Progress in Ab-Initio Techniques in Nuclear Physics
TRIUMF -- 17-20 February 2015

Evolution of correlations and shell model charges from SCGF

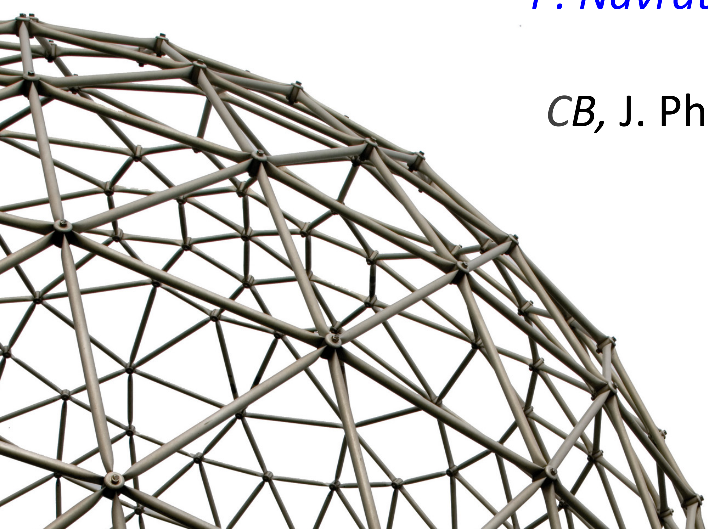
Carlo Barbieri — University of Surrey

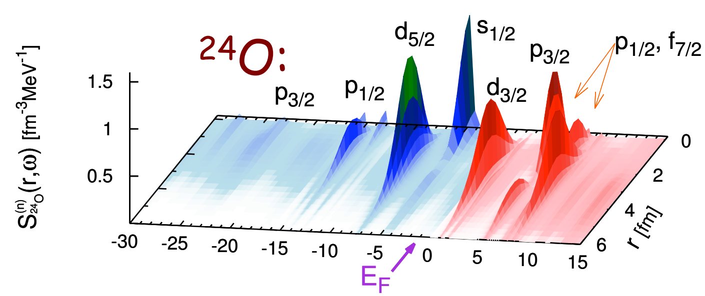
Collaborators:

A. Cipollone, CB, P. Navrátil: — *Phys. Rev. Lett.* ***111****, 062501 (2013)*
arXiv:1412.0491 [nucl-th] (2014)

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

CB, J. Phys.: Conf. Ser. **529,** 012005 (2014)

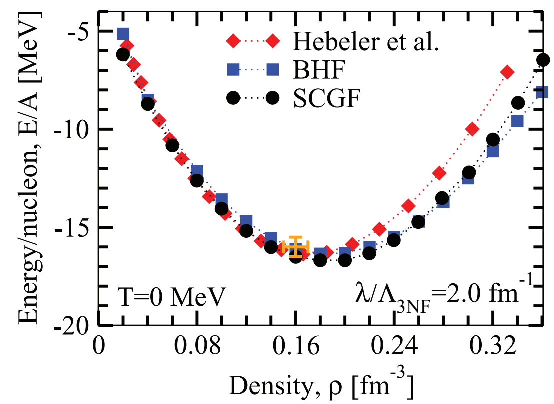




Nuclear forces in exotic nuclei

Nucleon interactions are very complex and difficult to handle

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

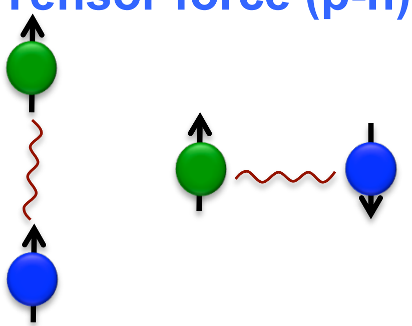


Change of regime from stable to dripline isotopes !

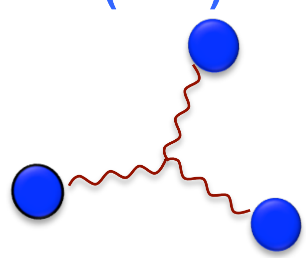
Symmetric matter:
N ≈ Z

Neutron-rich matter (N ≫ Z):
- **Neutron star matter EoS**
- **Symmetry energy**

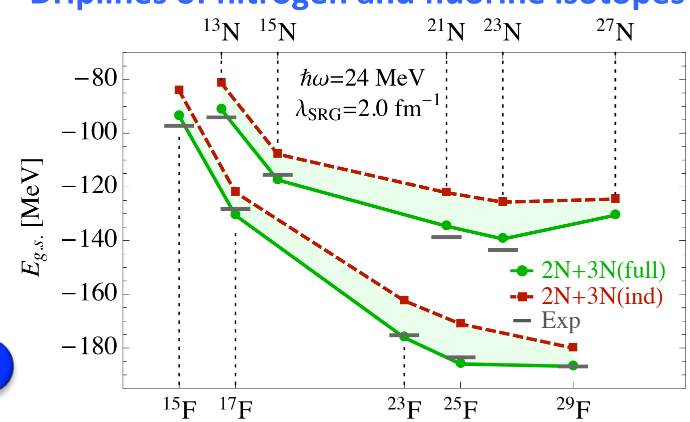
Tensor force (p-n)



Three-nucleon Force (3NF)



Driplines of nitrogen and fluorine isotopes



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

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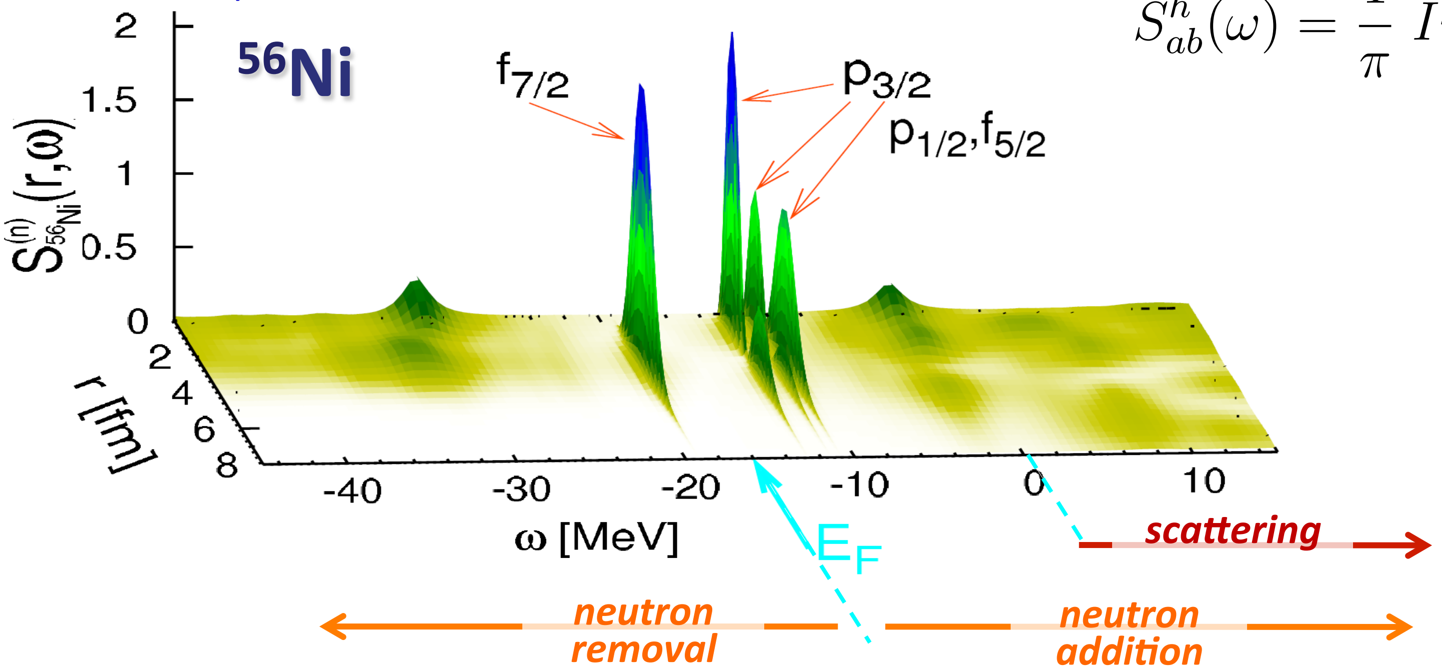
Example of spectral function ^{56}Ni

