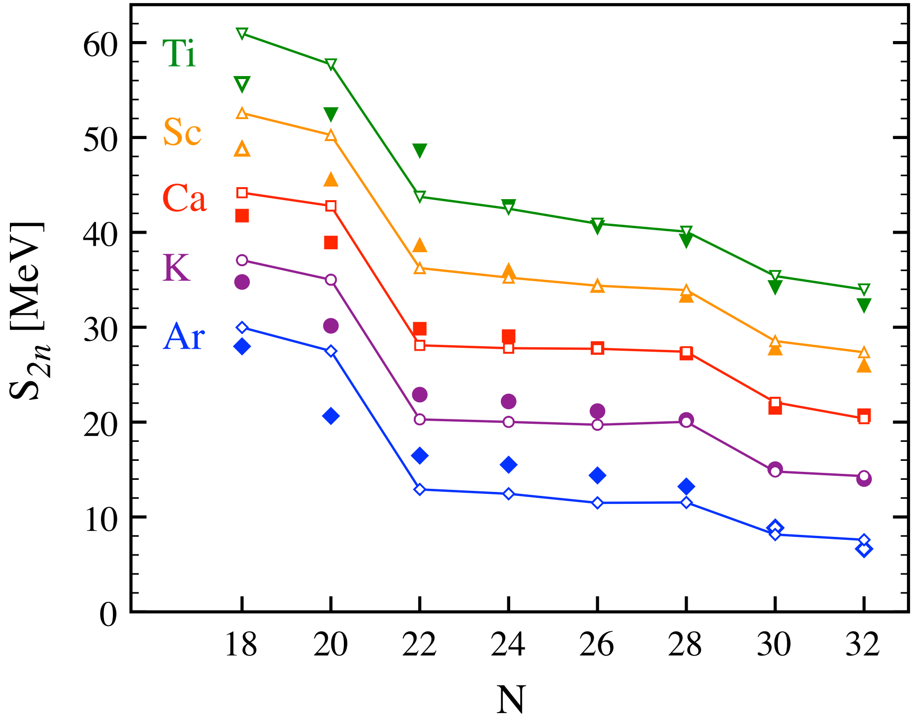
→ Full 3NF give a correct trend but over bind!

V. Somà, CB *et al.* Phys. Rev. C**89**, 061301R (2014)

Neighbouring Ar, K, Ca, Sc, and Ti chains

V. Somà, CB *et al.* Phys. Rev. C**89**, 061301R (2014)

Two-neutron separation energies predicted by chiral NN+3NF forces:



→ First *ab-initio* calculation over a contiguous portion of the nuclear chart—open shells are now possible through the Gorkov-GF formalism

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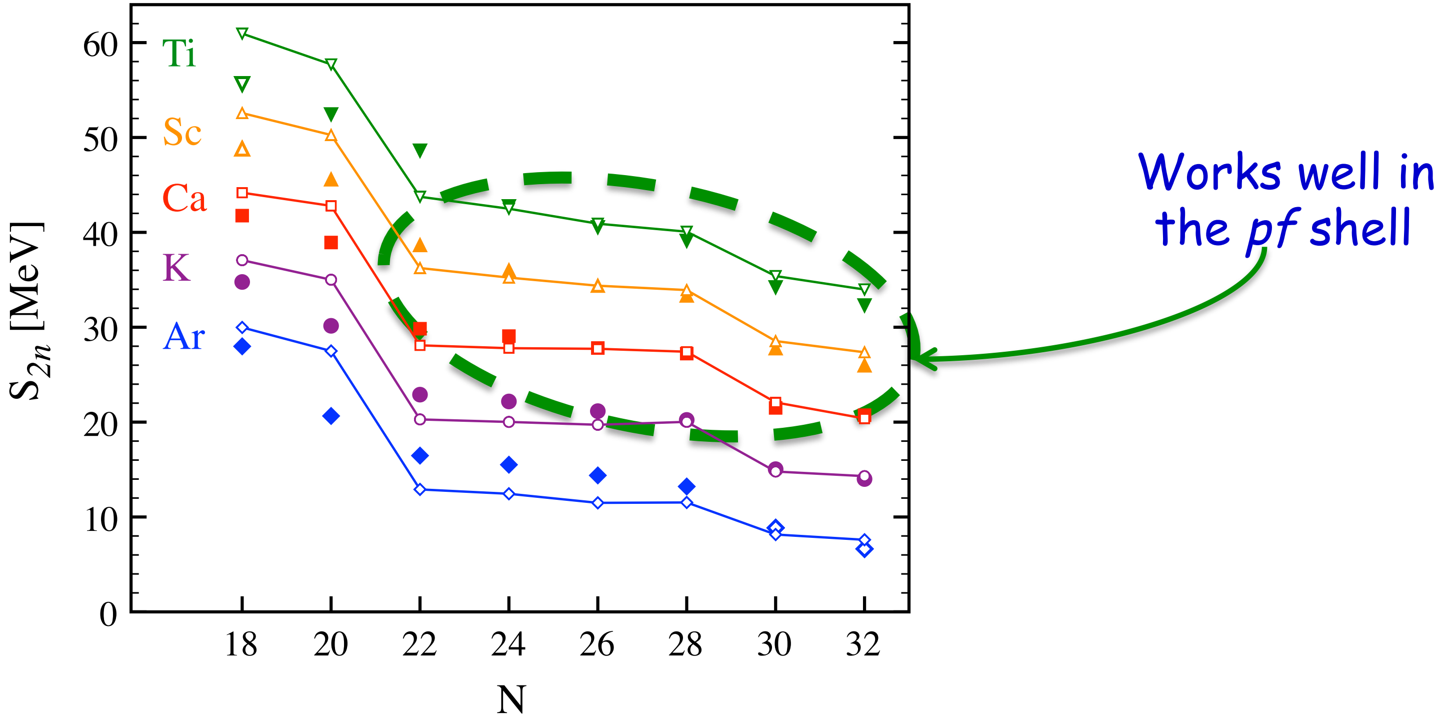

