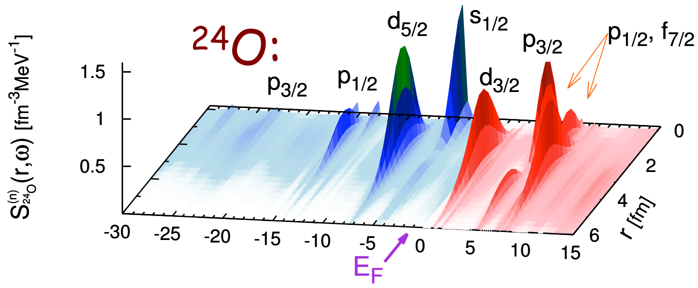
Chiral NN + 3N forces in medium mass isotopes

Carlo Barbieri — University of Surrey



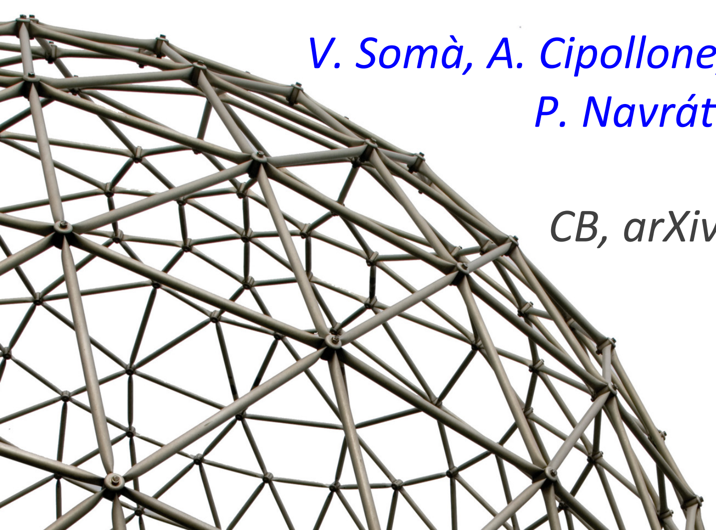
Collaborators:

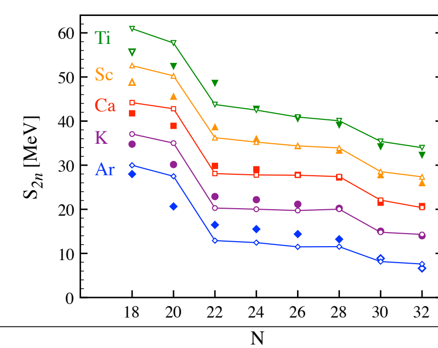
A. Cipollone, CB, P. Navrátil: *Phys. Rev. Lett.* ***111**, 062501 (2013)*

arXiv:1412.3002 [nucl-th] (2014)

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

CB, arXiv:1405.0491 [nucl-th] (2014)

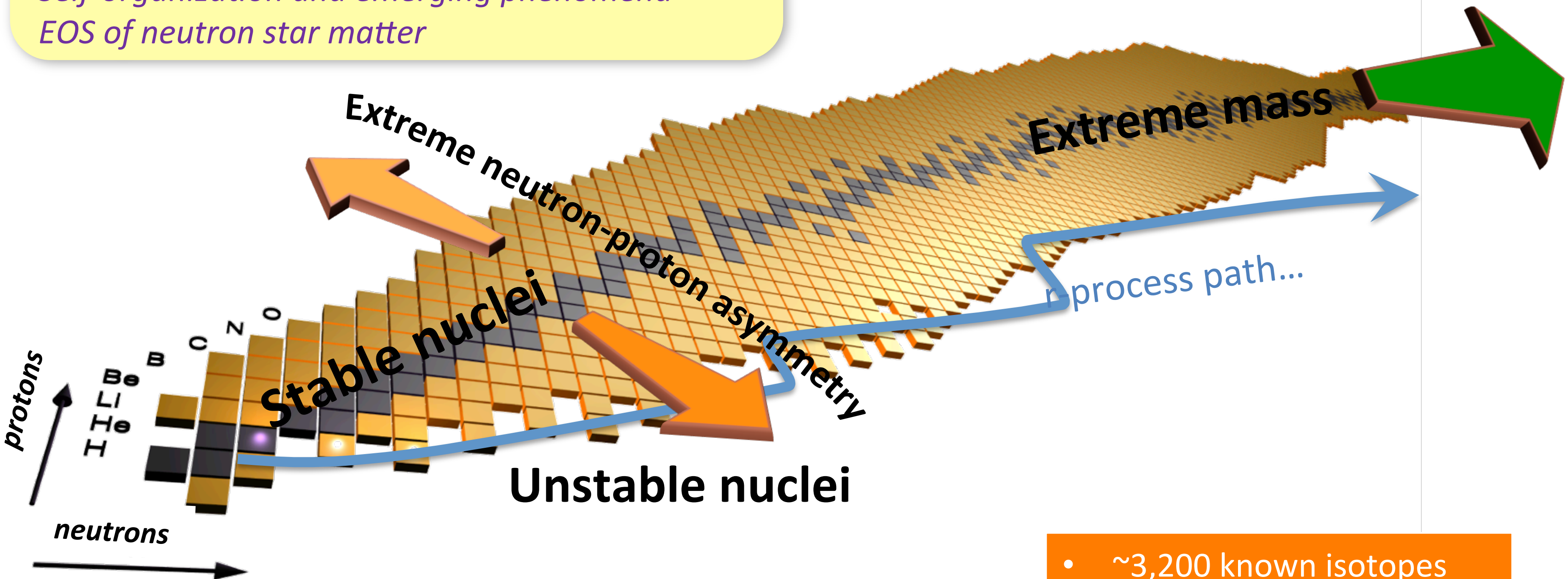




Current Status of low-energy nuclear physics

Composite system of interacting fermions
Binding and limits of stability
Coexistence of individual and collective behaviors
Self-organization and emerging phenomena
EOS of neutron star matter

Experimental programs RIKEN, FAIR, FRIB



- ~3,200 known isotopes
- ~7,000 predicted to exist
- Correlation characterised in full for ~283 stable

Nature **473**, 25 (2011); **486**, 509 (2012)

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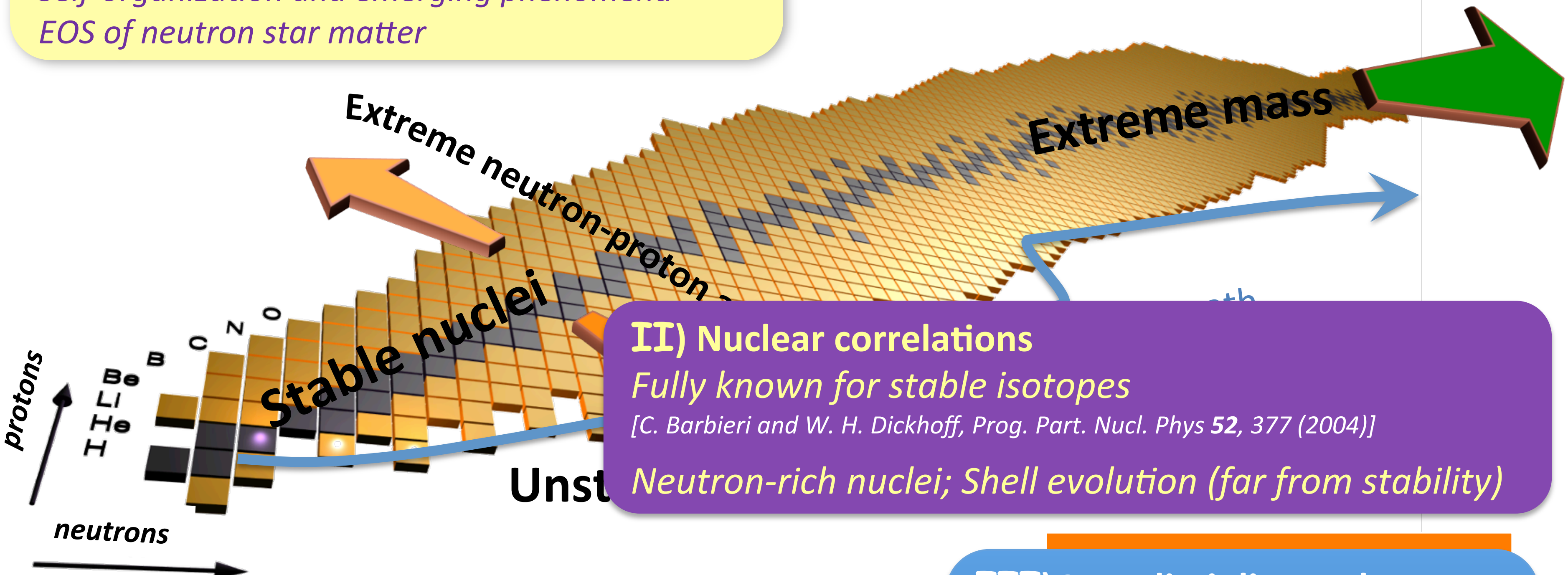


II) Nuclear correlations

Fully known for stable isotopes
*[C. Barbieri and W. H. Dickhoff, Prog. Part. Nucl. Phys **52**, 377 (2004)]*
Neutron-rich nuclei; Shell evolution (far from stability)

I) Understanding the nuclear force

QCD-derived; 3-nucleon forces (3NFs)
First principle (ab-initio) predictions

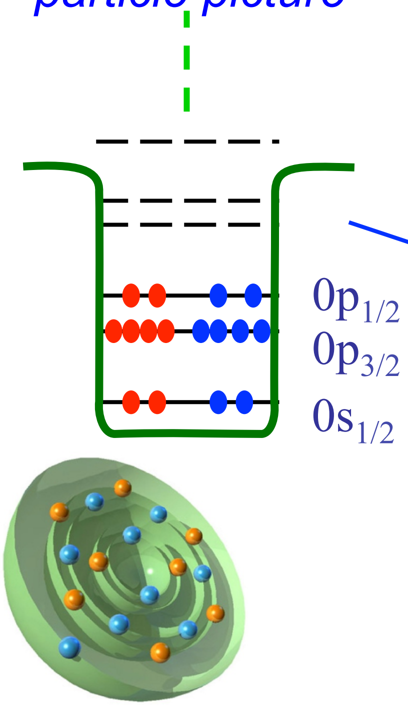
III) Interdisciplinary character

Astrophysics
Tests of the standard model
Other fermionic systems:
ultracold gasses; molecules;

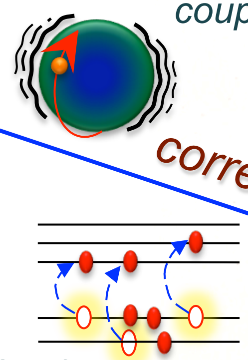
Concept of correlations

Spectral function: distribution of momentum (p_m) and energies (E_m)

independent particle picture

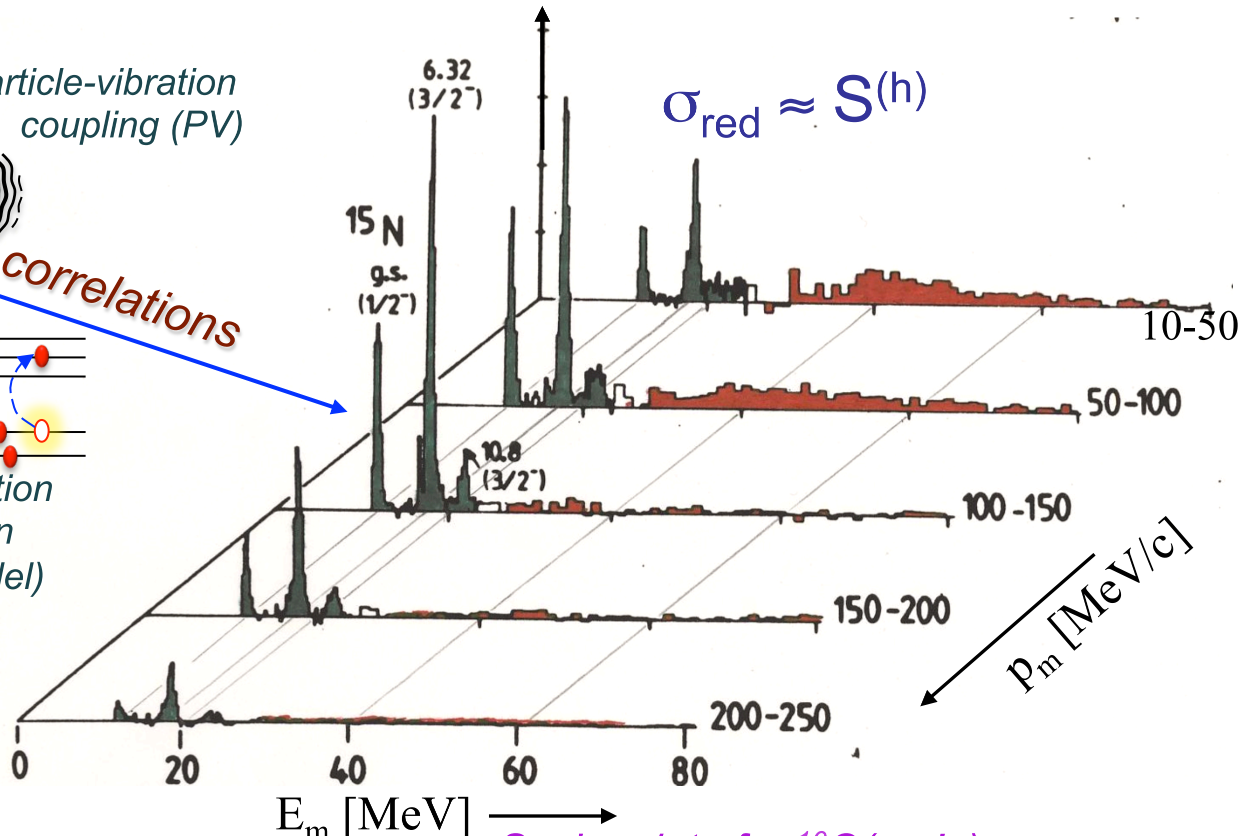


Particle-vibration coupling (PV)