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

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

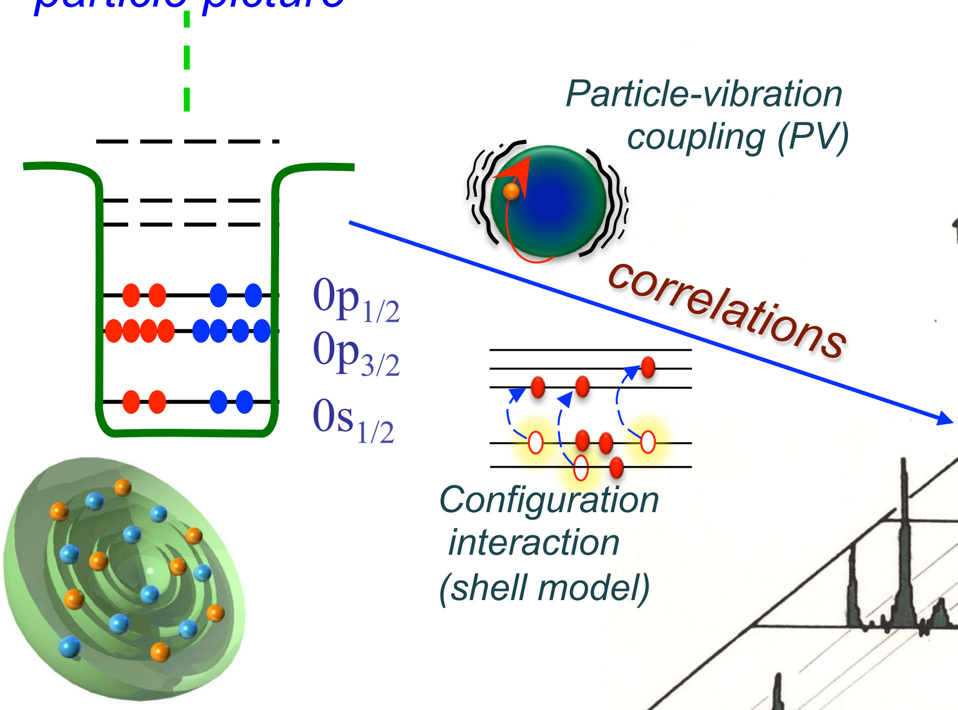
…this contains all the structure information probed by nucleon transfer (spectral function):

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

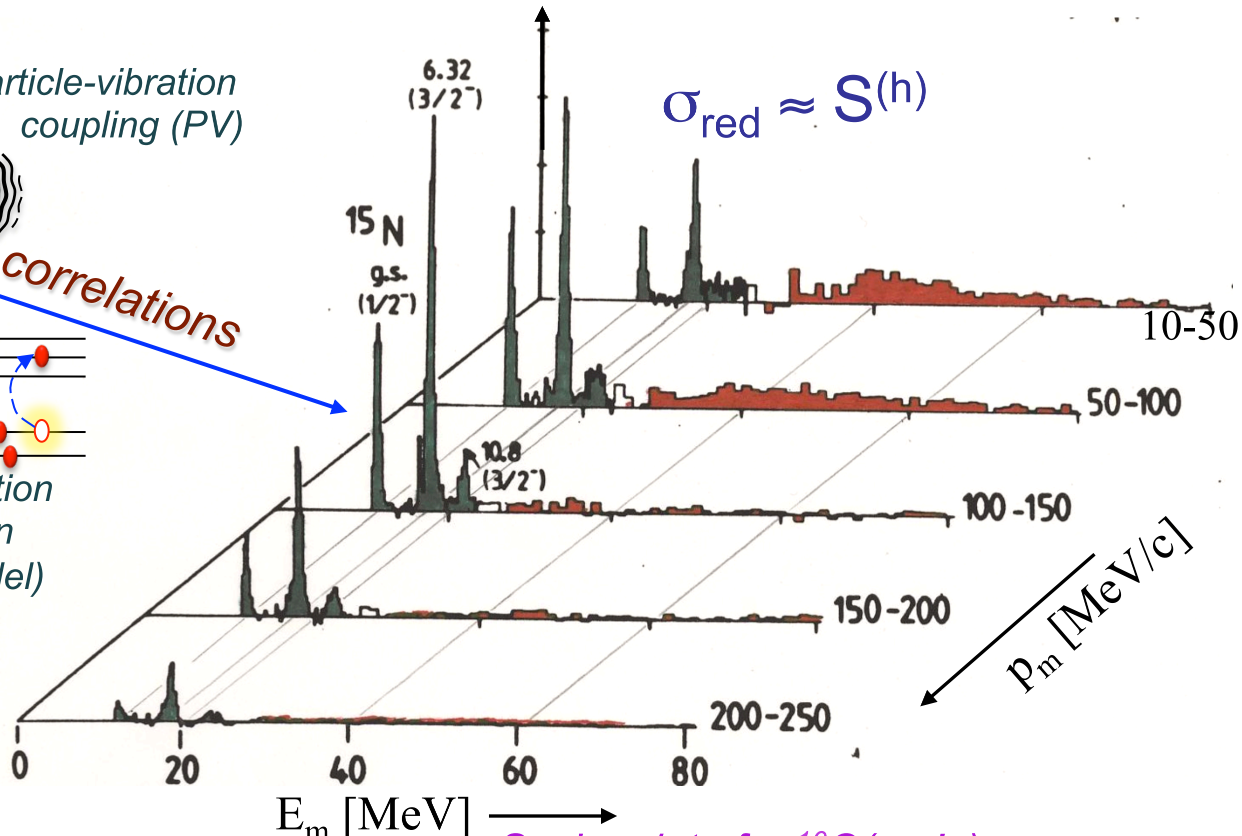


[CB, M.Hjorth-Jensen, Pys. Rev. C**79**, 064313 (2009); CB, Phys. Rev. Lett. **103**, 202502 (2009)]

Concept of correlations



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



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

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

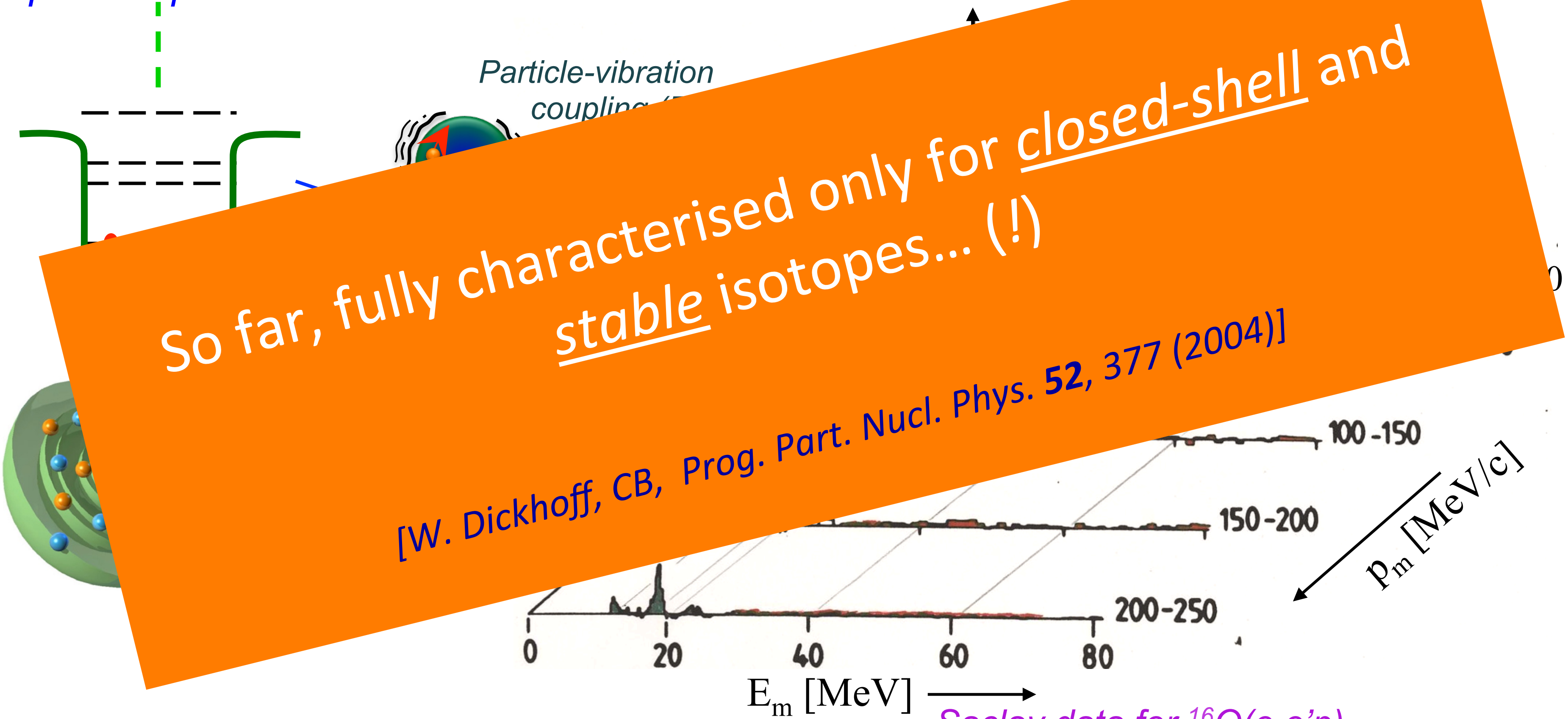
*[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys **52**, 377 (2004)]*

Concept of correlations

independent particle picture

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

Particle-vibration coupling (...)



So far, fully characterised only for closed-shell and stable isotopes… (!)