Works well in the *pf* shell

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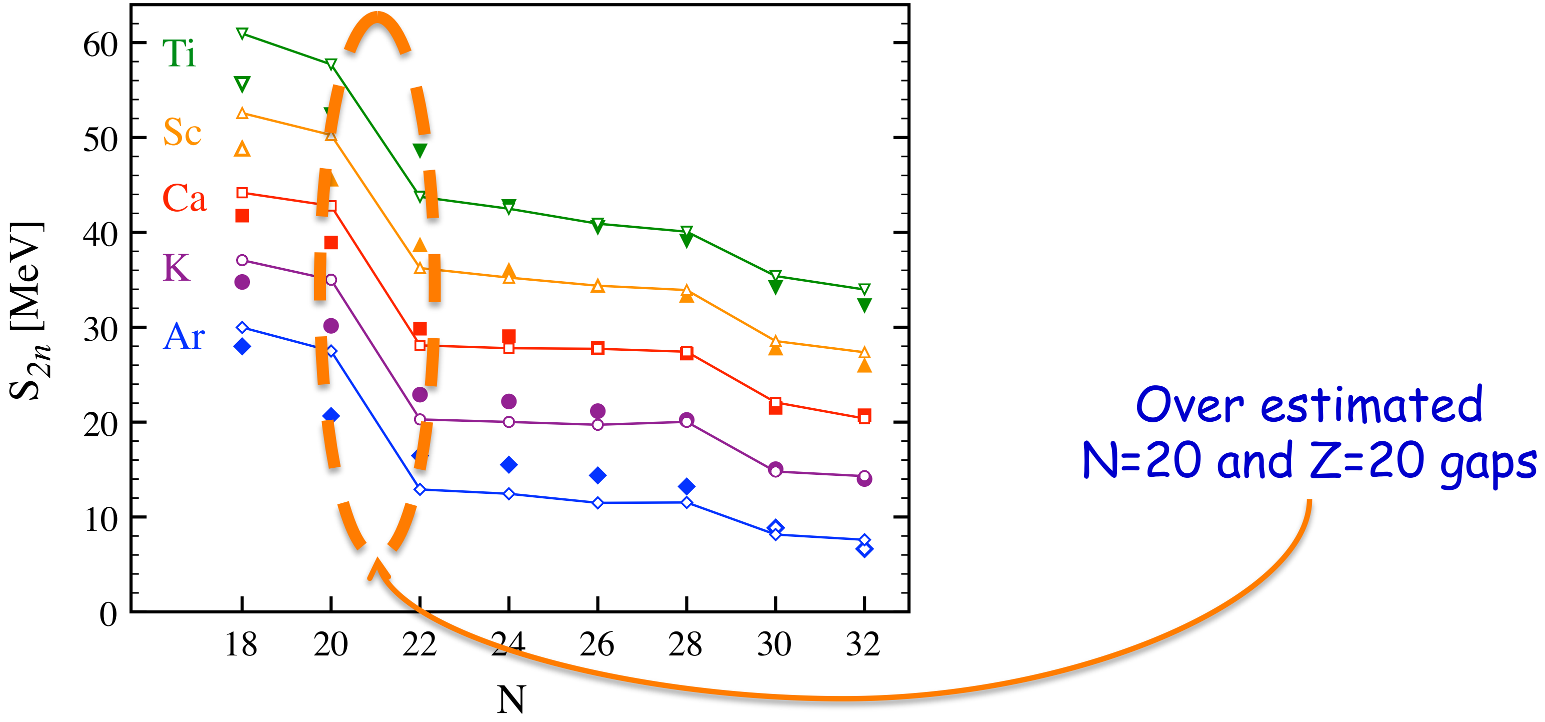

Over estimated
N=20 and Z=20 gaps

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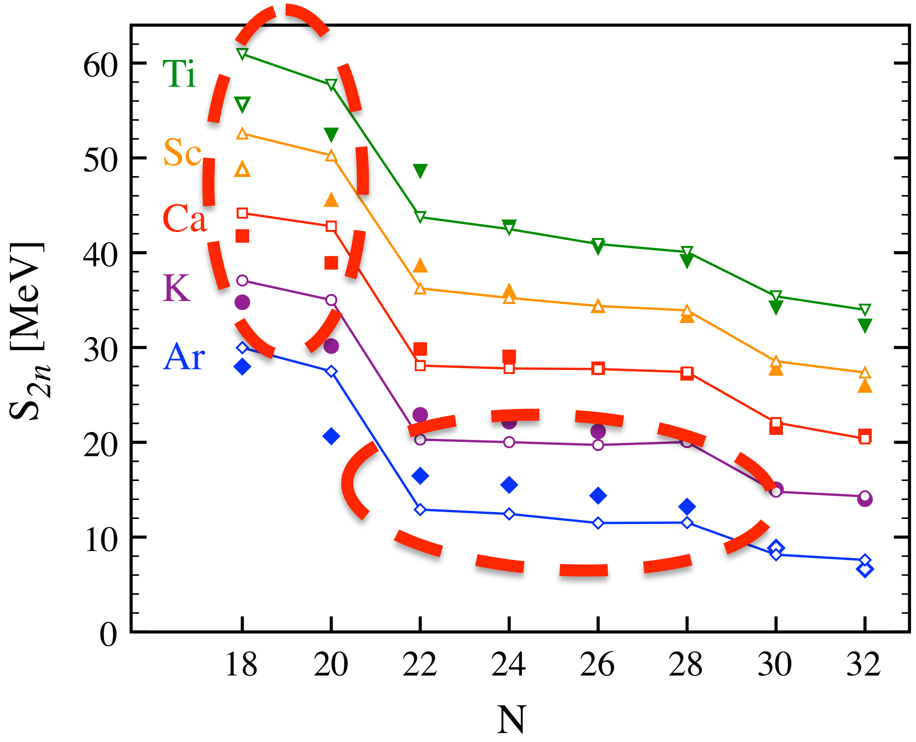