Configuration interaction (shell model)

correlations



Saclay data for $^{16}O(e,e'p)$

[Mougey et al., Nucl. Phys. A335, 35 (1980)]

Understood for a few stable closed shells:

[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys ***52****, 377 (2004)]*

Concept of correlations

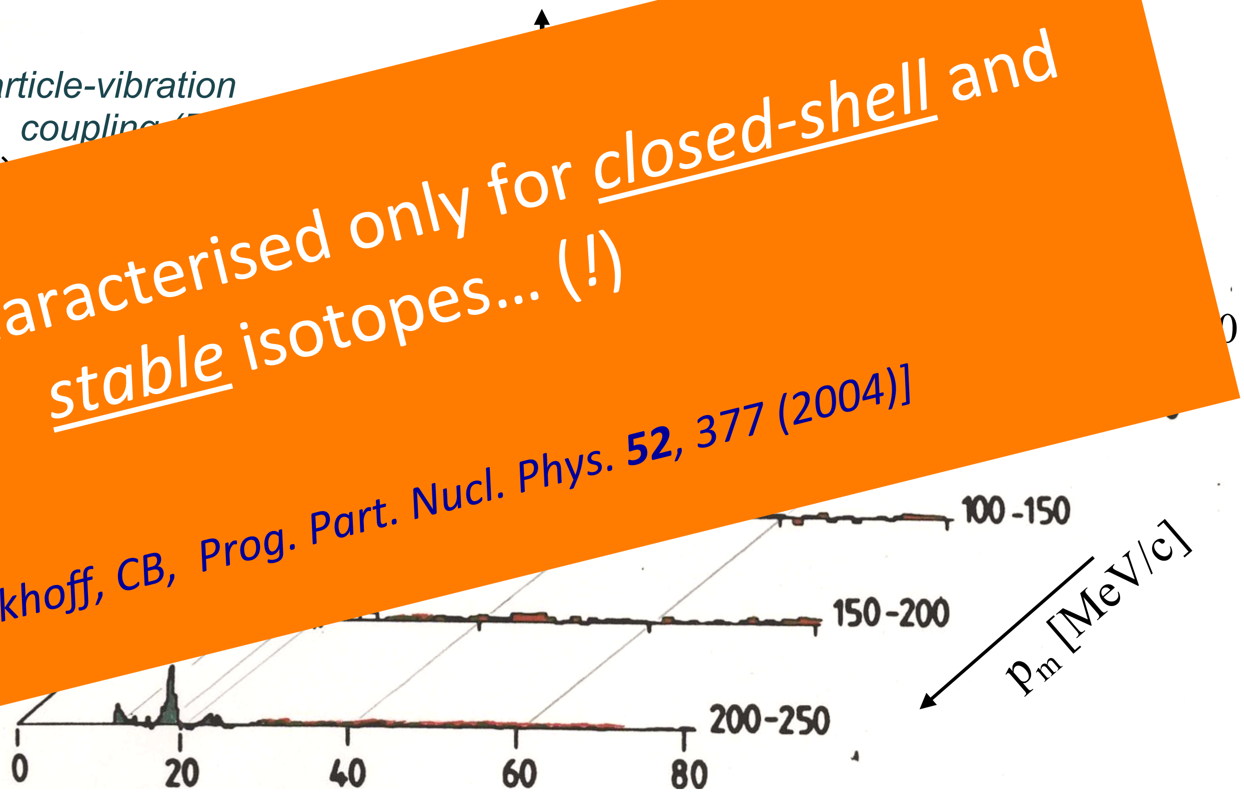
independent particle picture

Spectral function: distribution of momentum (p_m) and en...)

Particle-vibration coupling

So far, fully characterised only for <u>closed-shell</u> and <u>stable</u> isotopes... (!)

[W. Dickhoff, CB, Prog. Part. Nucl. Phys. **52**, 377 (2004)]



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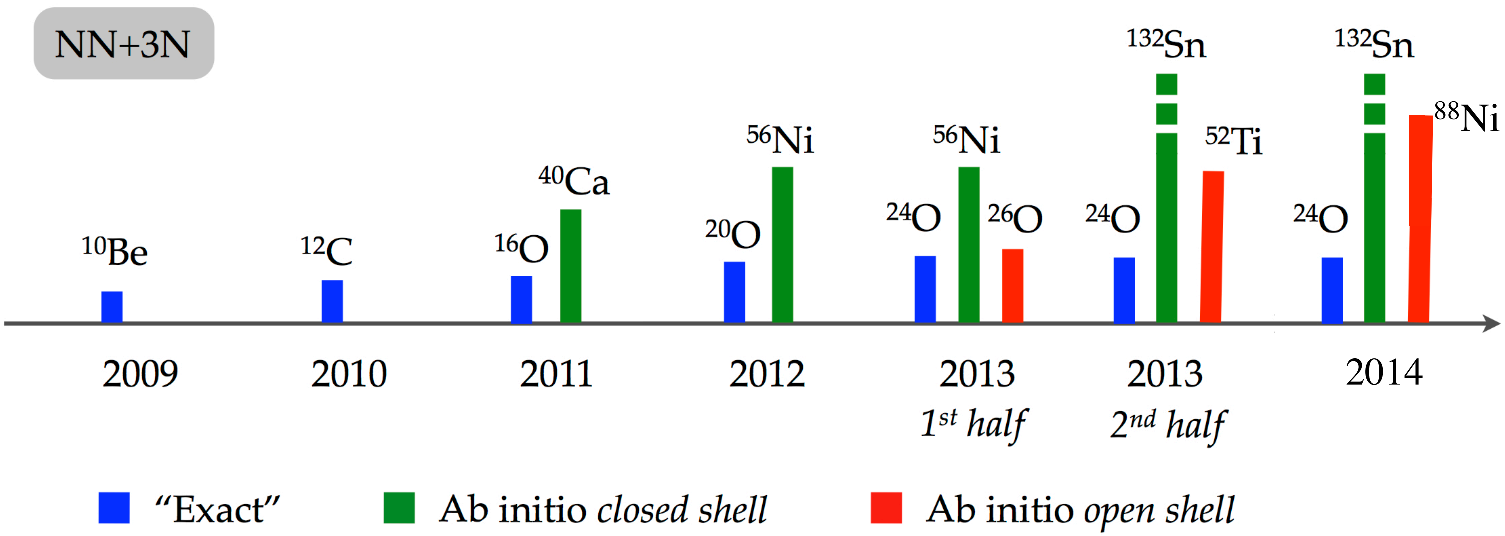
Reaching medium mass and neutron rich isotopes

→Degenerate system (open shells, deformations…)

→Hamiltoninan, including three nucleon forces

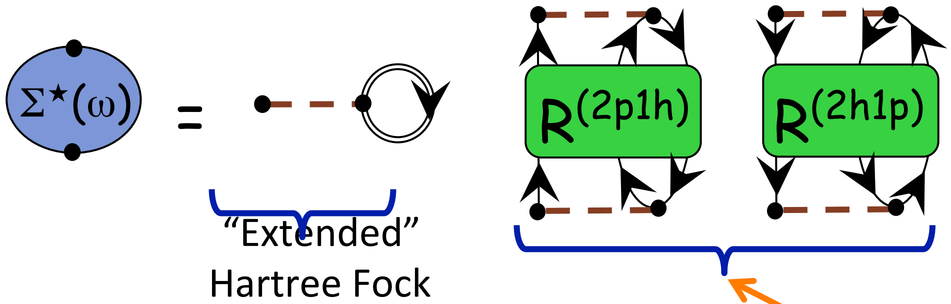


Ab-Initio SCGF approaches

The FRPA Method in Two Words

Particle vibration coupling is the main cause driving the distribution of particle strength—on both sides of the Fermi surface…

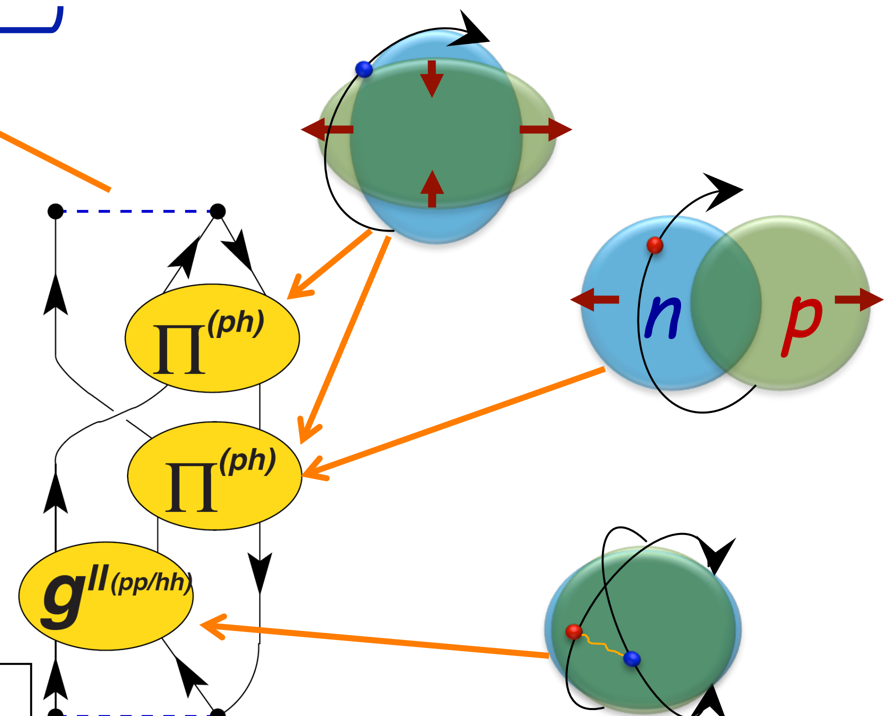
CB et al.,
Phys. Rev. C ***63***, *034313 (2001)*
Phys. Rev. A ***76***, *052503 (2007)*
Phys. Rev. C ***79***, *064313 (2009)*

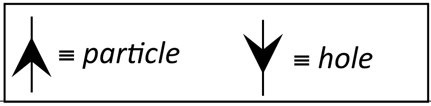


• *A complete expansion requires* ***all types*** of particle-vibration coupling

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

• The Self-energy $\Sigma^\star(\omega)$ yields *both* single-particle states and scattering





Gorkov and symmetry breaking approaches

V. Somà, CB, T. Duguet, , Phys. Rev. C **89**, 024323 (2014)
V. Somà, CB, T. Duguet, Phys. Rev. C **87**, 011303R (2013)
V. Somà, T. Duguet, CB, Phys. Rev. C **84**, 064317 (2011)

- Ansatz $\ldots \approx E_0^{N+2} - E_0^N \approx E_0^N - E_0^{N-2} \approx \ldots \approx 2\mu$

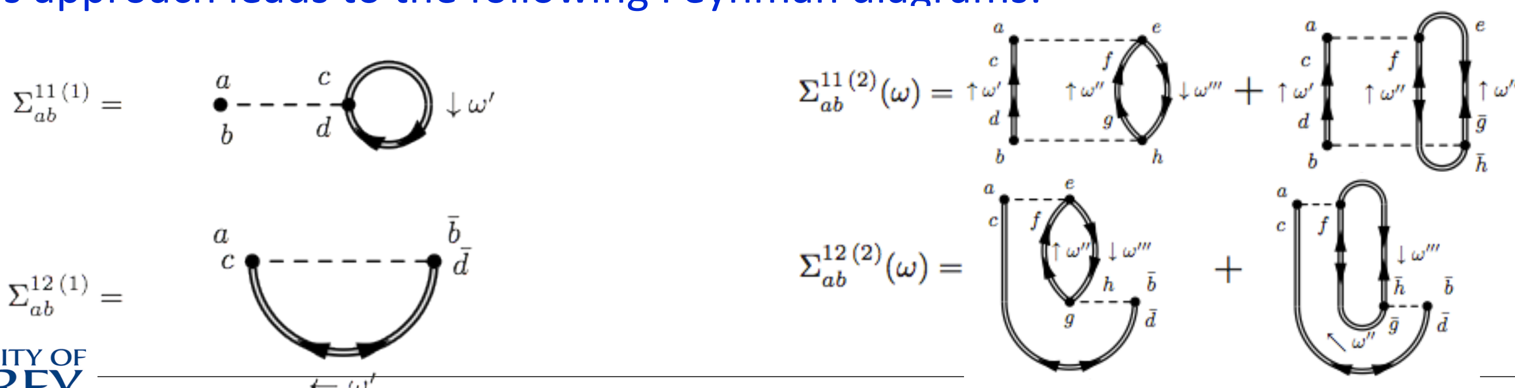
- Auxiliary many-body state $|\Psi_0\rangle \equiv \sum_N^{\text{even}} c_N \, |\psi_0^N\rangle$