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

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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

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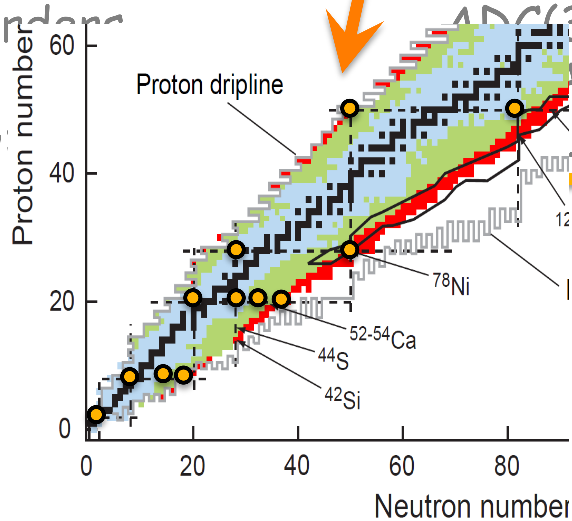
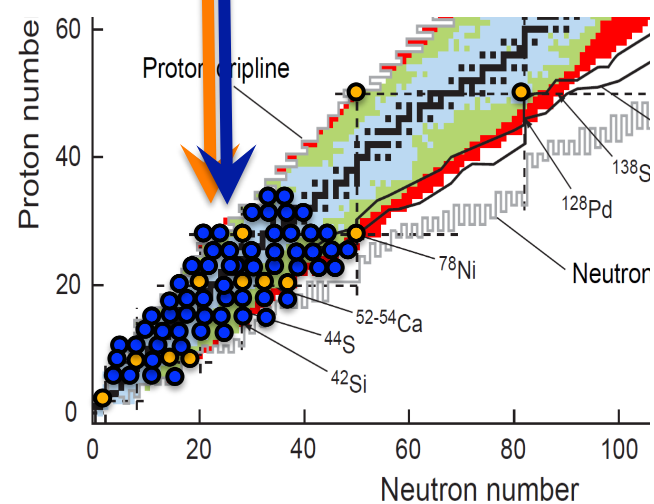
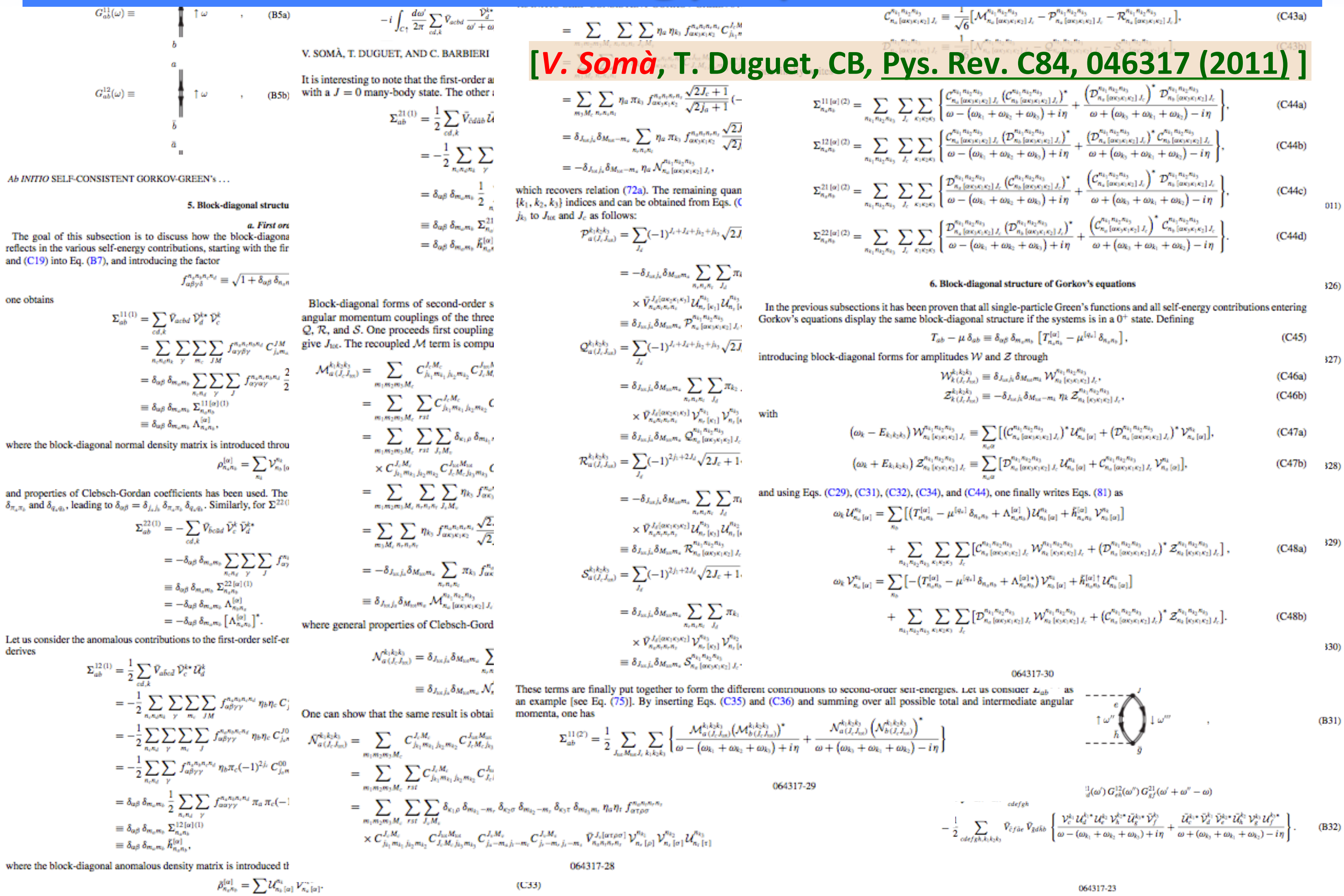




Gorkov self-energy up to 2nd order

[*V. Somà*, T. Duguet, CB, Pys. Rev. C84, 046317 (2011)]

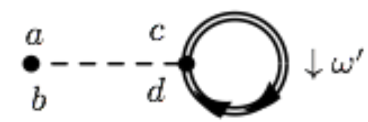


Gorkov self-energy up to 2nd order

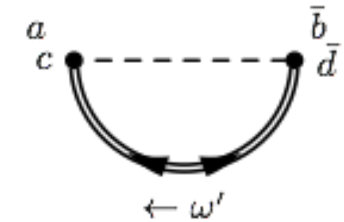
V. Somà, CB, T. Duguet, , Phys. Rev. C **89**, 024323 (2014)
V. Somà, CB, T. Duguet, Phys. Rev. C **87**, 011303R (2013)
V. Somà, T. Duguet, CB, Phys. Rev. C **84**, 064317 (2011)