Lack of deformation due to quenched cross-shell quadrupole excitations

→ First *ab-initio* calculation over a contiguous portion of the nuclear chart—open shells are now possible through the Gorkov-GF formalism

Inversion of $d_{3/2}$—$s_{1/2}$ at N=28

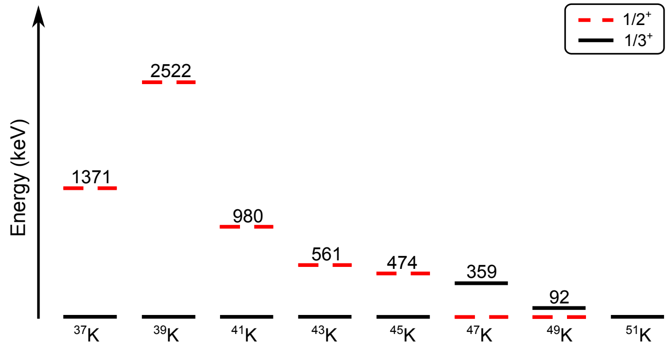


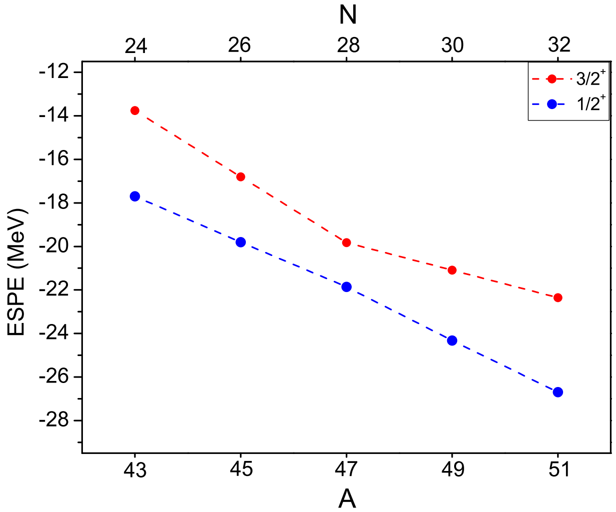
FIG. 1. (color online) Experimental energies for $1/2^+$ and $3/2^+$ states in odd-K isotopes. Inversion of the nuclear spin is obtained in ^{47,49}K and reinversion back in ^{51}K. Results are

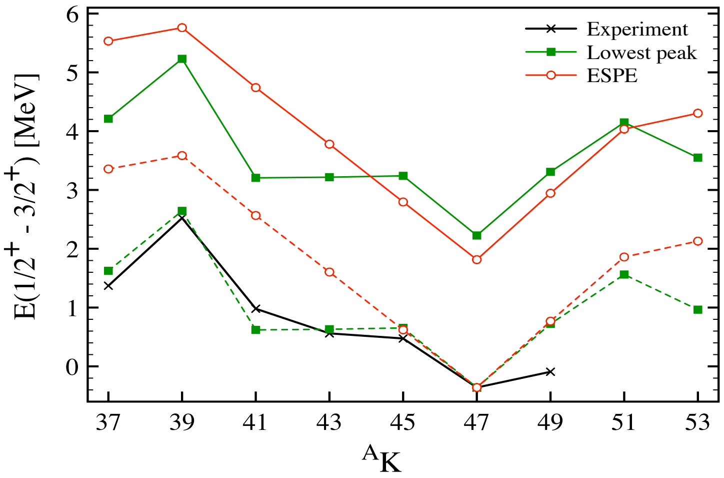
J. Papuga, et al., PRL **110**, 172503 (2013)

^{A}K isotopes

Laser spectroscopy @ ISOLDE

Change in separation described by chiral NN+3NF:

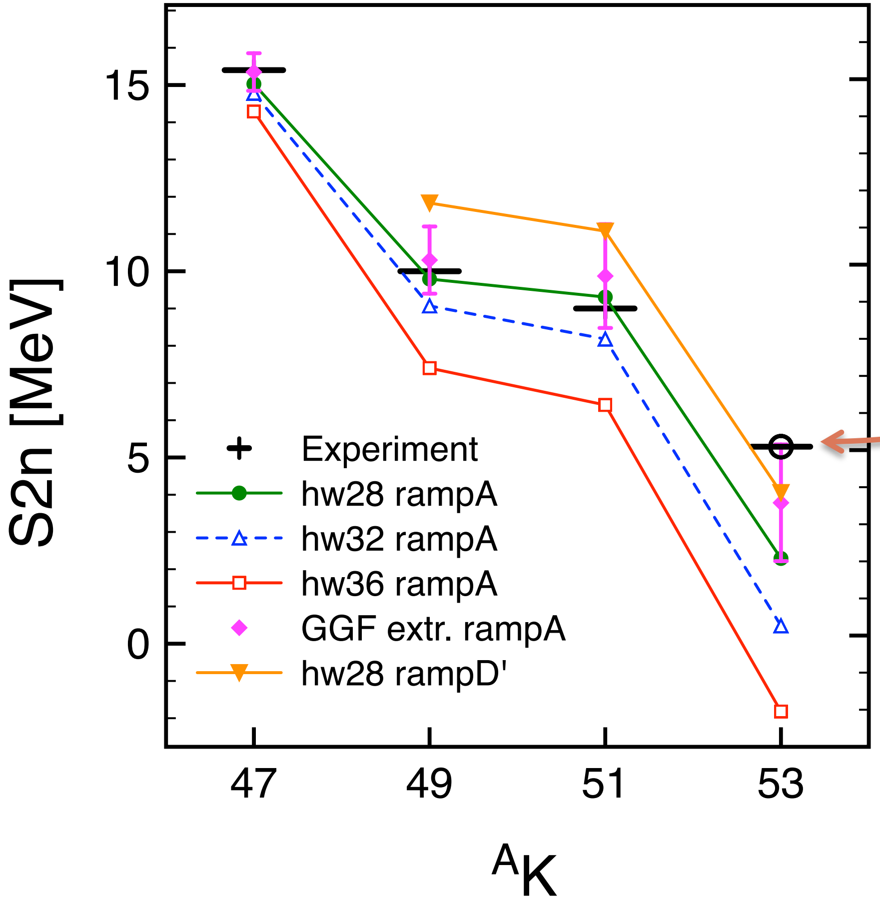




ESPE: "centroid" energies

(Gorkov calculations at 2nd order)

Two-neutron separation energies for neutron rich K isotopes



AME extraplation

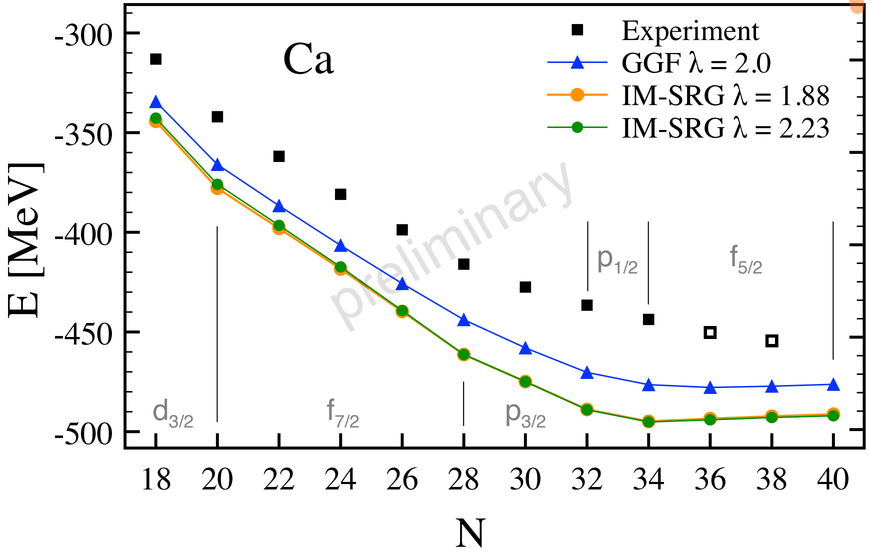
→ *Error bar in predictions* are from extrapolating the many-body expansion to convergence of the model space.

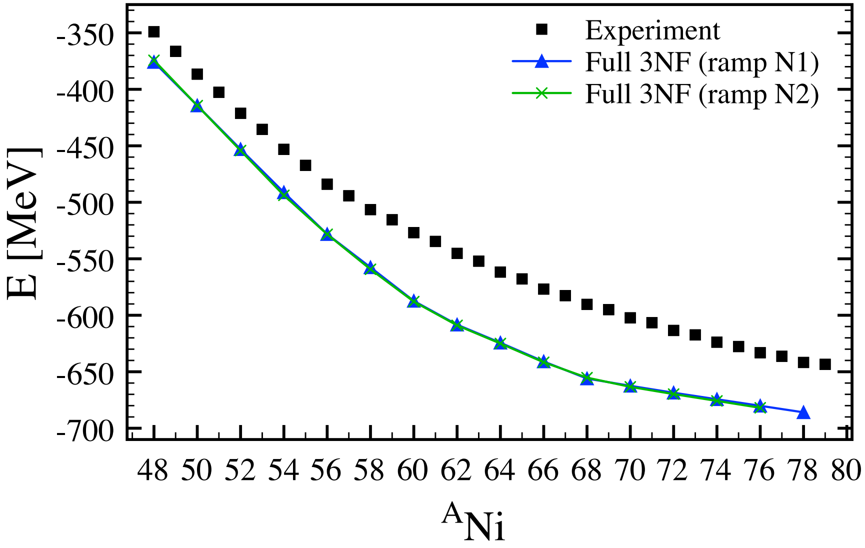
V. Somà, CB *et al.*, in prep.

Ca and Ni isotopic chains

Calculations based on ramps D, N1, N2:

Preliminary





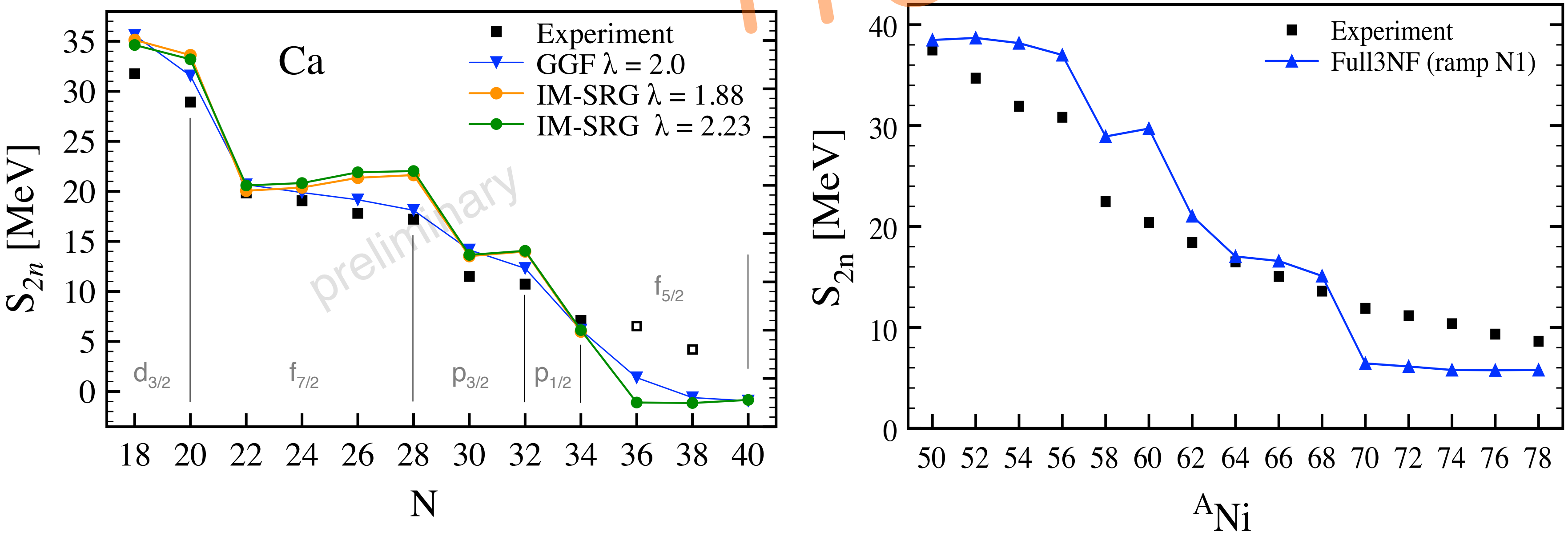
→ Large J in free space SRG matter (must pay attention to its convergence)

→ Overall conclusions regarding over binding and S_{2n} remain but details change

IM-SRG results from H. Hergert

Ca and Ni isotopic chains

Calculations based on ramps D, N1, N2:



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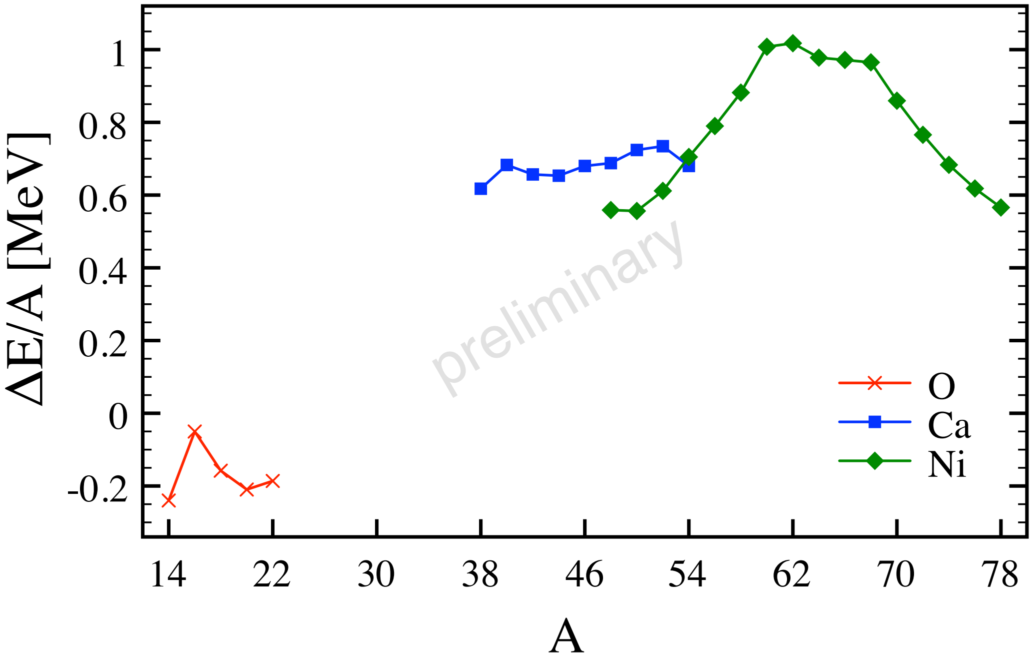
IM-SRG results from H. Hergert

Ca and Ni isotopic chains

Difference of calculated BEs to the experiment for different masses:



→ In general over binding per nucleon (E/A) appear to stabilize above A~40-50 but more investigations are required.

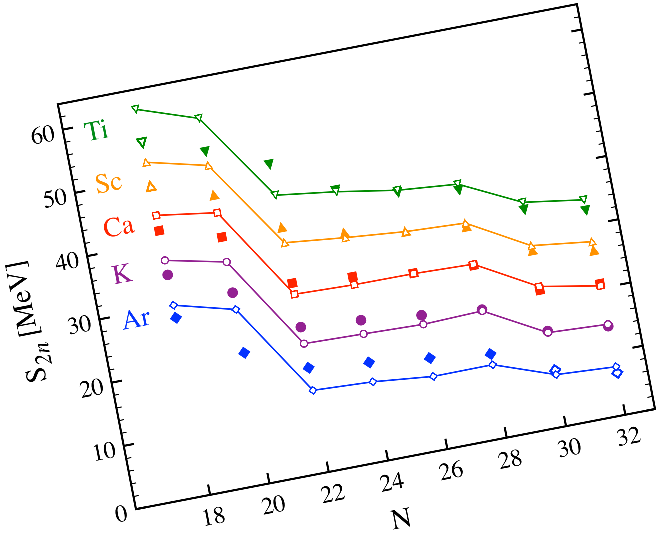
Conclusions

- What to did we learn about realistic chiral forces from ab-initio calculation ?