  → Mixes various particle numbers

  → Introduce a “grand-canonical” potential $\Omega = H - \mu N$

⇒ $|\Psi_0\rangle$ minimizes $\Omega_0 = \langle \Psi_0 | \Omega | \Psi_0 \rangle$ under the constraint $N = \langle \Psi_0 | N | \Psi_0 \rangle$

- This approach leads to the following Feynman diagrams:



Approaches in GF theory

Truncation scheme:	Dyson formulation (closed shells)	Gorkov formulation (semi-magic)
1^{st} order:	Hartree-Fock	HF-Bogolioubov
2^{nd} order:	2^{nd} order	2^{nd} order (w/ pairing)
. . .	. . .	
3^{rd} and all-orders sums, P-V coupling:	ADC(3) FRPA etc…	G-ADC(3) …work in progress

Approaches in GF theory

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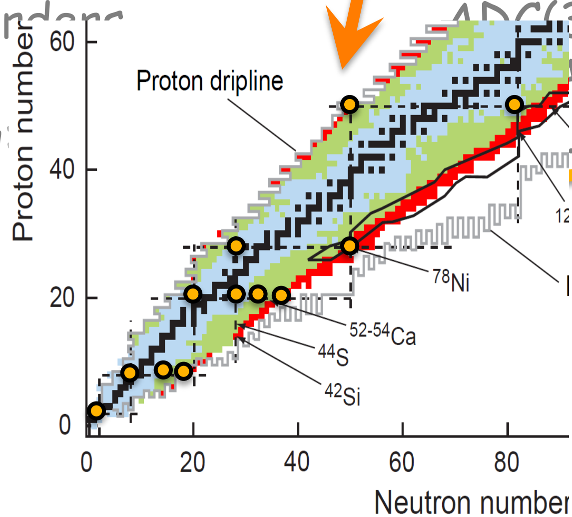
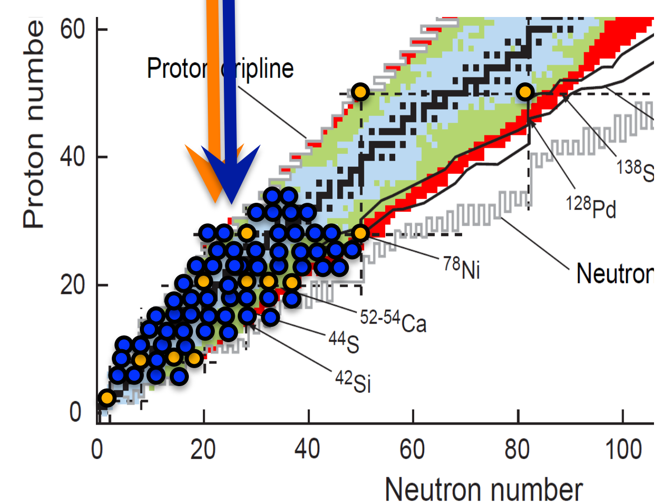




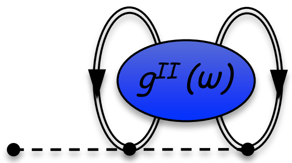
Adding 3-nucleon forces

Inclusion of NNN forces

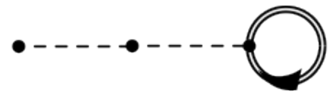
*A. Carbone, CB, et al., Phys. Rev. C**88**, 054326 (2013)*

- NNN forces can enter diagrams in three different ways:

$\frac{1}{4}$



Correction to external 1-Body interaction



Correction to *non-contracted* 2-Body interaction

pure 3-Body contribution

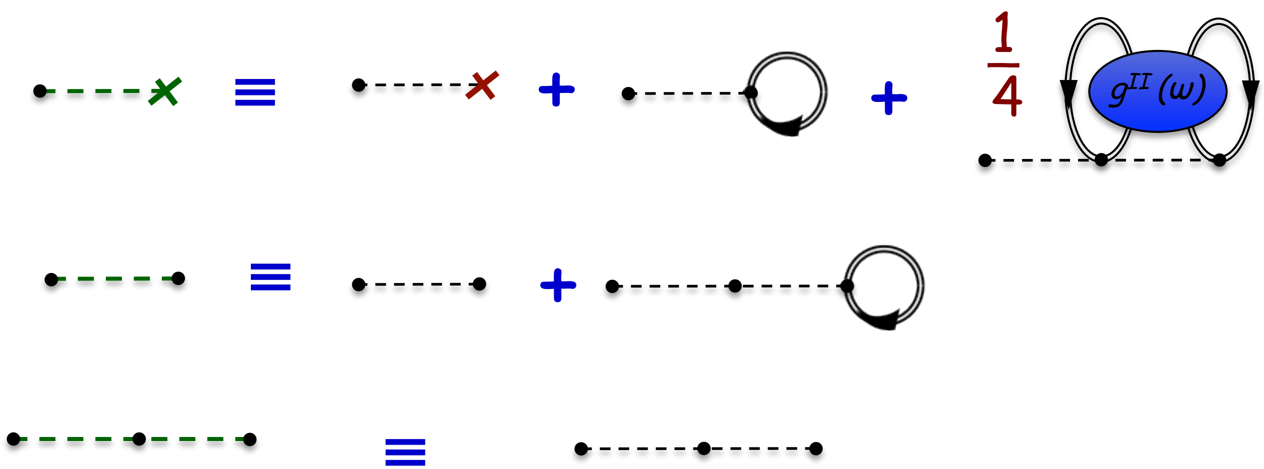
- Contractions are with *fully correlated density matrices* (BEYOND a normal ordering…)

Inclusion of NNN forces

A. Carbone, CB, et al., Phys. Rev. C**88**, 054326 (2013)

- NNN forces can enter diagrams in three different ways:

→ Define new 1- and 2-body interactions and
use <u>only</u> interaction-irreducible diagrams



- Contractions are with *fully correlated density matrices*
(BEYOND a normal ordering…)

Inclusion of NNN forces

A. Carbone, A. Cipollone, CB, A. Rios, A Polls, arXiv:1309.yyyy

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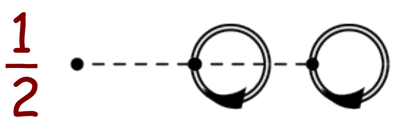

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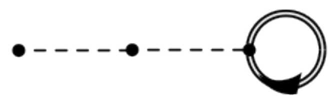

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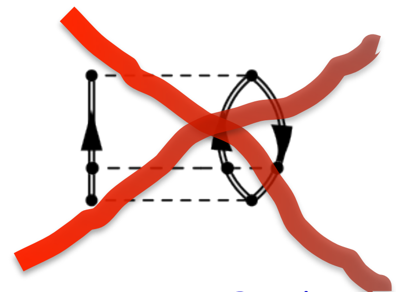
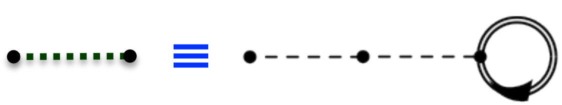
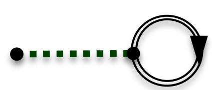


pure 3-Body contribution

BEWARE that defining:



and then:

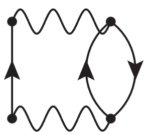


would *double count* the 1-body term.

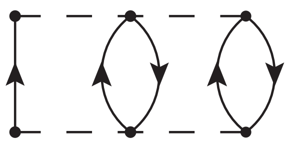
Inclusion of NNN forces

A. Carbone, CB, et al., Phys. Rev. C88, 054326 (2013)

- *Second order* PT diagrams with 3BFs:



(a)



(b)

- *Third order* PT diagrams with 3BFs:

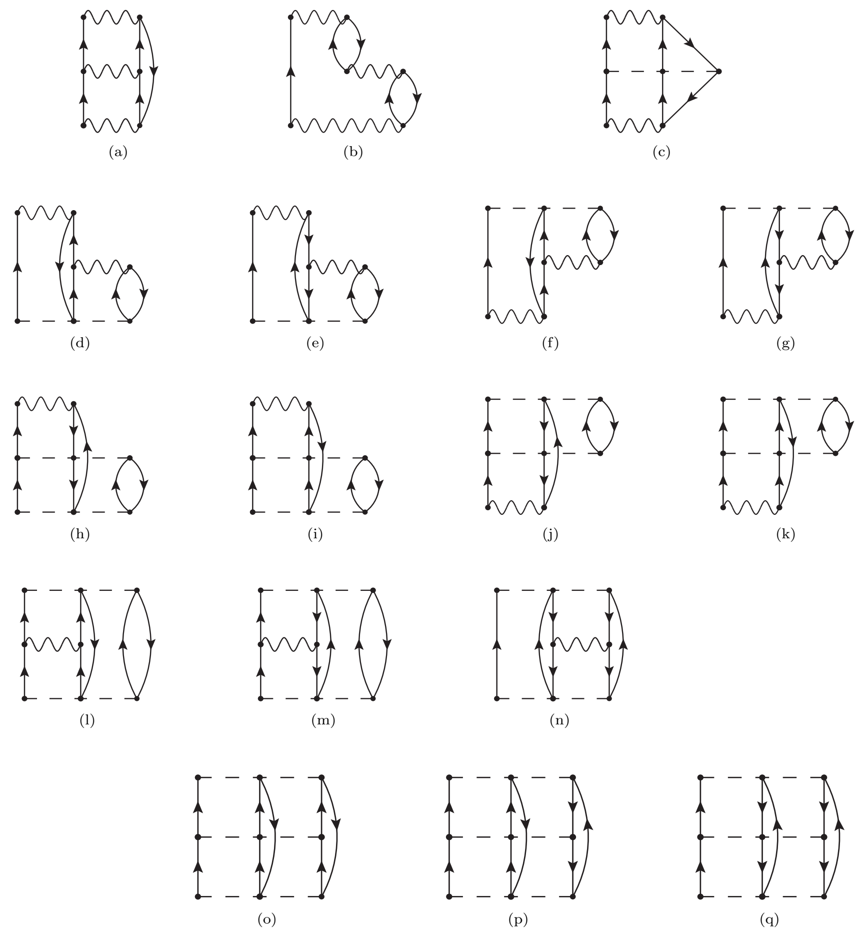


FIG. 5. 1PI, *skeleton* and *interaction irreducible* self-energy diagrams appearing at 3^{rd}-order in perturbative expansion (7), making use of the effective hamiltonian of Eq. (9).

Inclusion of NNN forces

*A. Carbone, CB, et al., Phys. Rev. C**88**, 054326 (2013)*

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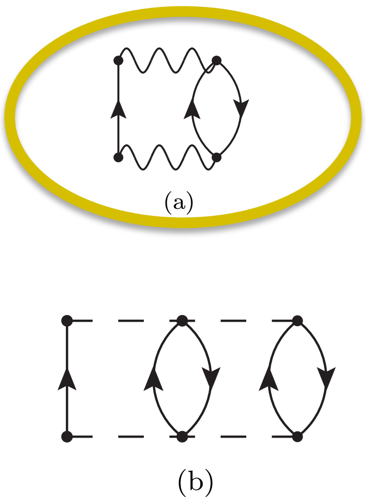


- Third order PT diagrams with 3BFs:

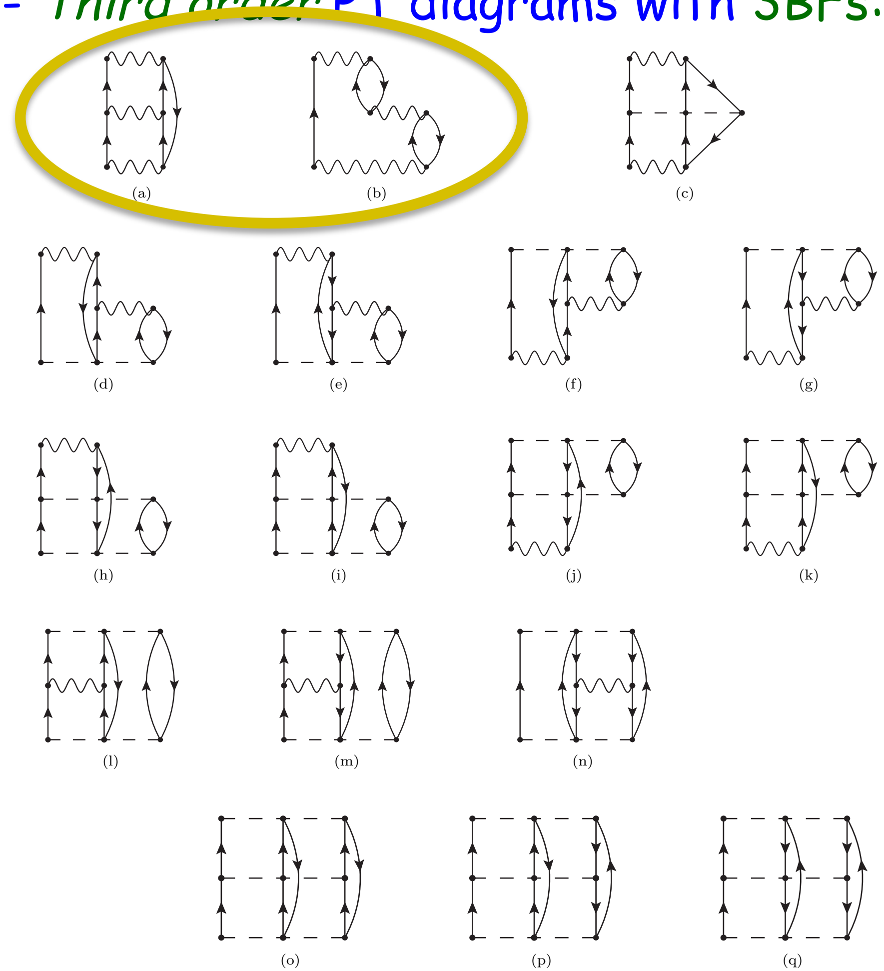


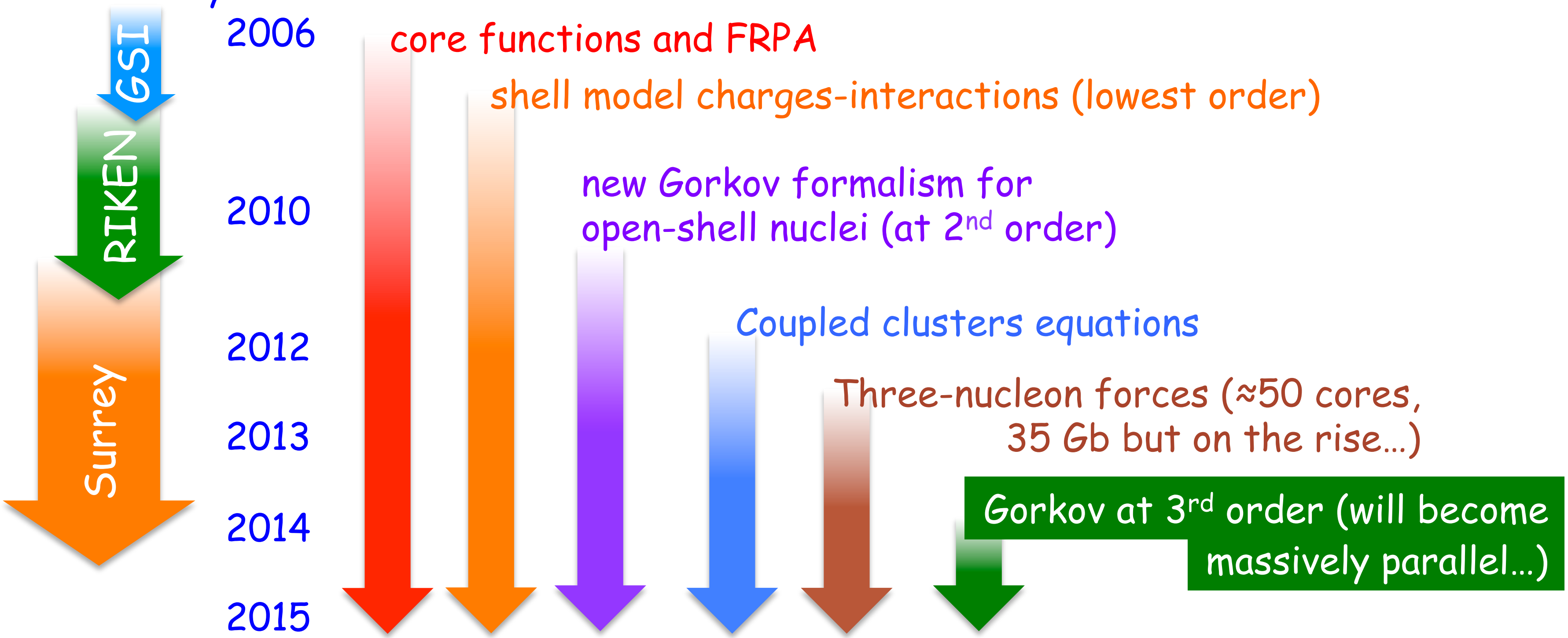
FIG. 5. 1PI, *skeleton* and *interaction irreducible* self-energy diagrams appearing at 3^{rd}-order in perturbative expansion (7), making use of the effective hamiltonian of Eq. (9).

Ab-initio Nuclear Computation & BcDor code

BoccaDorata code:
(C. Barbieri 2006-14
V. Somà 2011-14
A. Cipollone 2012-13)

- Provides a *C++ class library* for handling many-body propagators (≈40,000 lines, OpenMPI based).
- Allows to solve for nuclear spectral functions, many-body propagators, RPA responses, coupled cluster equations and effective interaction/charges for the shell model.

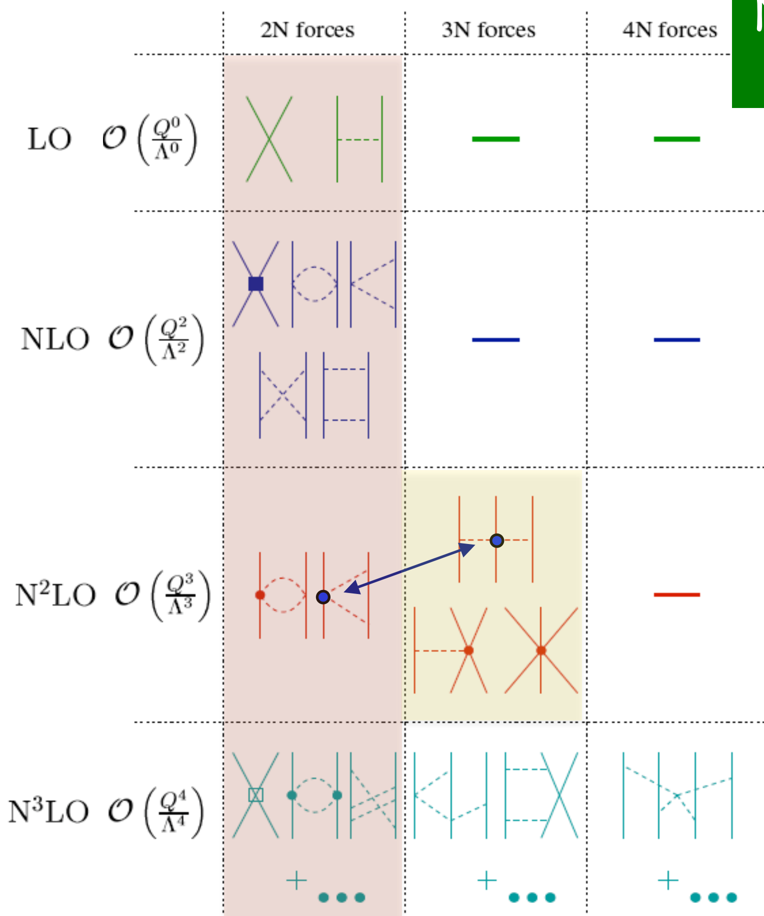
Code history:

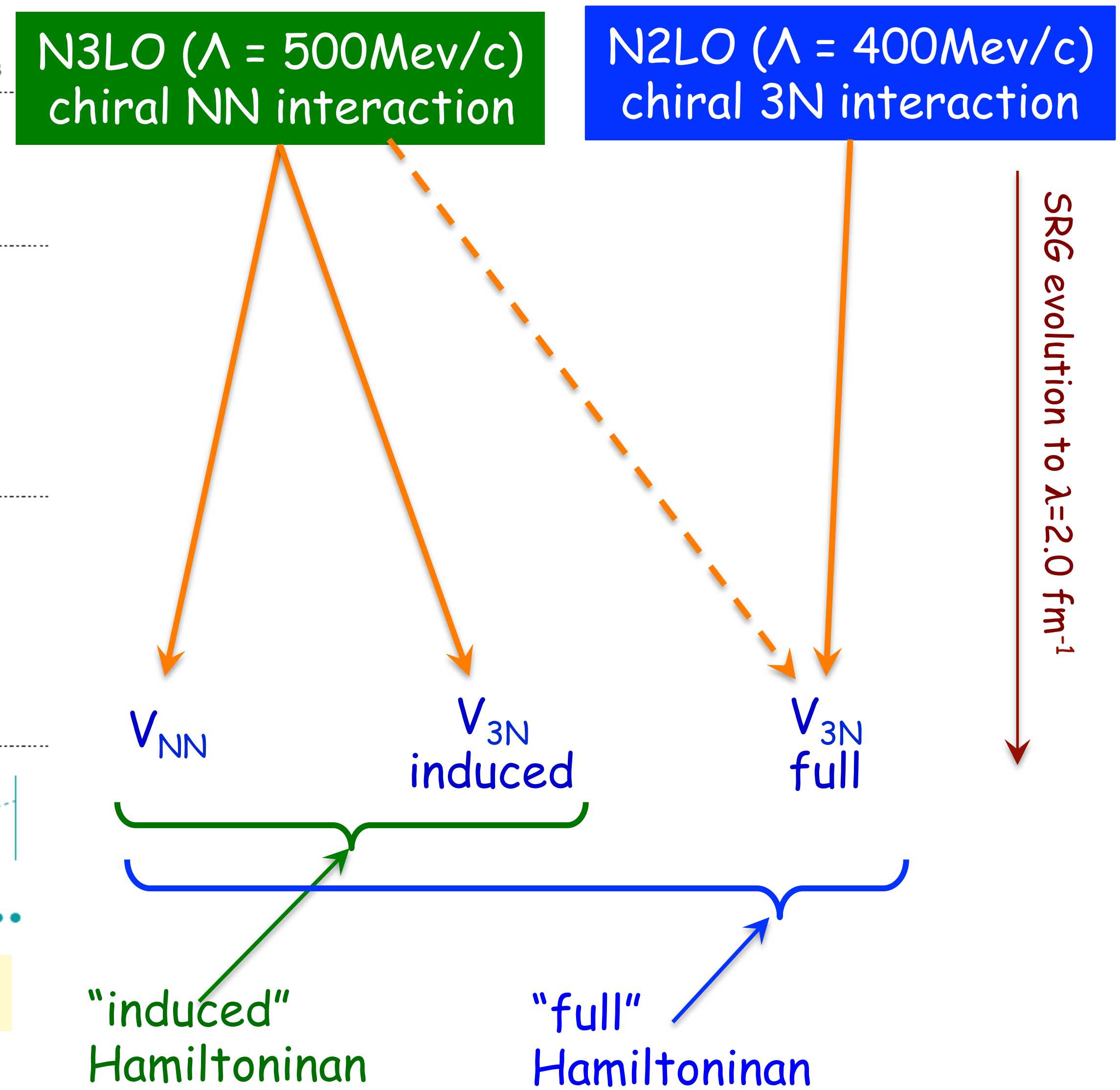


… applications …

Results

Chiral Nuclear forces - SRG evolved





(3NFs arise naturally at N2LO)

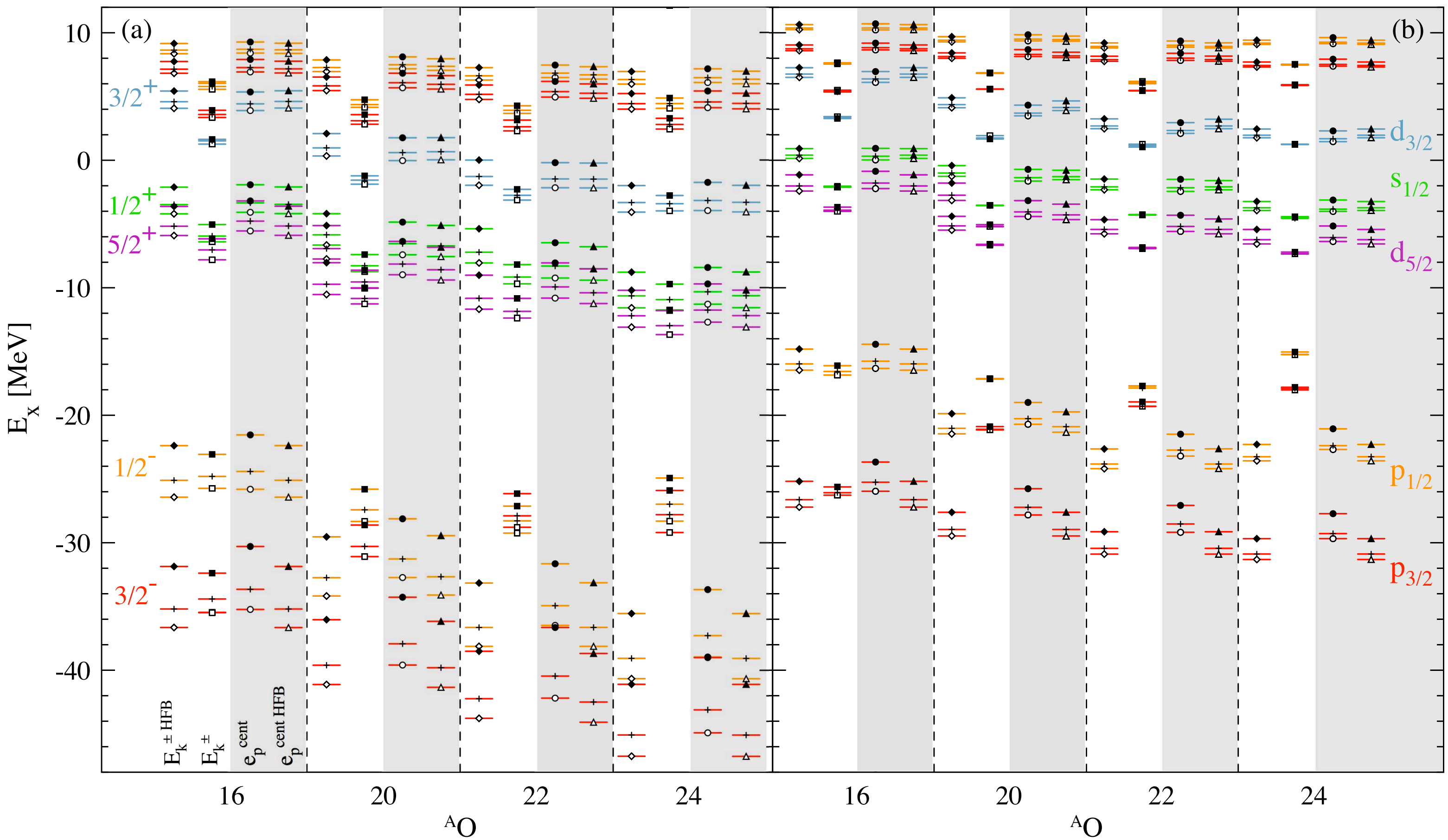
[Jurgenson, Navrátil, Furnstahl, Phys. Rev. Lett. **103**, 082501 (2009); Hebeler, Phys. Rev. C 85, 021002 (2012)]