1st order ➠ energy-independent self-energy

$$\Sigma^{11\,(1)}_{ab} =$$

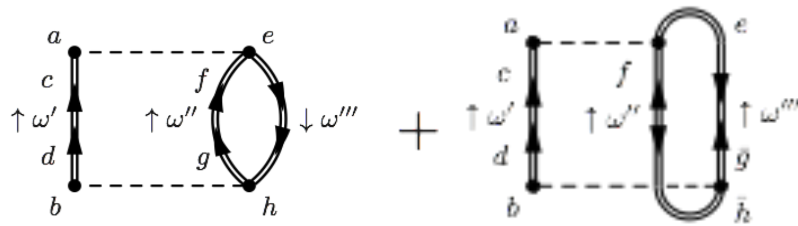


$$\Sigma^{12\,(1)}_{ab} =$$

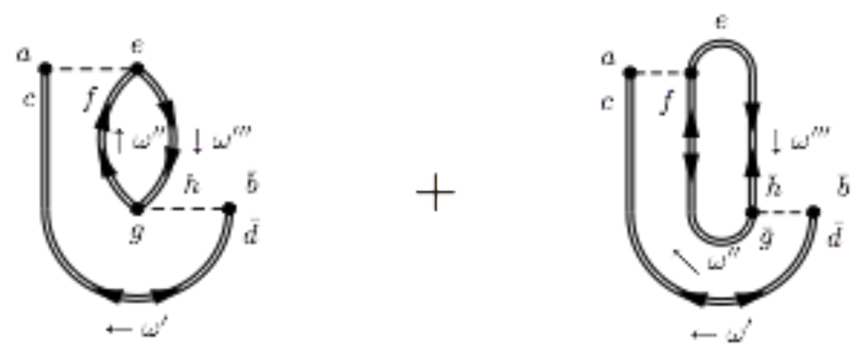


2nd order ➠ energy-dependent self-energy

$$\Sigma^{11\,(2)}_{ab}(\omega) =$$



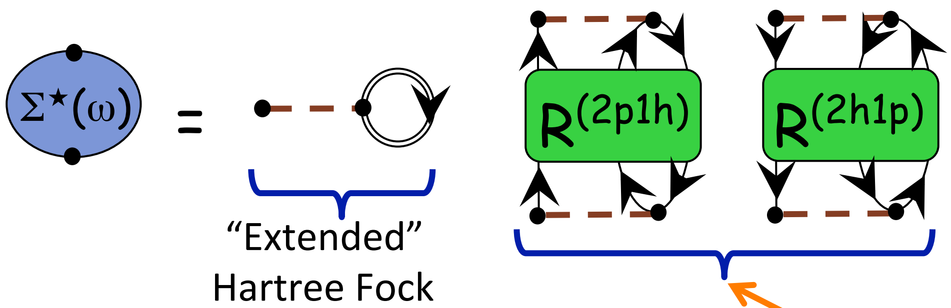
$$\Sigma^{12\,(2)}_{ab}(\omega) =$$



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…

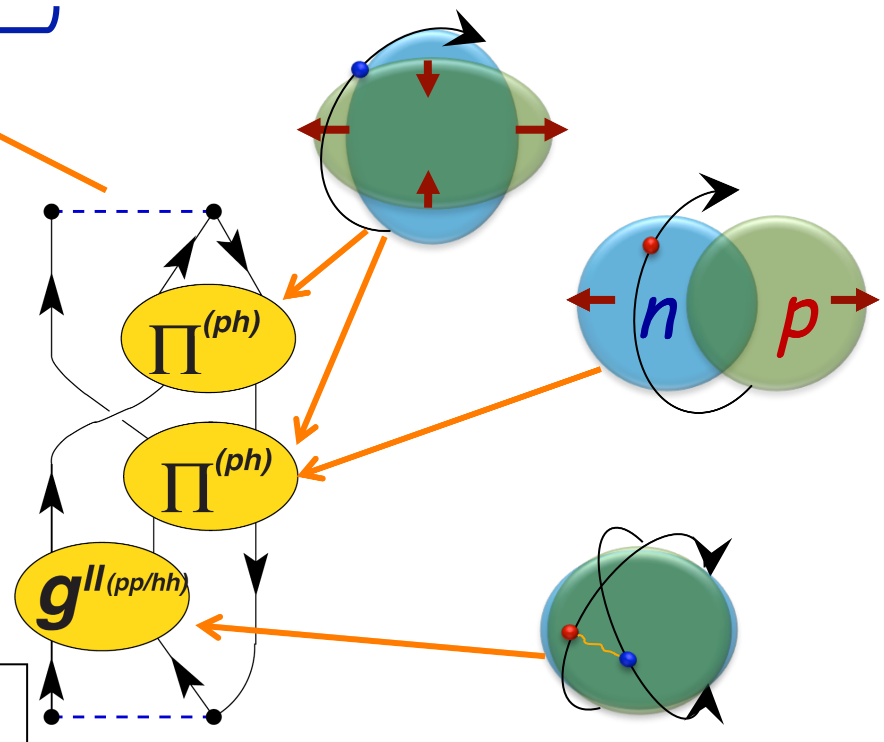
CB et al.,
*Phys. Rev. C***63***, 034313 (2001)*
*Phys. Rev. A***76***, 052503 (2007)*
*Phys. Rev. C***79***, 064313 (2009)*

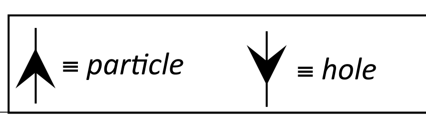


•*A complete expansion requires* *__all__* *__types__* of particle-vibration coupling

…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



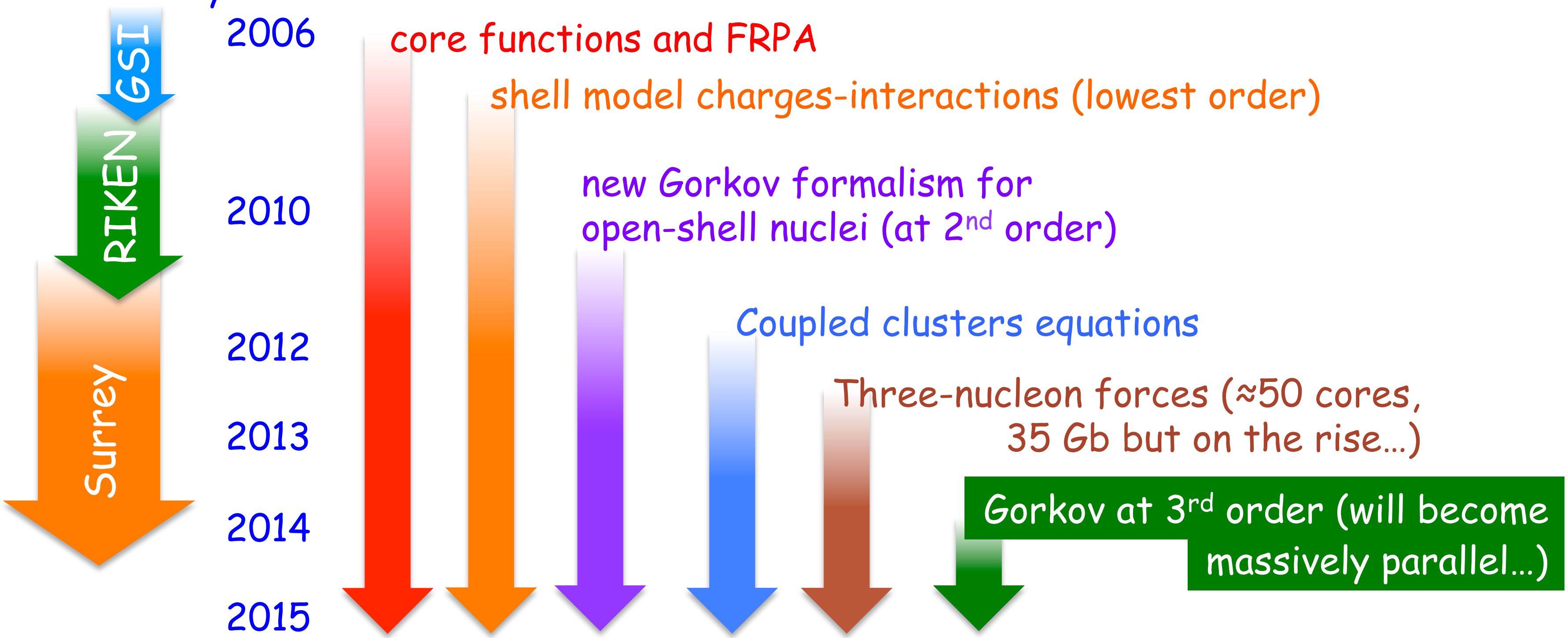


Ab-initio Nuclear Computation & BcDor code

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 …

Quenching of absolute spectroscopic factors

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

Overall quenching of *spectroscopic factors* is driven by:

SRC → *~10%*

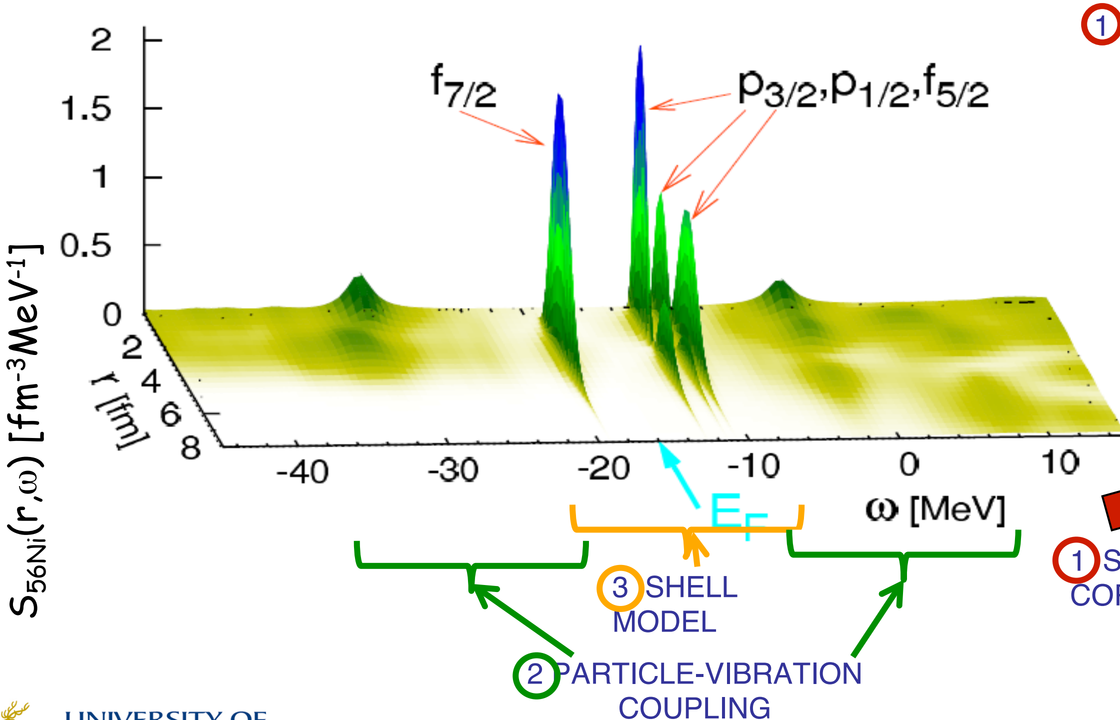
part-vibr. coupling → *dominant*

"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	^{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	^{55}Ni:							
	$\nu 0f_{7/2}$	0.95	0.72	0.69		0.89	0.86	-0.03
		①	② + ③			③		

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



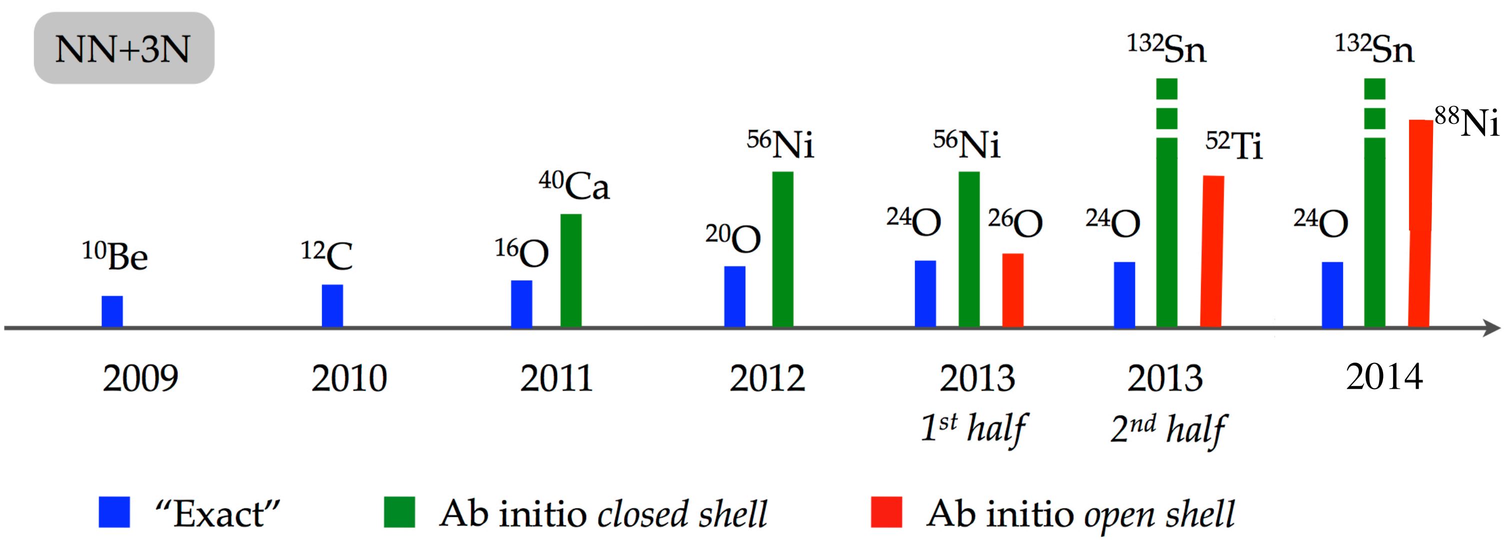
① SHORT RANGE CORRELATIONS

^{56}Ni
NN-N3LO(500)