→ *Leading order 3NF are crucial to predict many important features that are observed experimentally (drip lines, saturation, orbit evolution, etc…)*

→ *Experimental binding is predicted accurately up to the lower sd shell (A≈30) but deteriorates for medium mass isotopes (Ca and above) with roughly 1 MeV/A over binding.*

→ *This hints to the need of more repulsion in future generations of chiral realistic forces.*



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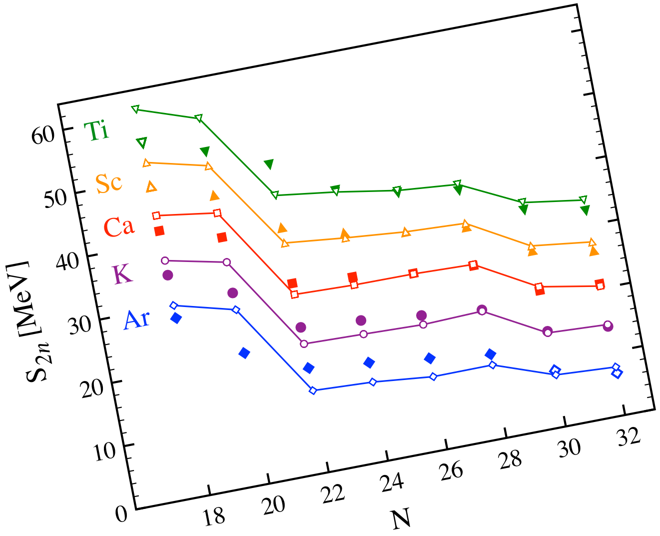
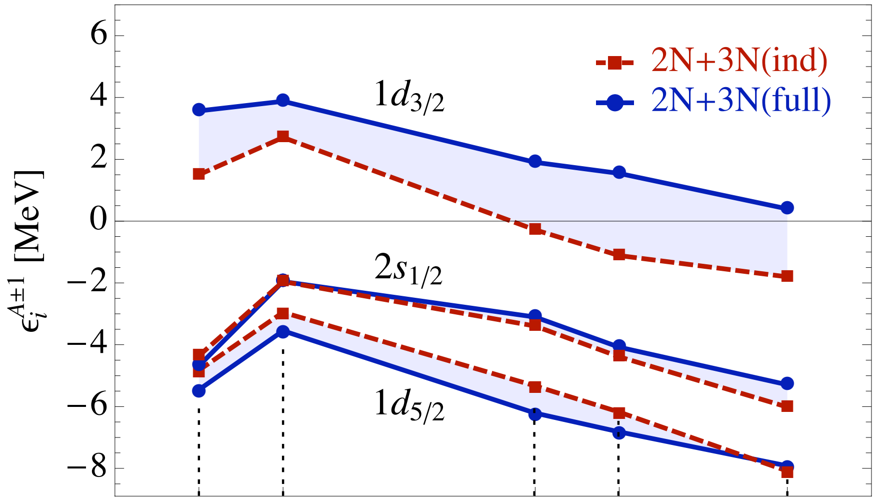
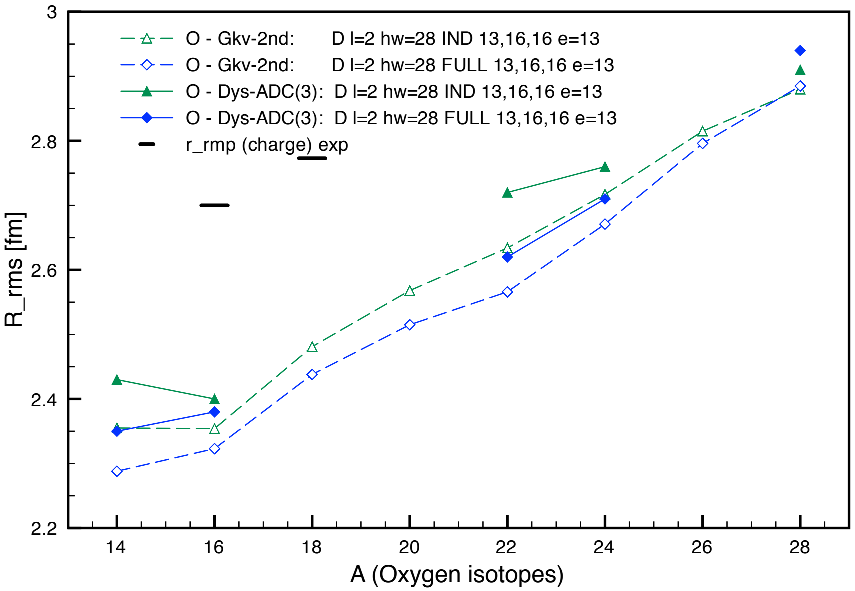


Thank you for your attention!!!