Convergence of s.p. spectra w.r.t. SRG

Cutoff dependence is reduces, indicating good convergence of many-body truncation and many-body forces

arXiv:1411.1237 (2014)

✓only dominant s.p. states shown



NN terms (no induced 3NF) ← → NN+3NF fully included

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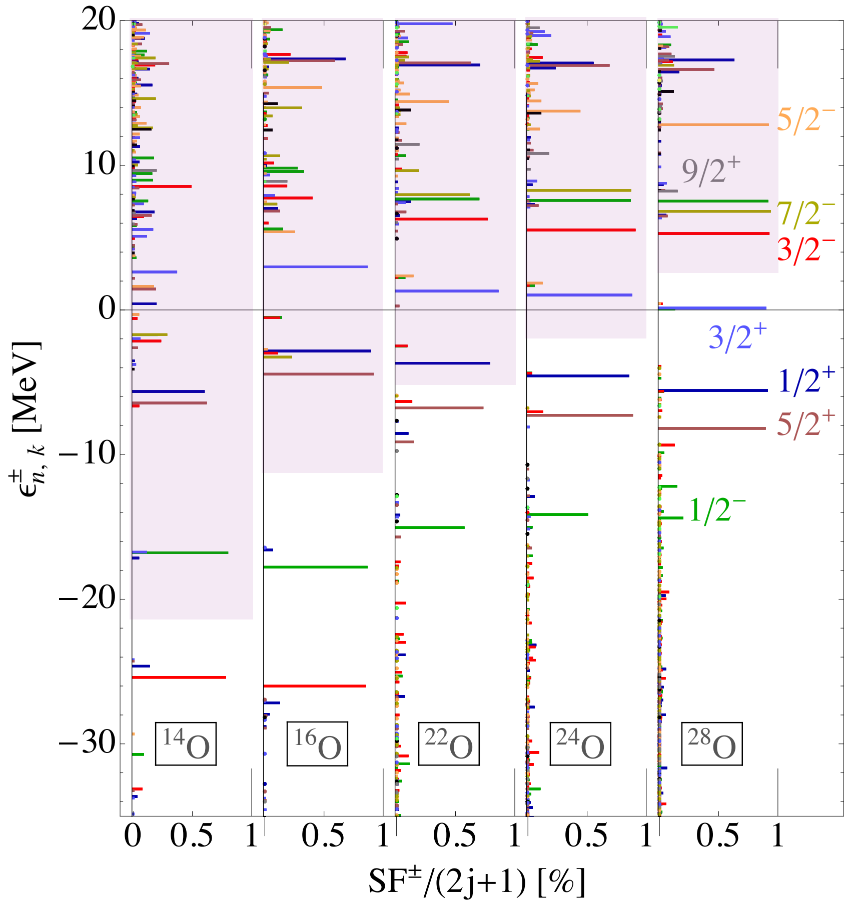
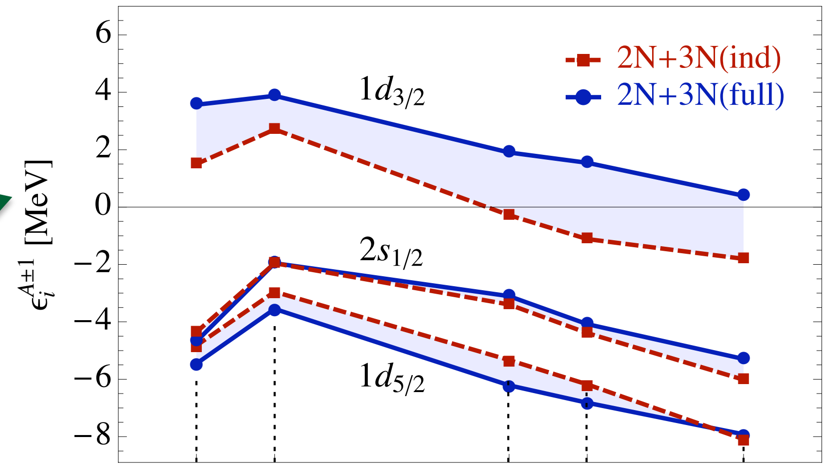
Results for the N-O-F chains

A. Cipollone, CB, P. Navrátil, Phys. Rev. Lett. **111**, 062501 (2013)
and arXiv:1412.3002 [nucl-th] (2014)





→ *$d_{3/2}$ raised* by genuine 3NF

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

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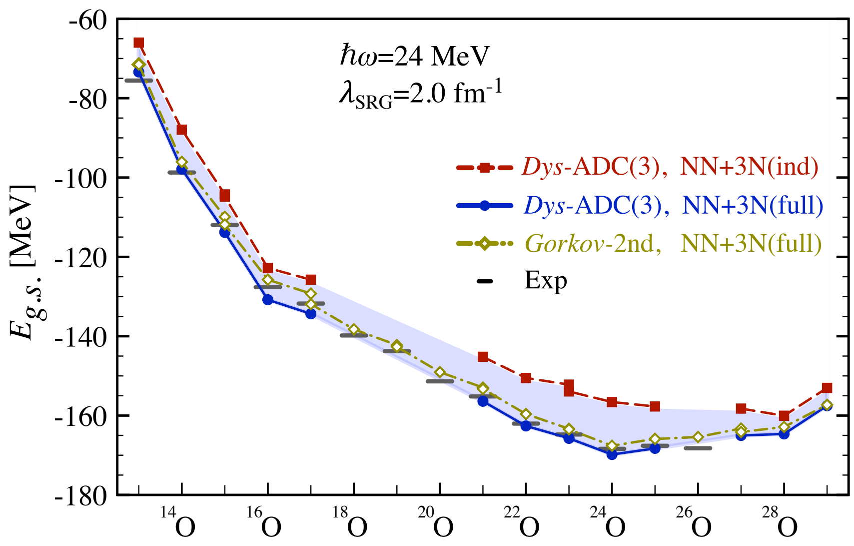

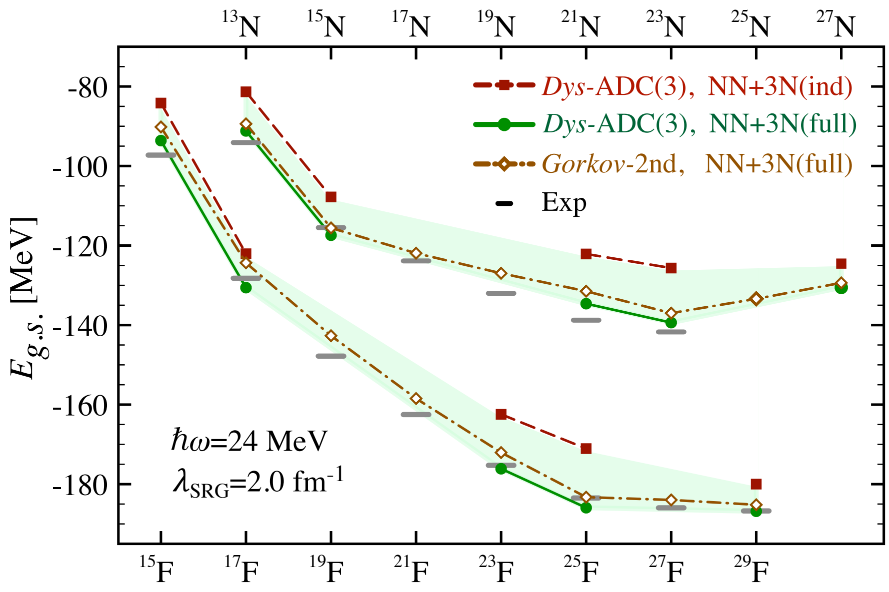

→ 3NF crucial for reproducing binding energies and driplines around oxygen

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

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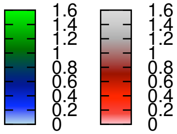
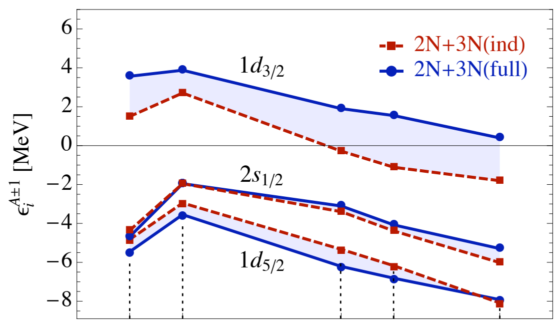
N3LO (Λ = 500Mev/c) chiral NN interaction evolved to 2N + 3N forces (2.0fm^{-1})
N2LO (Λ = 400Mev/c) chiral 3N interaction evolved (2.0fm^{-1})

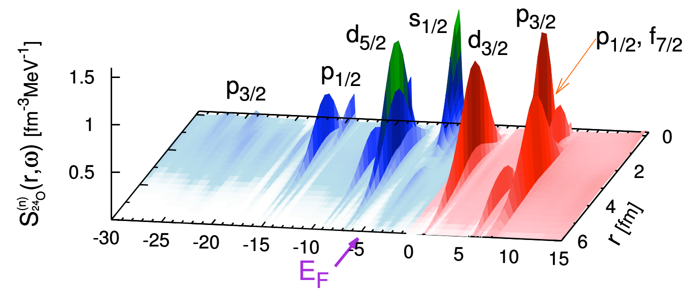
Neutron spectral function of Oxygens

A. Cipollone, CB P. Navrátil, *PRC submitted* (2014)

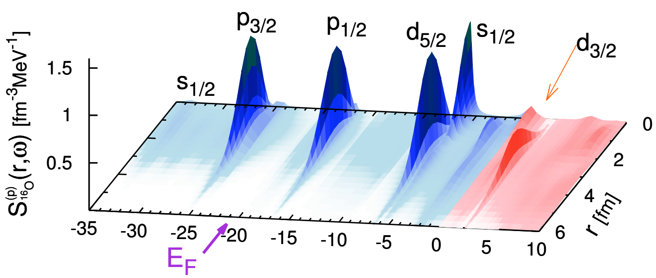




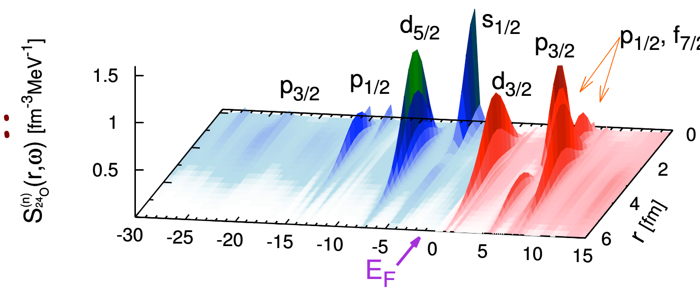
^{22}O:



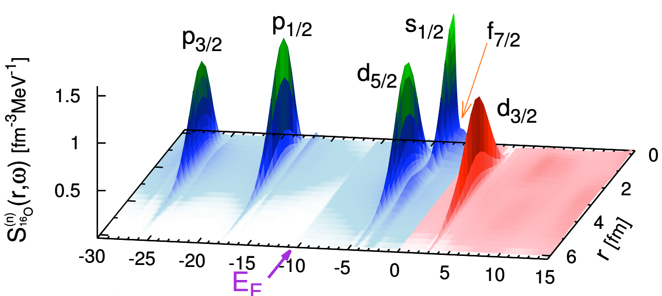
^{14}O:



^{24}O:

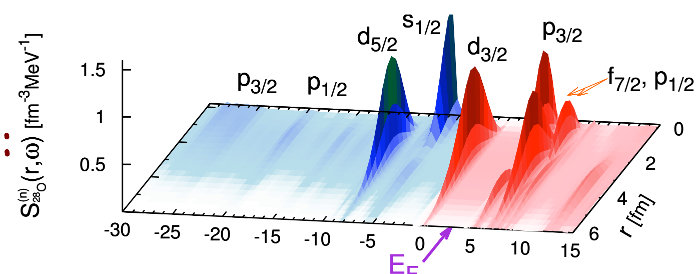


^{16}O:



^{15}O ← → ^{17}O

^{28}O:



^{27}O ← → ^{29}O

Quenching of absolute spectroscopic factors

[CB, *Phys. Rev. Lett.* **103**, 202520 (2009)]

Overall quenching of *spectroscopic factors* is driven by:

SRC → *~10%*

part-vibr. coupling → *dominant*

"shell-model" → *in open shell*

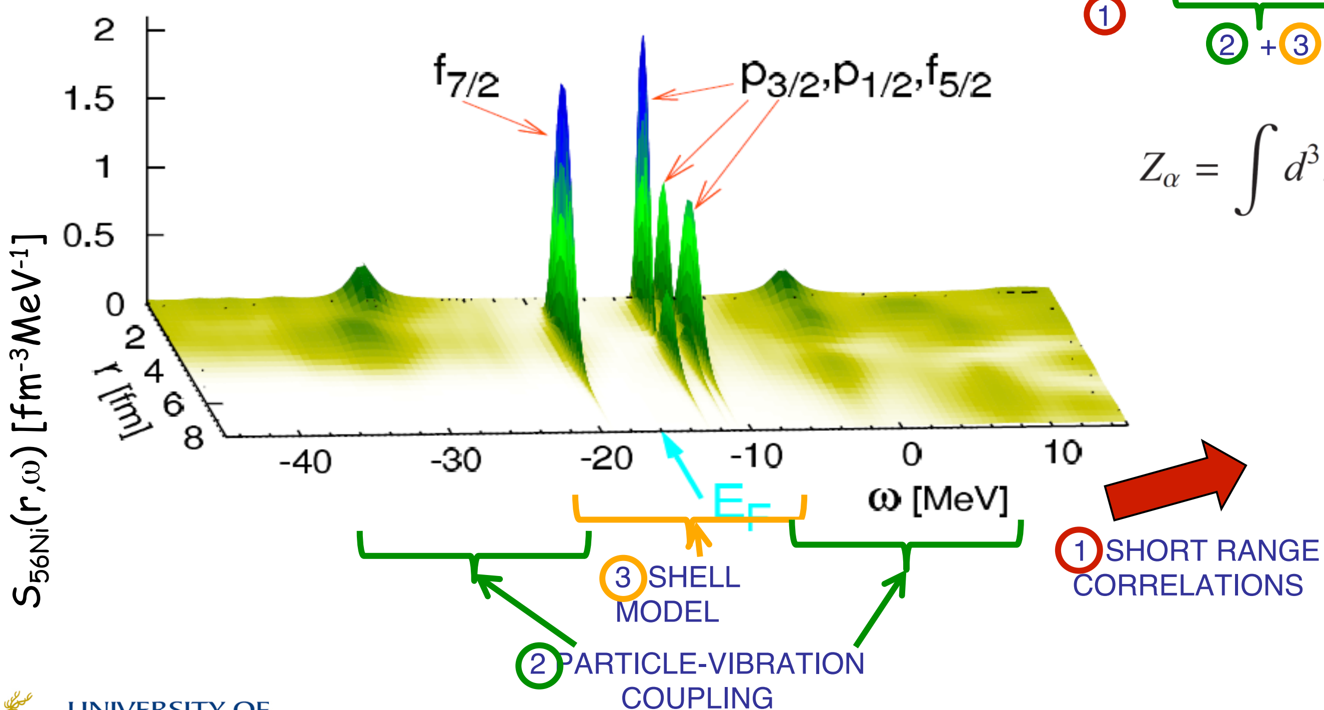
...with analogous conclusions for ^{48}Ca

	10 osc. shells			Exp. [30]	1p0f space		
	FRPA (SRC)	full FRPA	FRPA $+\Delta Z_\alpha$		FRPA	SM	ΔZ_α
^{57}Ni:							
$\nu 1p_{1/2}$	0.96	0.63	0.61		0.79	0.77	-0.02
$\nu 0f_{5/2}$	0.95	0.59	0.55		0.79	0.75	-0.04
$\nu 1p_{3/2}$	0.95	0.65	0.62	0.58(11)	0.82	0.79	-0.03
^{55}Ni:							
$\nu 0f_{7/2}$	0.95	0.72	0.69		0.89	0.86	-0.03

^{57}Ni, ^{55}Ni

(1) — (2) + (3) — (3)

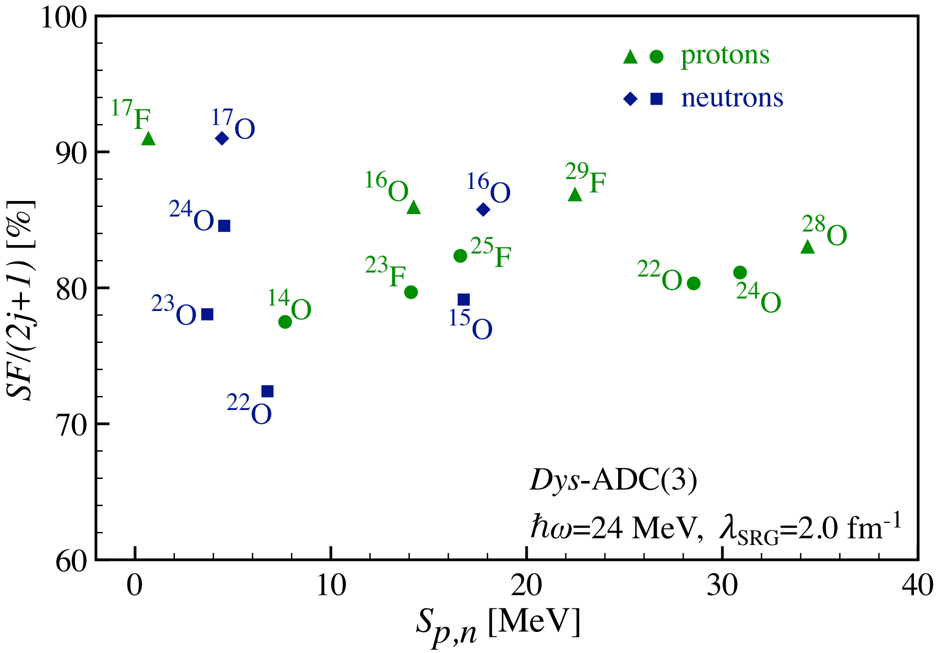
$$Z_\alpha = \int d^3r \, |\psi_\alpha^{overlap}(\mathbf{r})|^2 = \left.\frac{1}{1 - \frac{\partial \Sigma_{\hat\alpha\hat\alpha}(\omega)}{\partial \omega}}\right|_{\omega=\varepsilon_\alpha}$$



Z/N asymmetry dependence of SFs - Theory

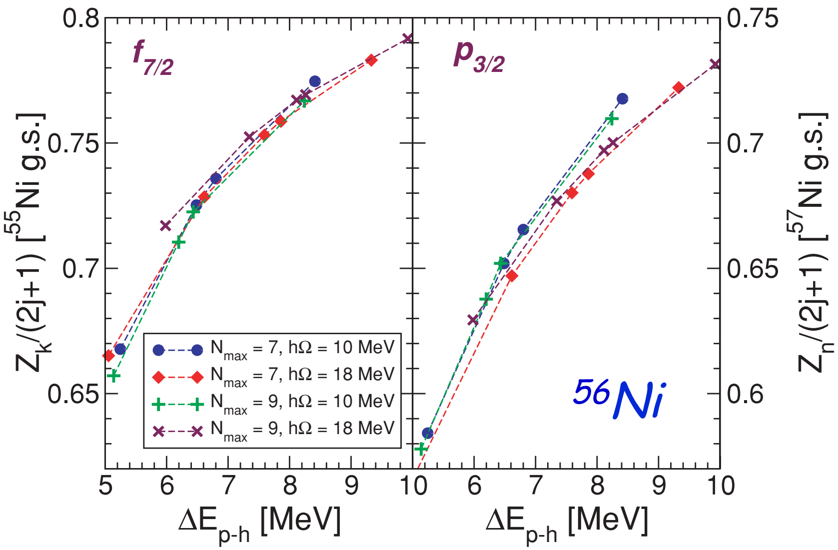
Ab-initio calculations explain the Z/N dependence but the effect is much lower than suggested by direct knockout

Effects of continuum become important at the driplines



arXiv:1412.3002 [nucl-th] (2014)

Spectroscopic factor are strongly correlated to p-h gaps:

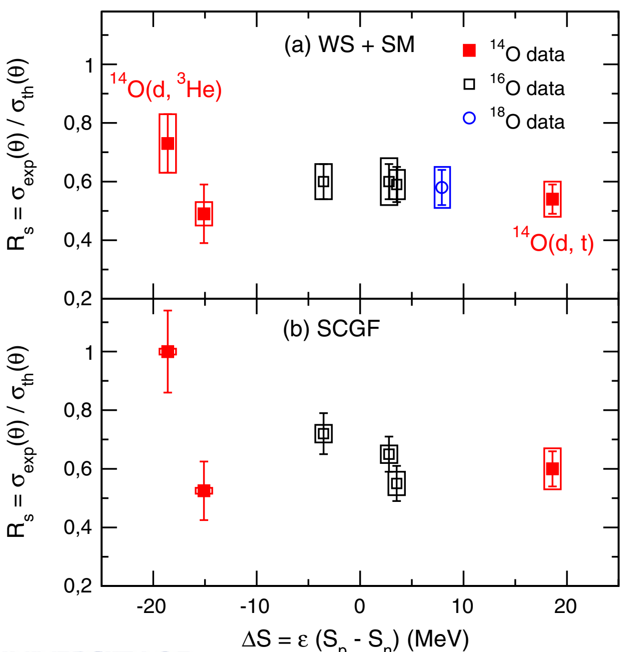


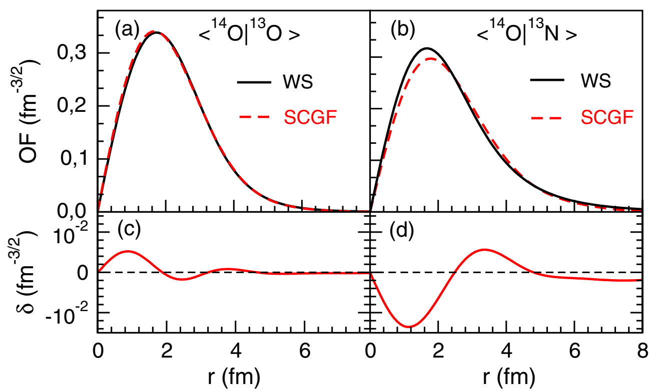
Single nucleon transfer in the oxygen chain

[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^{HFB}_{rms} (fm)	r_0 (fm)	C^2S_{exp} (WS)	C^2S_{th} $0p + 2\hbar\omega$	R_s (WS)	C^2S_{exp} (SCGF)	C^2S_{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 $(d, ^3He)$ ^{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 $(d, ^3He)$ ^{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 $(d, ^3He)$ ^{17}N [21]	0.00	$1/2^-$	2.91	1.46	0.92(9)(12)	1.58	0.58(6)(10)			



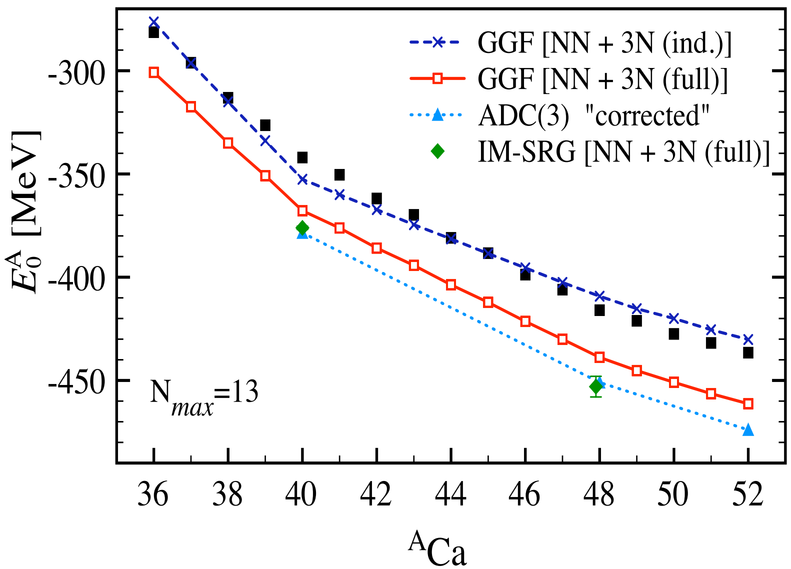


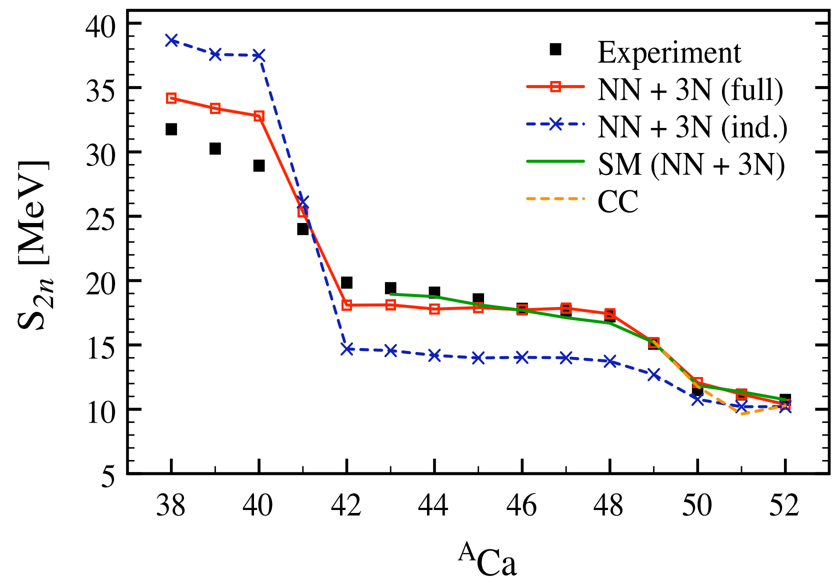
- Overlap functions and strengths from GF

- Rs independent of asymmetry

Calcium isotopic chain

Ab-initio calculation of the whole Ca: *induced* and full 3NF investigated





→ *induced* and full 3NF 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!