Reaching medium mass and neutron rich isotopes

➔Degenerate system (open shells, deformations…)

➔Hamiltoninan, including three nucleon forces

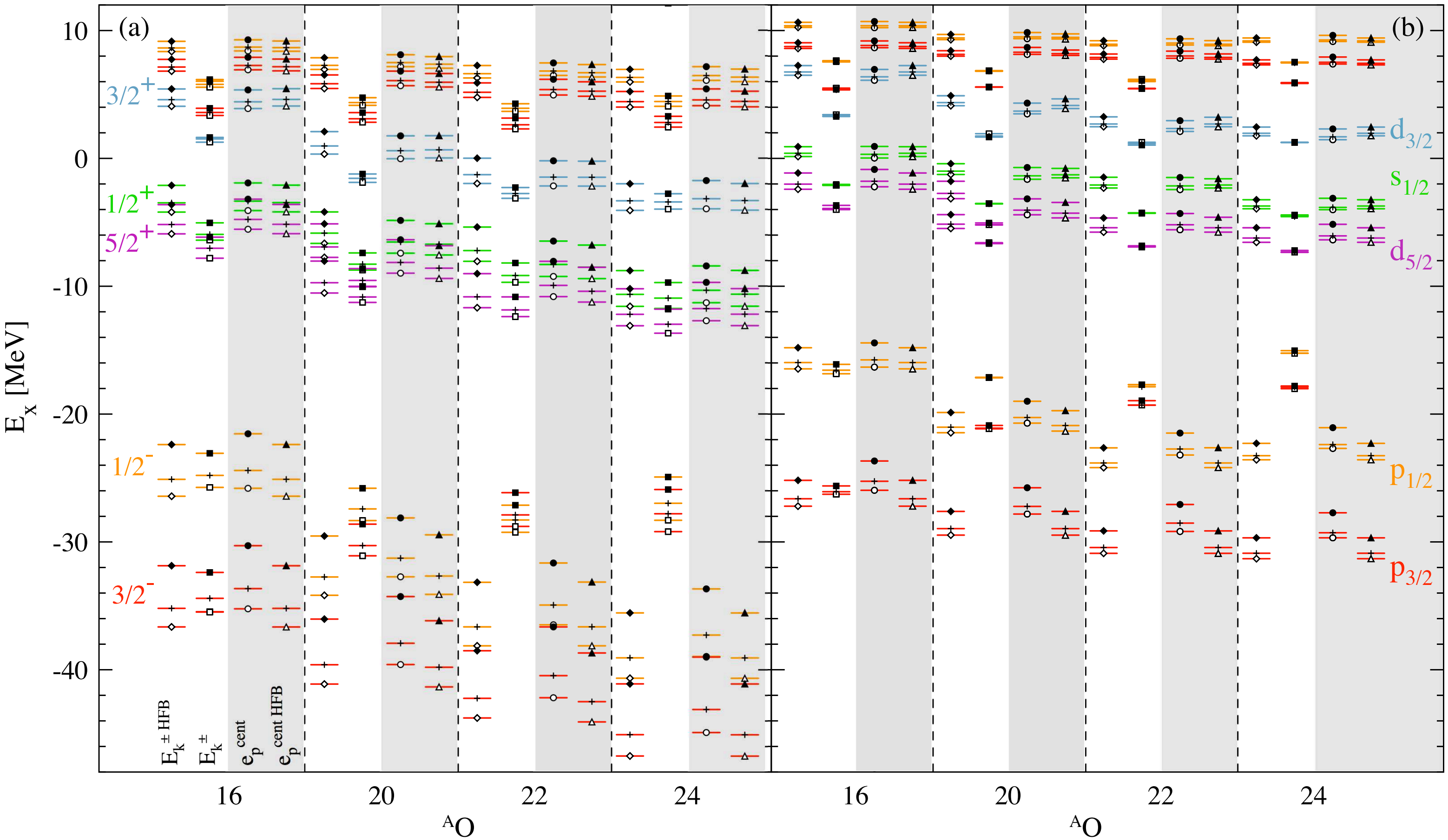


Convergence of s.p. spectra w.r.t. SRG

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

arXiv:1411.1237 (2014)