Results for the N-O-F chains

A. Cipollone, CB, P. Navrátil, Phys. Rev. Lett. **111**, 062501 (2013)





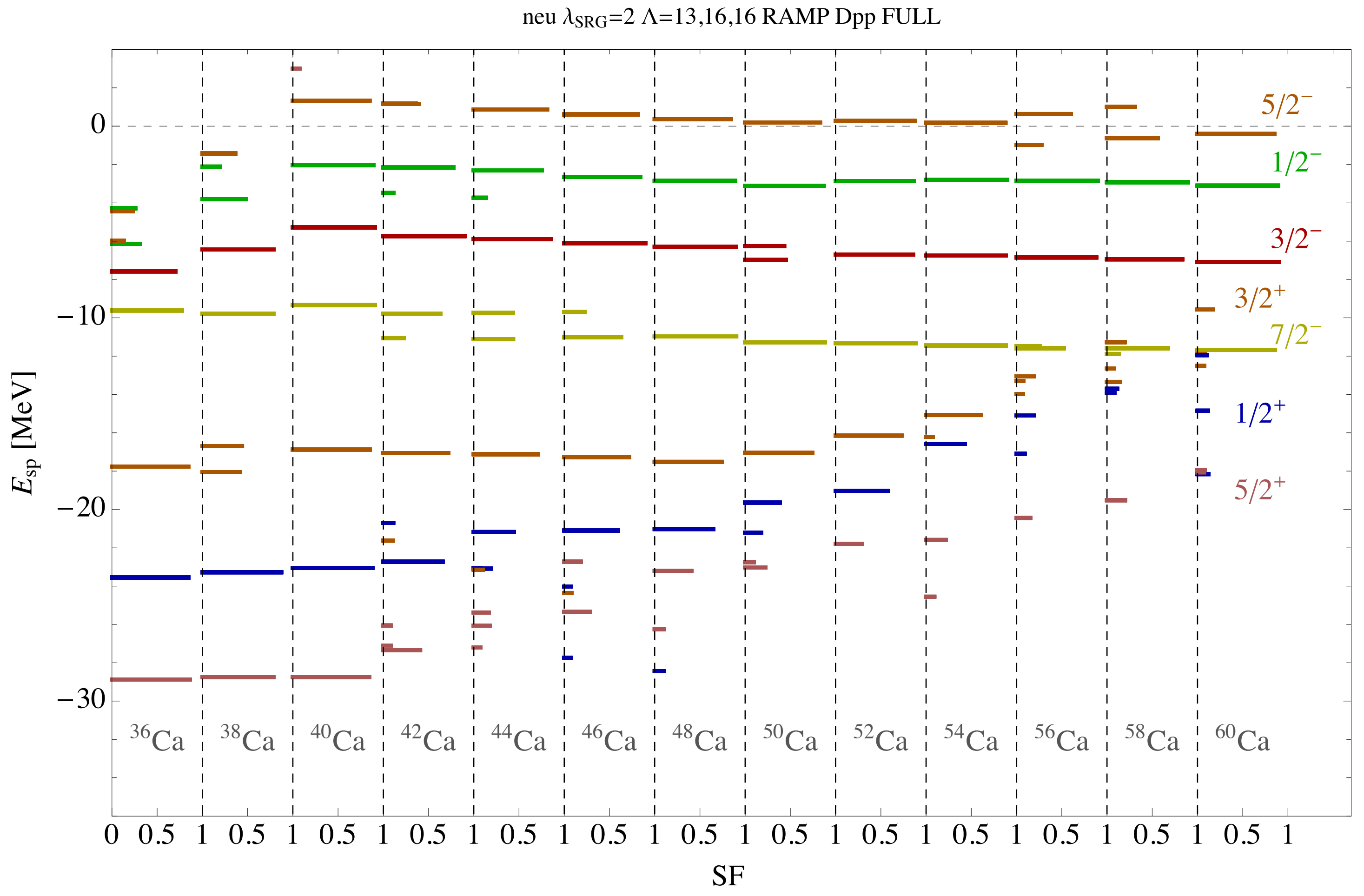
→ *d3/2 raised* by genuine 3NF

→ systematic underestimation of radii

N3LO (Λ = 500Mev/c) chiral NN interaction evolved to 2N + 3N forces (2.0fm^{-1})

N2LO (Λ = 400Mev/c) chiral 3N interaction evolved (2.0fm^{-1})

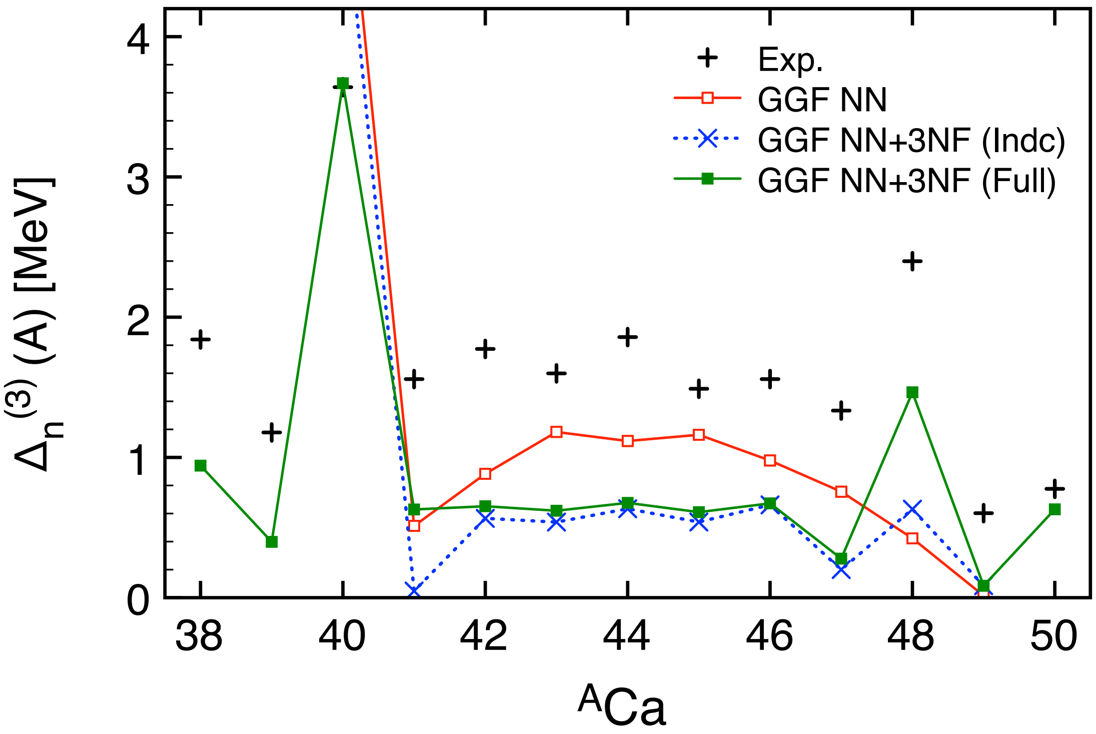
Ca spectral distributions – at 2nd order