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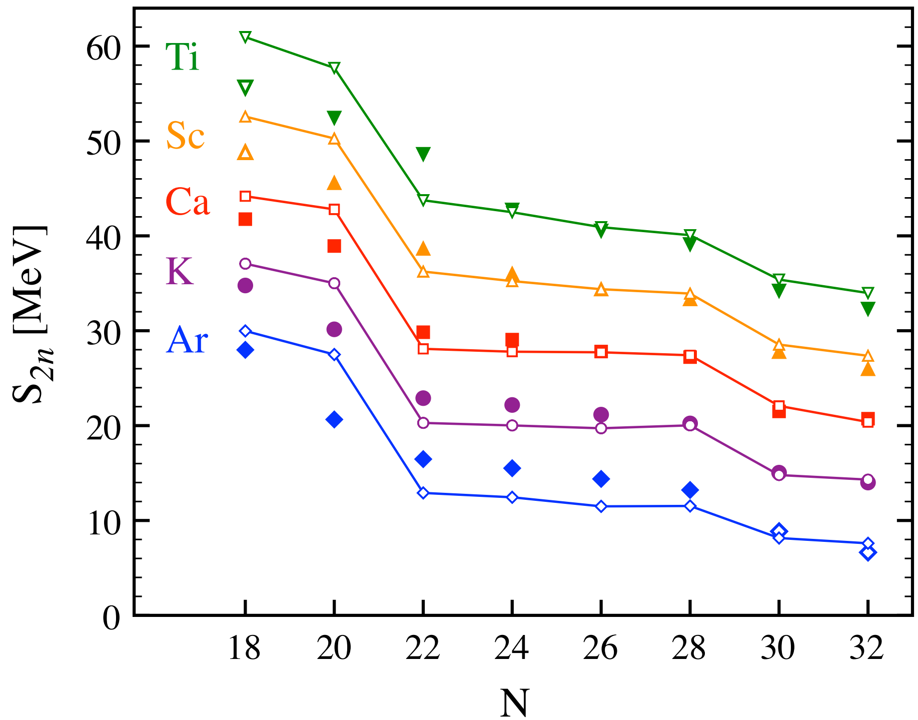
V. Somà, CB *et al.* Phys. Rev. C**89**, 061301R (2014)

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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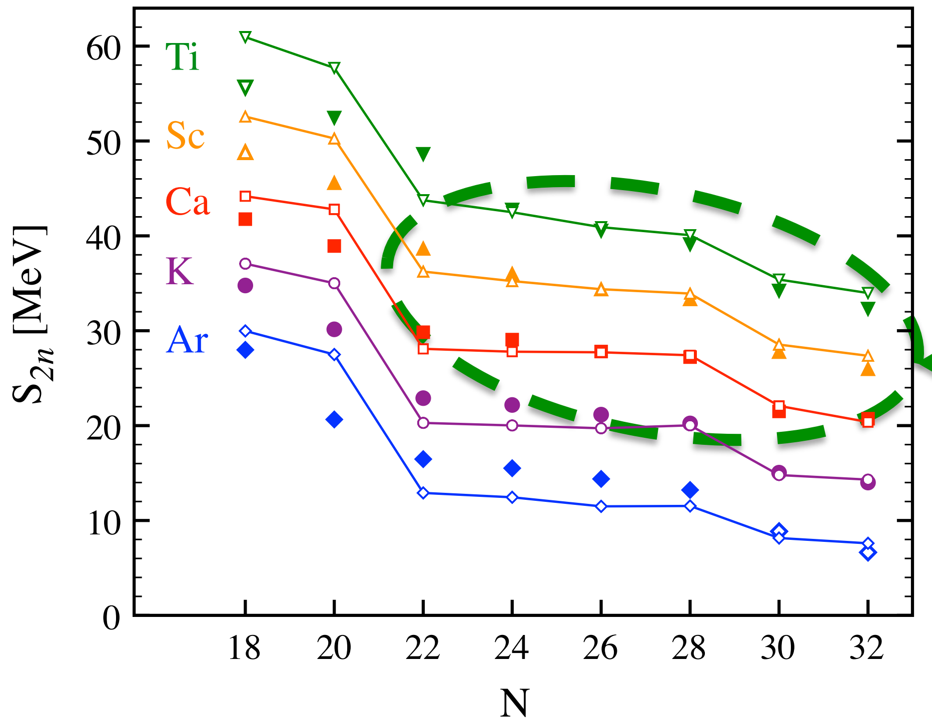

Works well in the *pf* shell

→ 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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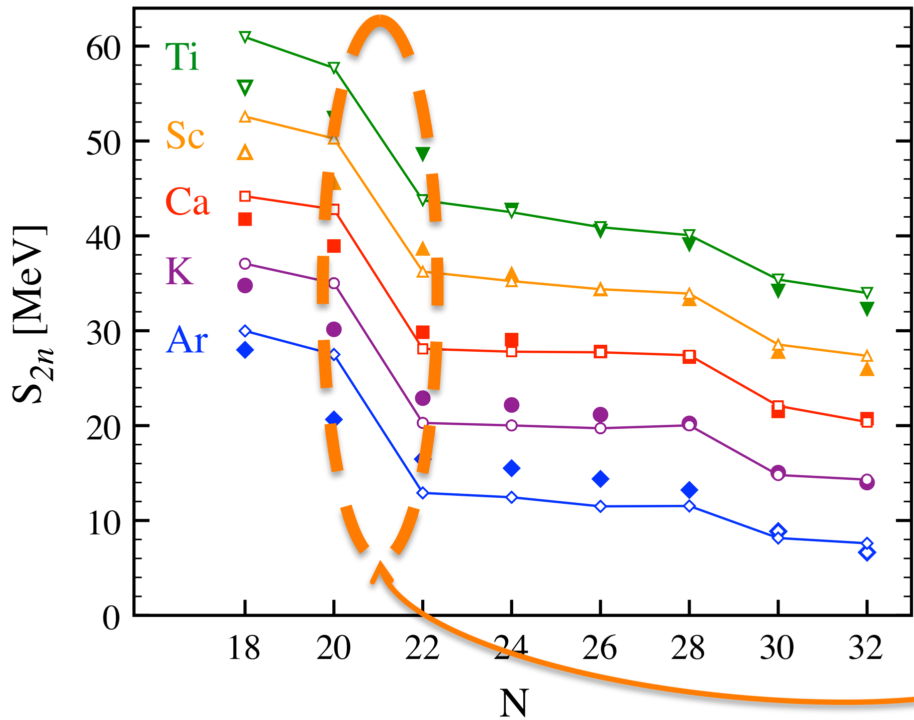

Over estimated
N=20 and Z=20 gaps

→ 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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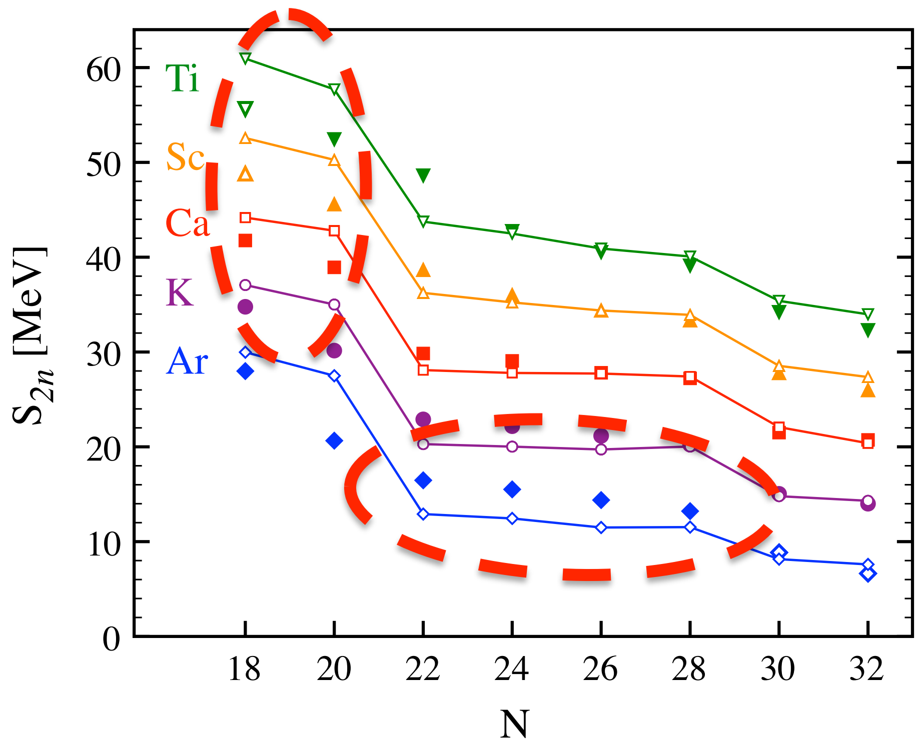


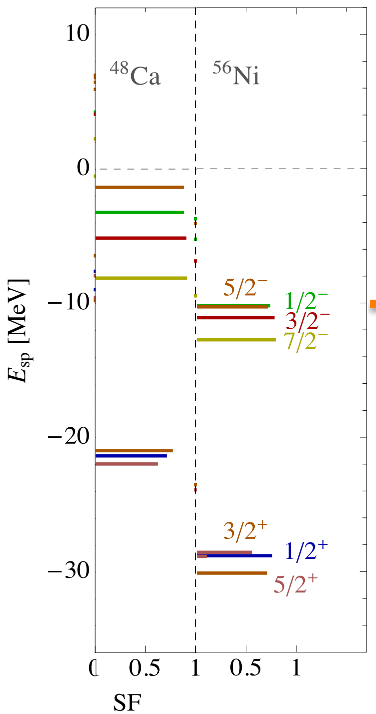
Lack of deformation due to quenched cross-shell quadrupole excitations

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

The sd-pf shell gap

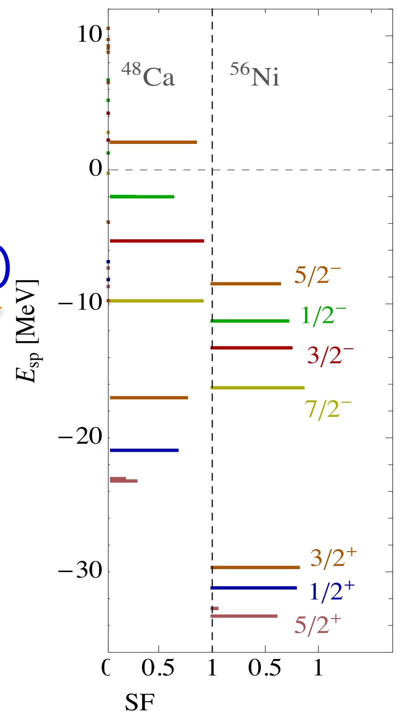
Neutron spectral distributions for ^{48}Ca and ^{56}Ni:

2N + 3NF (induced)



+3NFs (NNLO)

2N + 3NF (FULL)



- *sd-pf separation is overestimated* <u>even</u> with leading order N2LO 3NF
- Correct increase of *$p_{3/2}$-$f_{7/2}$* splitting (see Zuker 2003)

	2NF only	2+3NF(ind.)	2+3NF(full)	Experiment
^{16}O:	2.10	2. 41	2.38	2.718±0.210 [19]
^{44}Ca:	2.48	2.93	2.94	3.520±0.005 [20]

CB *et al.*, arXiv:1211.3315 [nucl-th]

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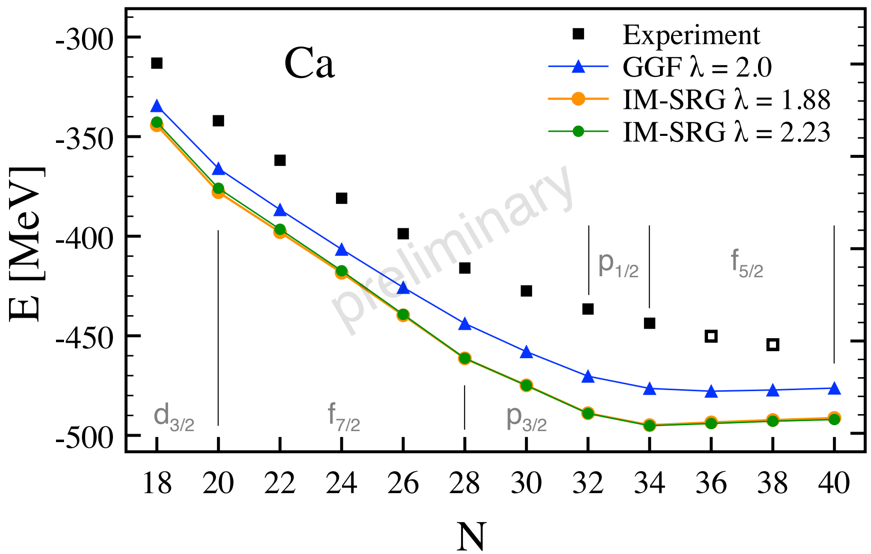
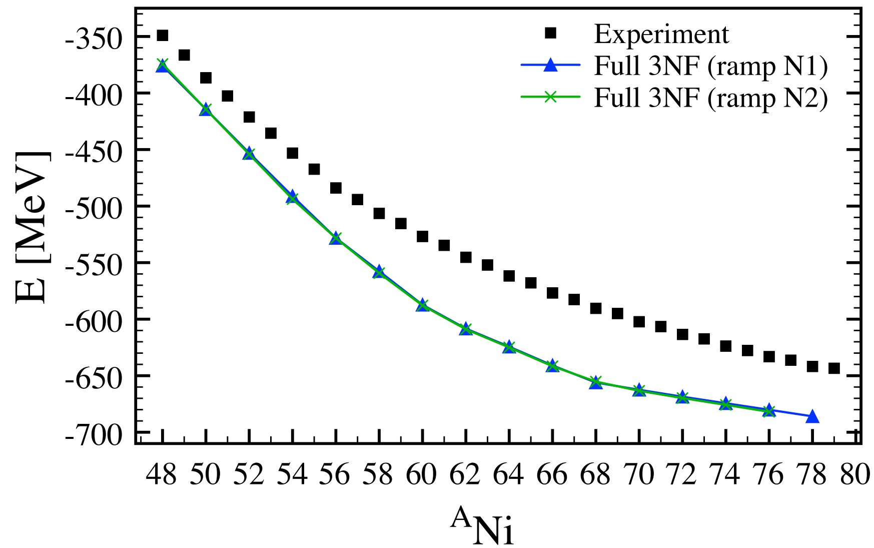
Ca and Ni isotopic chains