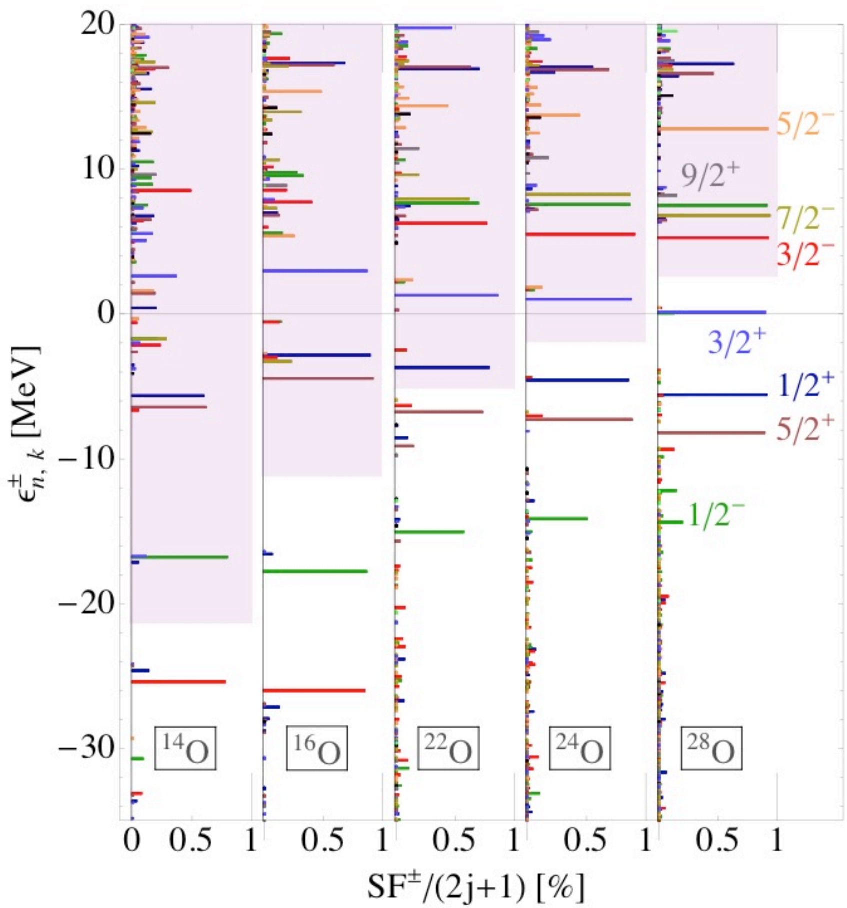
✔only dominant s.p. states shown

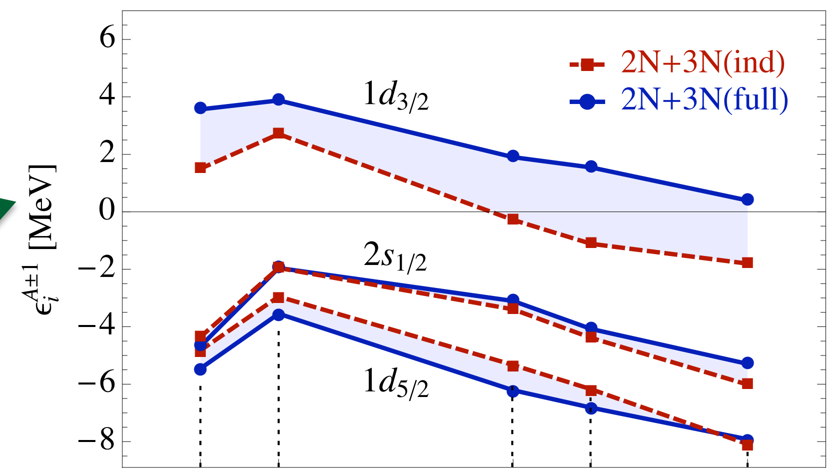


NN terms (no induced 3NF) ← → NN+3NF fully included

Results for the N-O-F chains

A. Cipollone, CB, P. Navrátil, Phys. Rev. Lett. **111**, 062501 (2013)
and arXiv:1412.0491 [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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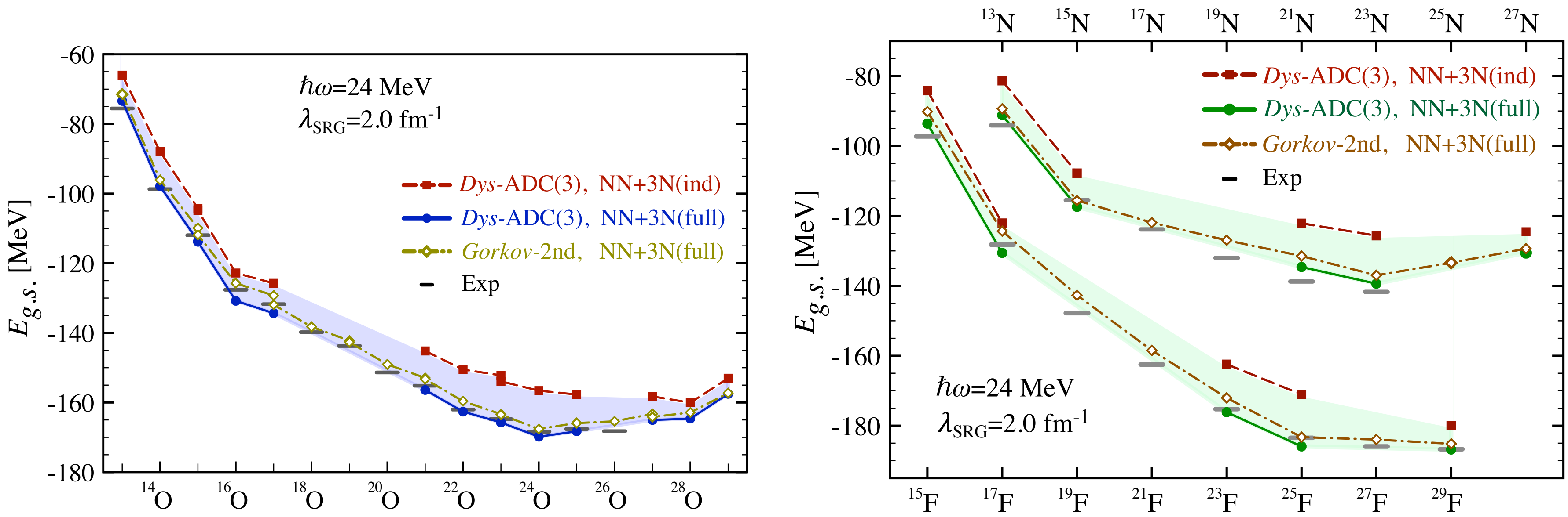

→ 3NF crucial for reproducing binding energies and driplines around oxygen

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

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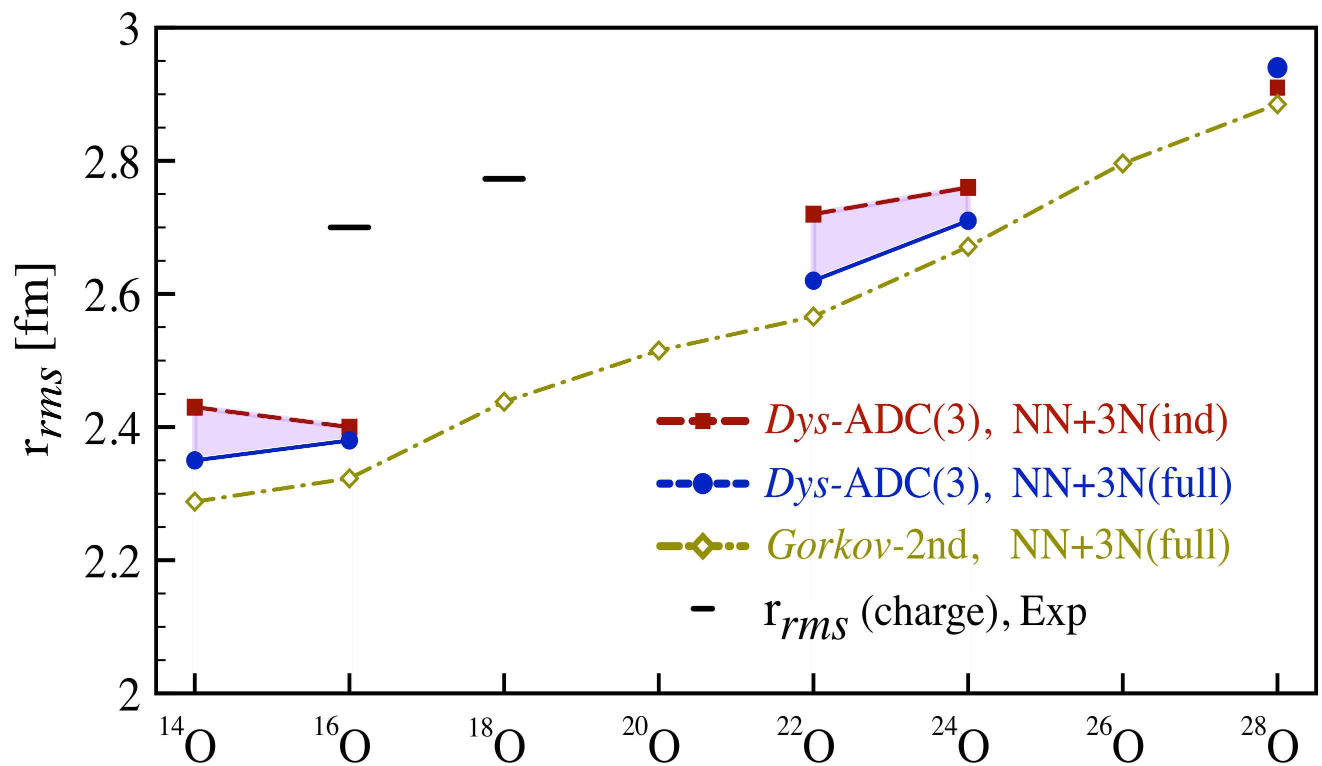
N3LO (Λ = 500Mev/c) chiral NN interaction evolved to 2N + 3N forces (2.0fm^{-1})
N2LO (Λ = 400Mev/c) chiral 3N interaction evolved (2.0fm^{-1})

Results for the oxygen chain

A. Cipollone, CB, P. Navrátil, arXiv:1412.0491 [nucl-th] (2014)



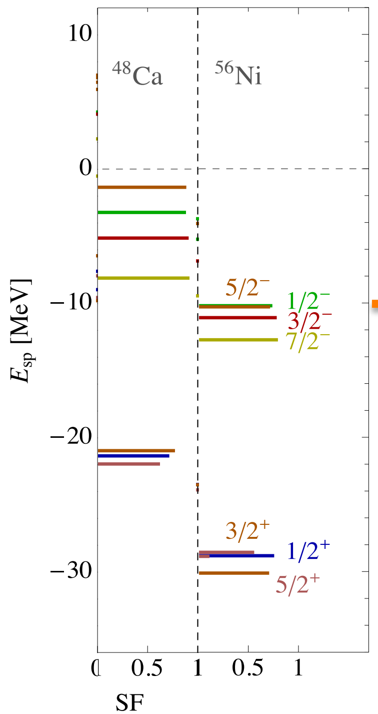
→ Single particle spectra slightly diluted and

→ systematic underestimation of radii

The sd-pf shell gap

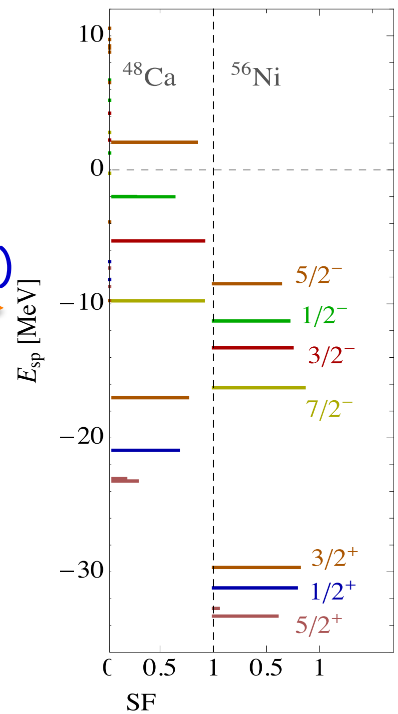
Neutron spectral distributions for ^{48}Ca and ^{56}Ni:

2N + 3NF (induced)



+3NFs (NNLO) →

2N + 3NF (FULL)



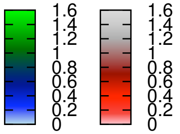
- *sd-pf separation is overestimated* even with leading order N2LO 3NF
- Correct increase of $p_{3/2}$-$f_{7/2}$ splitting (see Zuker 2003)

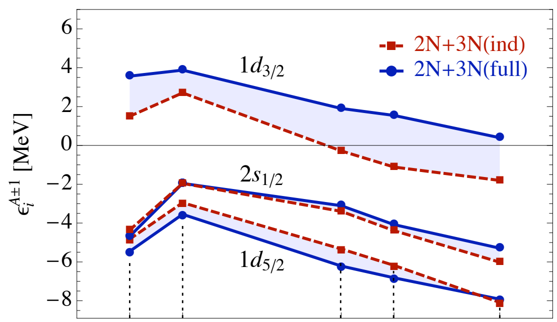
	2NF only	2+3NF(ind.)	2+3NF(full)	Experiment
^{16}O:	2.10	2. 41	2.38	2.718±0.210 [19]
^{44}Ca:	2.48	2.93	2.94	3.520±0.005 [20]