Pairing gaps

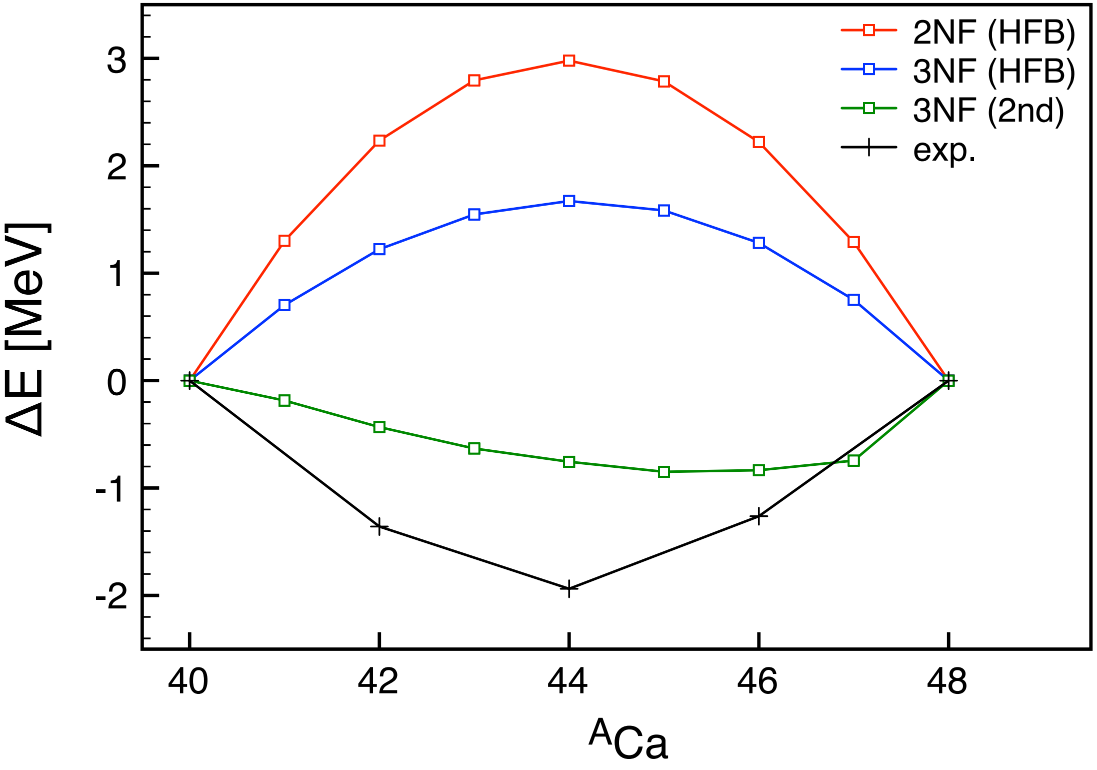
- ✪ Three-point mass differences

$$\Delta_n^{(3)}(A) = \frac{(-1)^A}{2}[E_0^{A+1} - 2\,E_0^A + E_0^{A-1}]$$



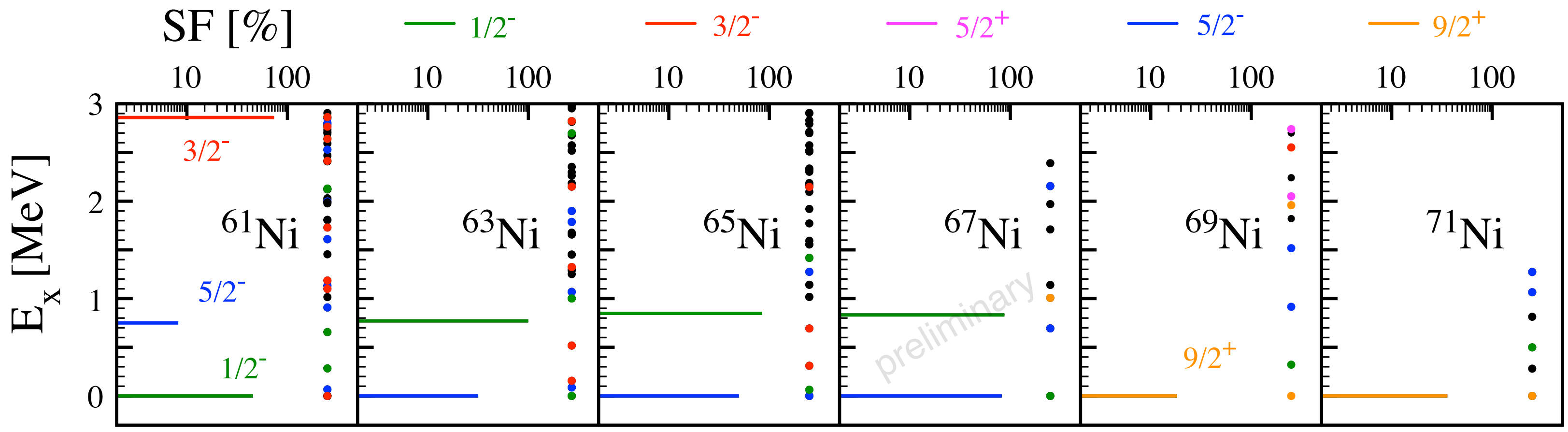
Pairing gaps

✪ Inversion of odd-even staggering



➟ Second order <u>and</u> 3NF necessary to invert the staggering

Ni spectral distributions – at 2nd order



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