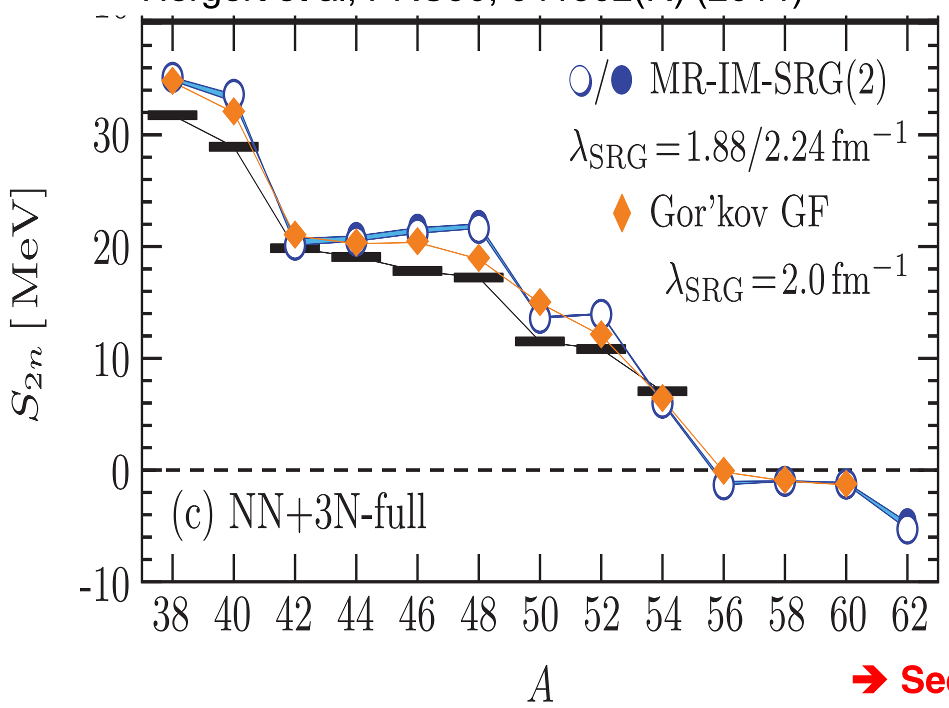
→ Large J in free space SRG matter (must pay attention to its convergence)

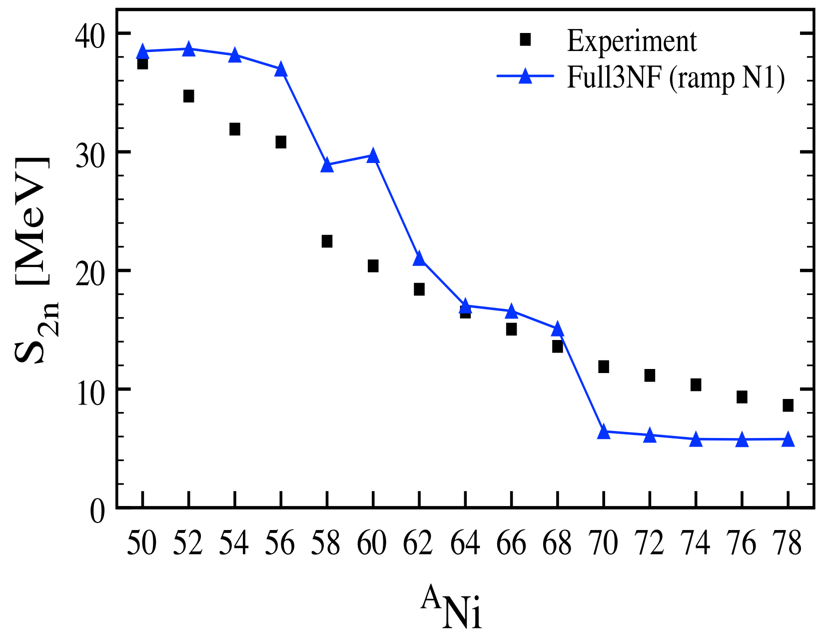
→ Overall conclusions regarding over binding and S_{2n} remain but details change

IM-SRG results from H. Hergert

Ca and Ni isotopic chains

Hergert et al, PRC**90**, 041302(R) (2014)





➔ **See also Heiko's talk on Thursday**

→ 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

Two-neutron separation energies for neutron rich K isotopes

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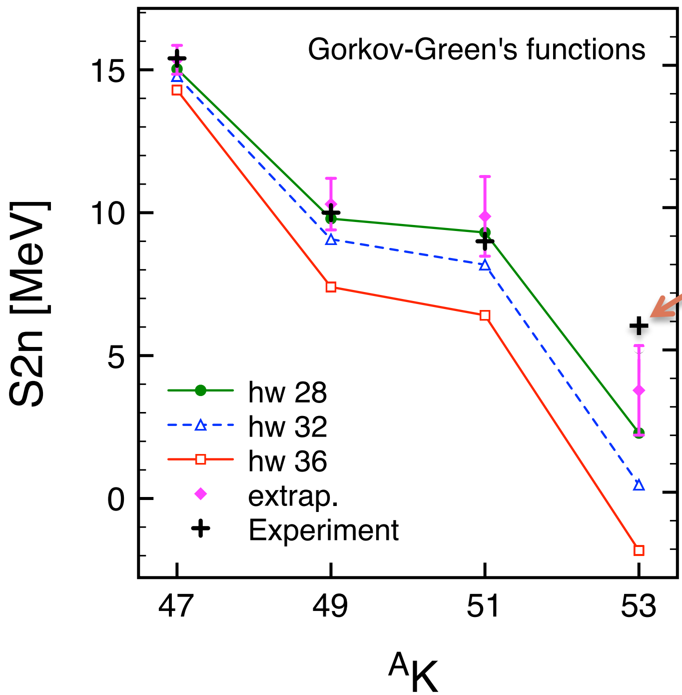
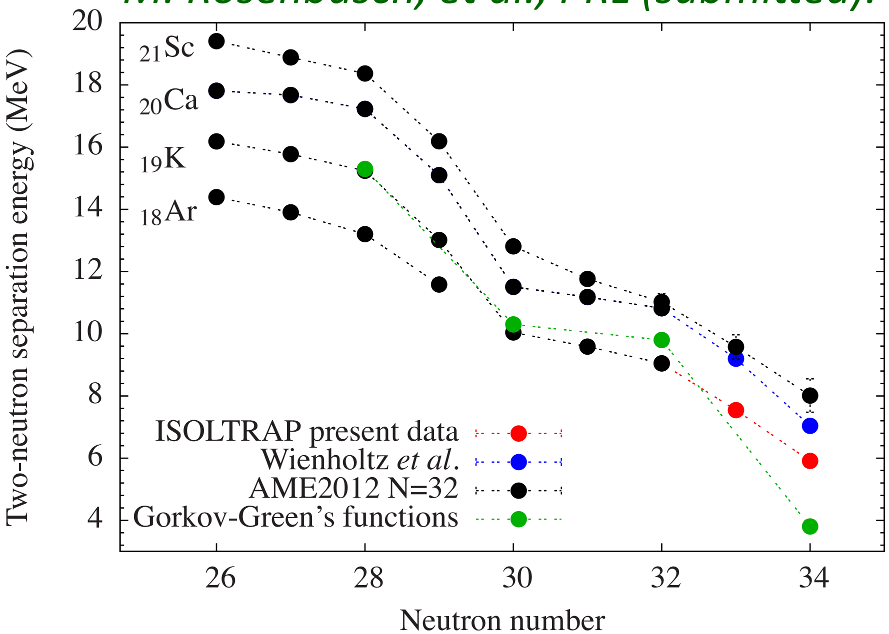


M. Rosenbusch, et al., PRL (submitted).



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

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

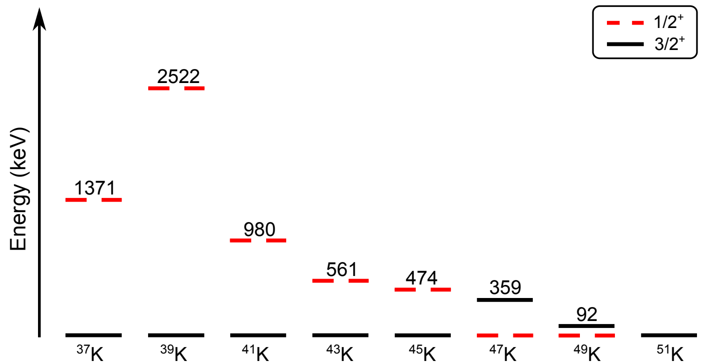


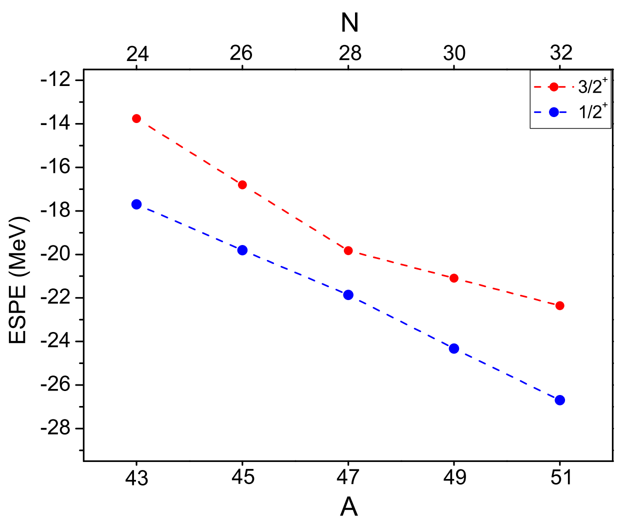
FIG. 1. (color online) Experimental energies for $1/2^+$ and $3/2^+$ states in odd-A K isotopes. Inversion of the nuclear spin is obtained in ^{47,49}K and reinversion back in ^{51}K. Results are

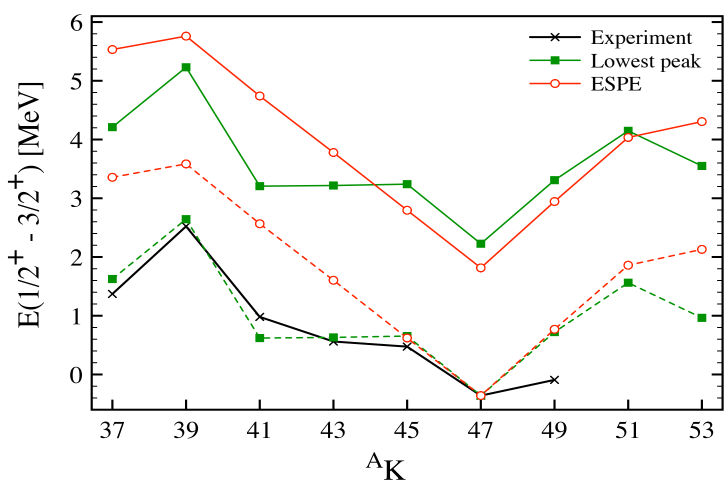
J. Papuga, et al., PRL **110**, 172503 (2013); PRC (2014), submitted.

^{A}K isotopes

Laser spectroscopy @ ISOLDE

Change in separation described by chiral NN+3NF:





ESPE: "centroid" energies

(Gorkov calculations at 2nd order)

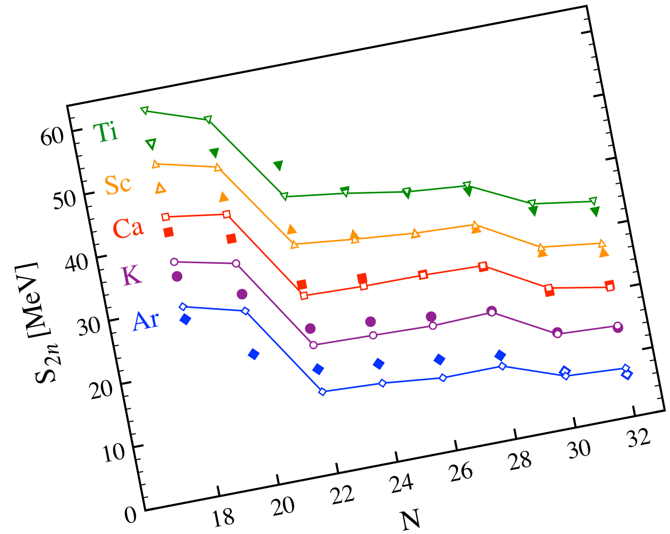
Conclusions

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

→ *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.*



Thank you for your attention!!!

Collaborators

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