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

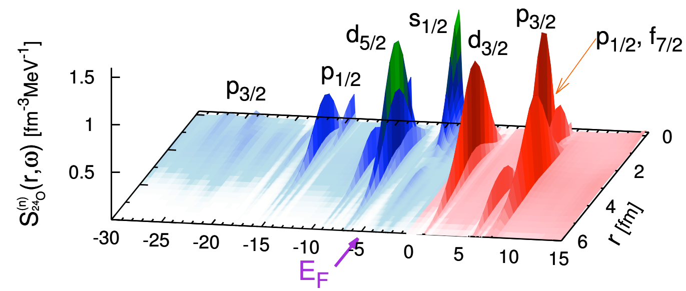
Neutron spectral function of Oxygens

A. Cipollone, CB P. Navrátil, *arXiv:1412.0491* (2014)

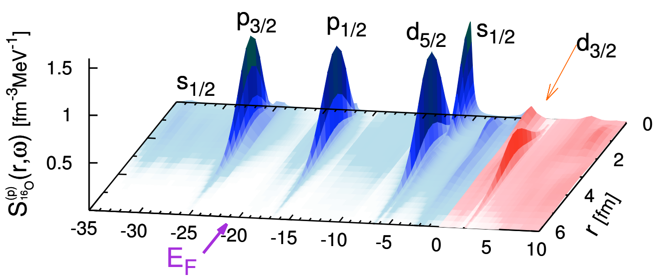




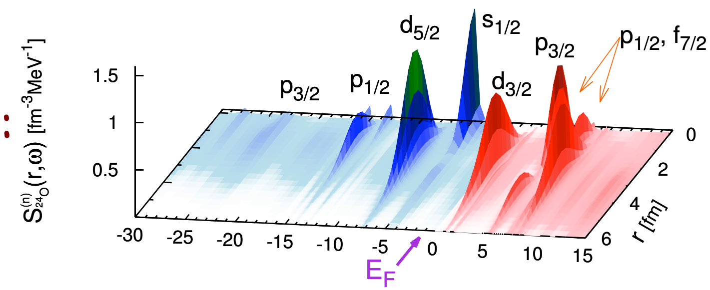
^{22}O:



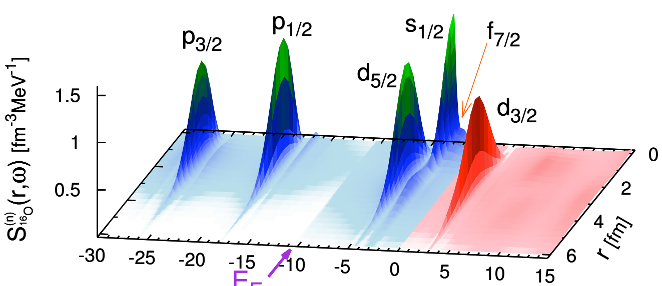
^{14}O:



^{24}O:

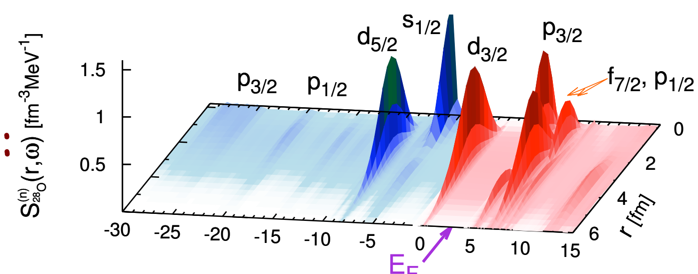


^{16}O:



^{15}O ← → ^{17}O

^{28}O:

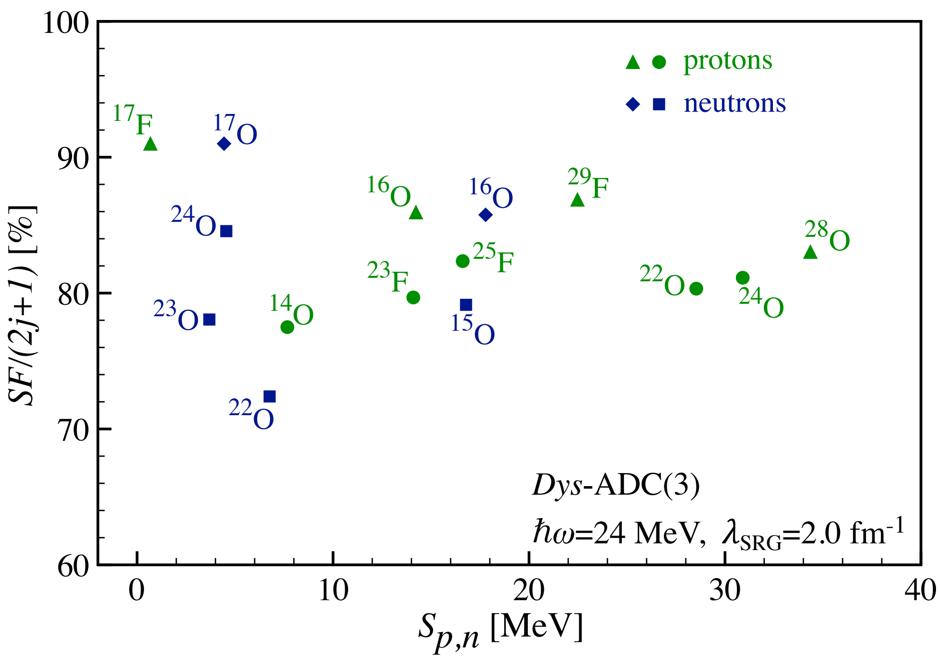


^{27}O ← → ^{29}O

Z/N asymmetry dependence of SFs - Theory

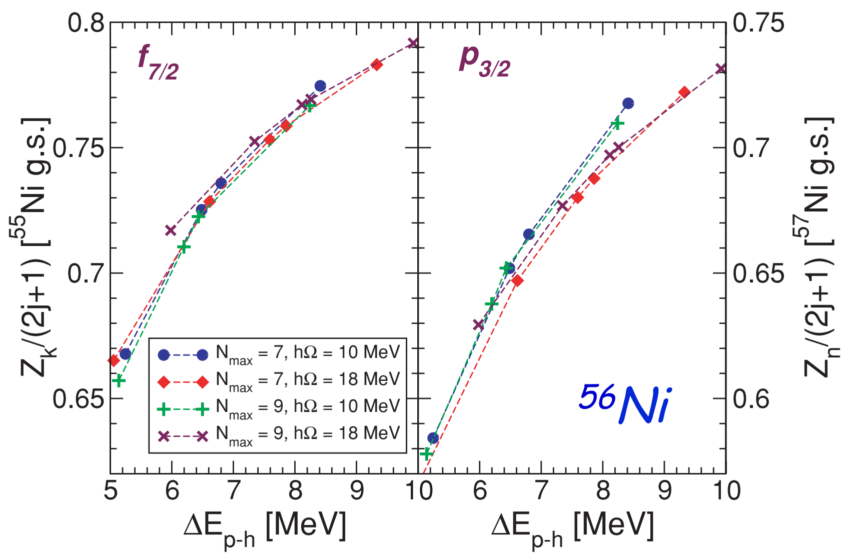
Ab-initio calculations explain the Z/N dependence but the effect is much lower than suggested by direct knockout

Effects of continuum become important at the driplines



arXiv:1412.0491 [nucl-th] (2014)

Spectroscopic factor are strongly correlated to p-h gaps:



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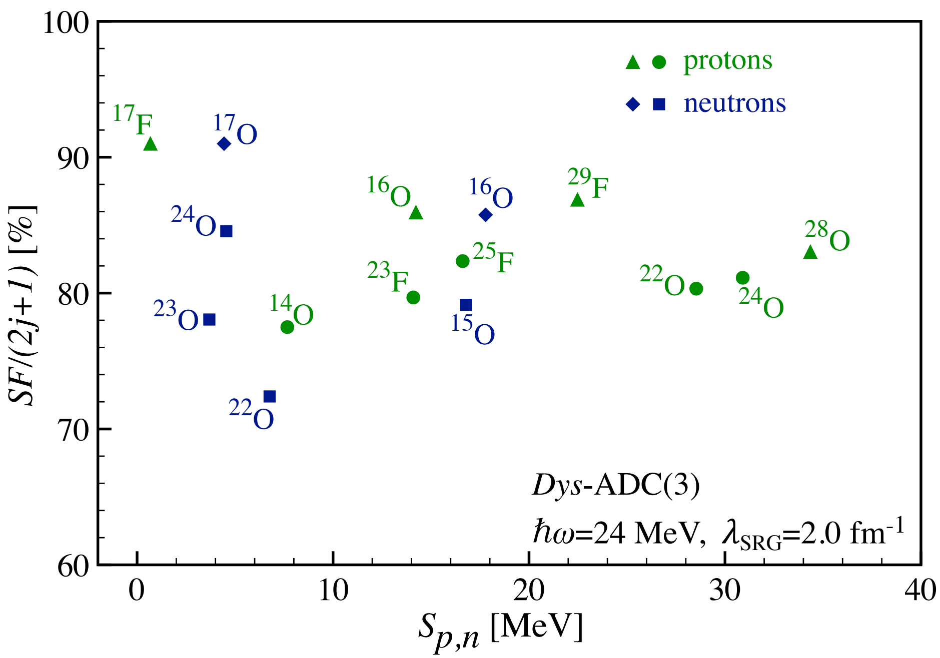

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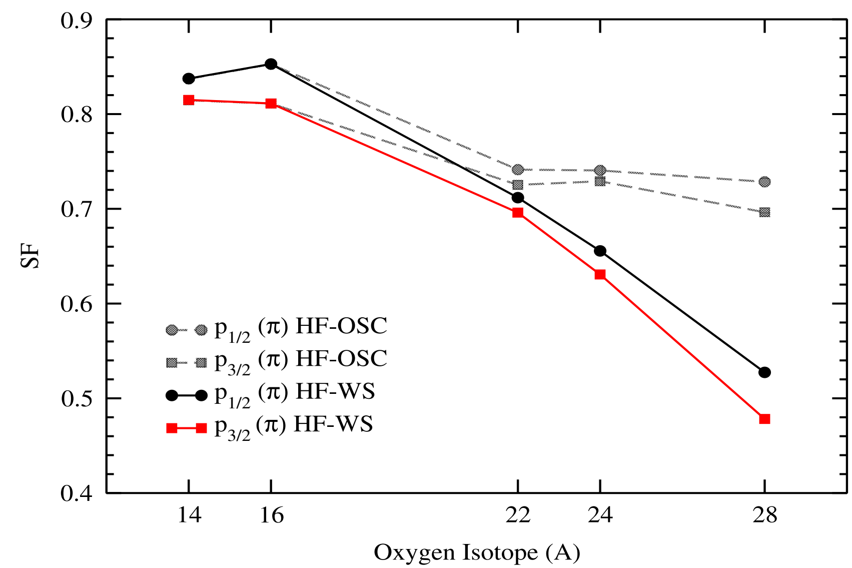

[Hagen et al.
Phys. Rev. Lett. 107, 032501 (2011)]

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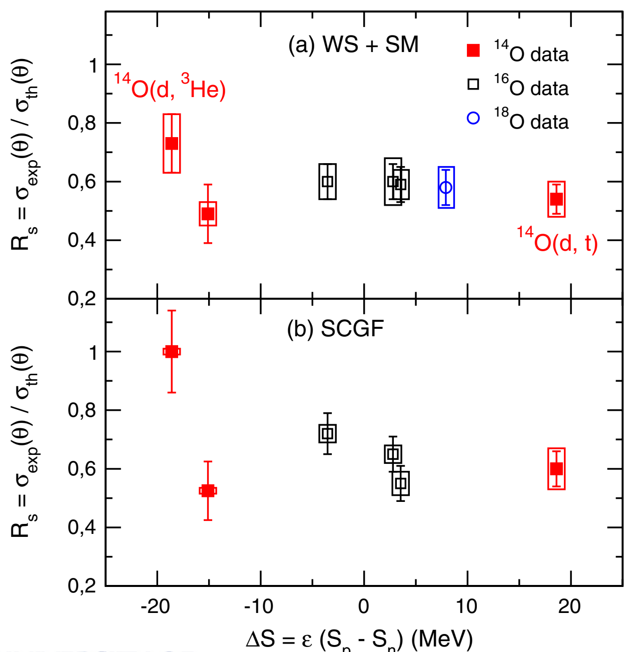
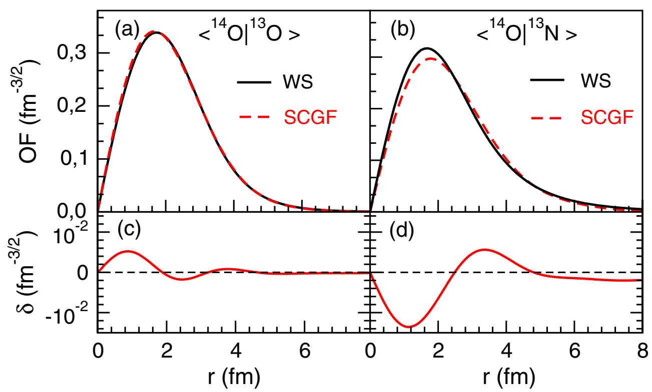
Single nucleon transfer in the oxygen chain

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

→ Analysis of $^{14}O(d,t)^{13}O$ and $^{14}O(d,^3He)^{13}N$ 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

Mapping Ab-Initio calculation into the shell model approach

Recent works through CCM and IMRSG:

Bogner et al Phys. Rev. Lett. 113, 142501 (2014)
Jansen et al Phys. Rev. Lett. 113, 142502 (2014)

✓ *works well for spectra*

Calculation of observables: need many-body corrections, to evolve operators, add electroweak currents, ect…

See Menendez , Stroberg, Pastore and other talks today…

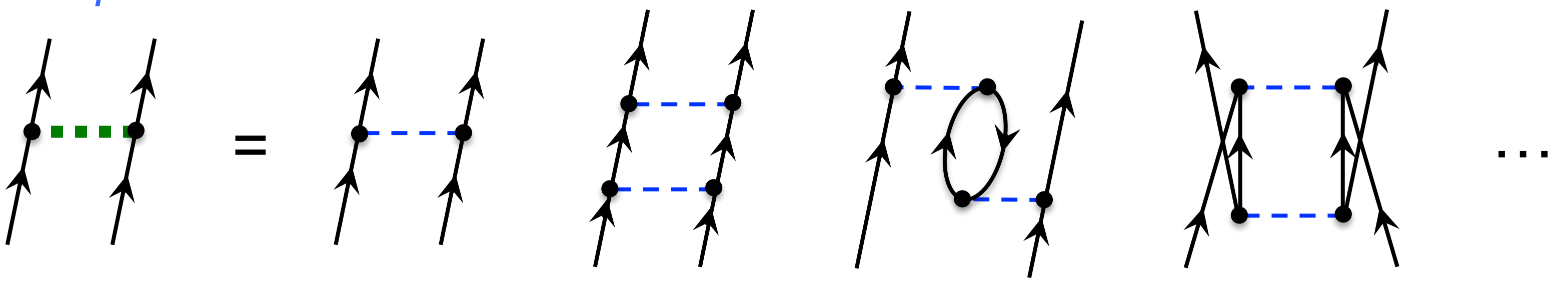
To have a look at the many-body and effects:

Extract vibration coupling form microscopic calculations…

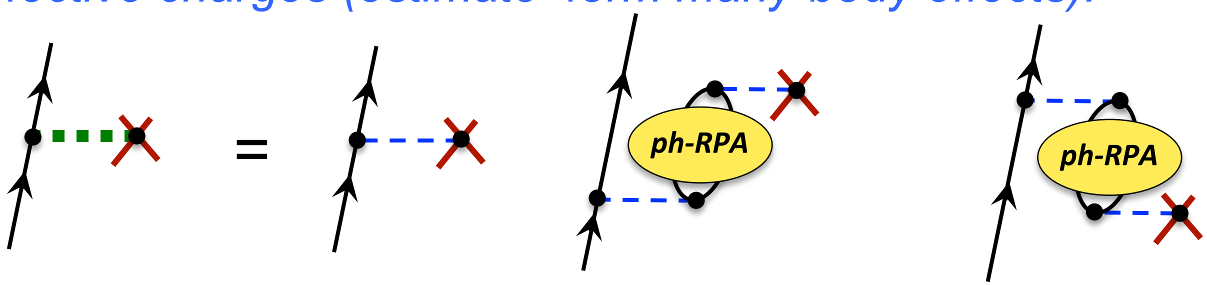
CB, T. Otsuka, in preparation

“traditional” MBPT approach

PT expansion of effective interactions:

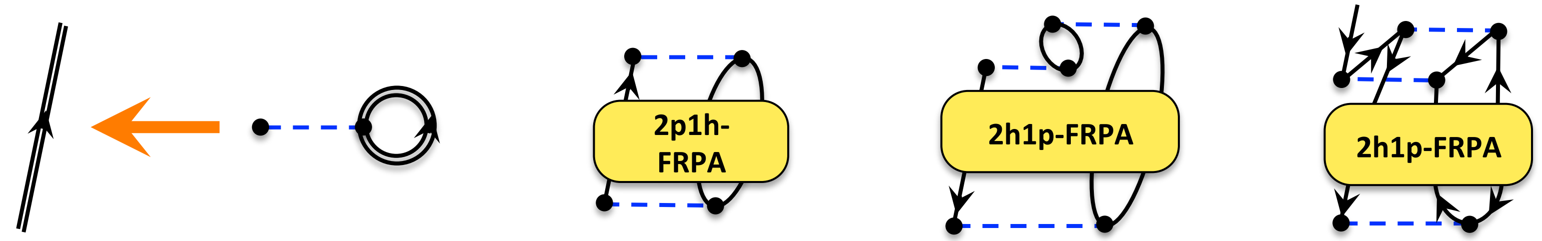


Effective charges (estimate form many-body effects):

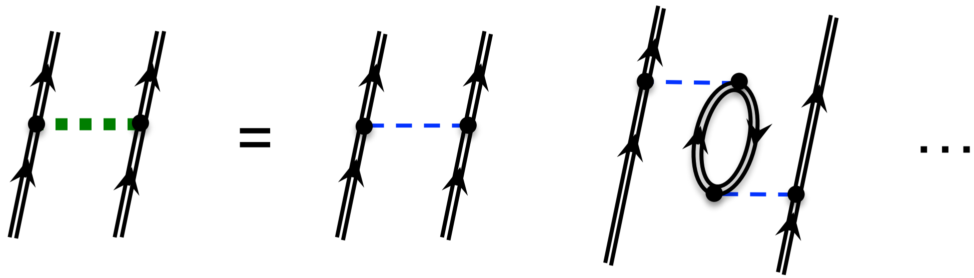


"upgrade" using SCGF's spect. funct.

Dressed (self consistent) propagator:

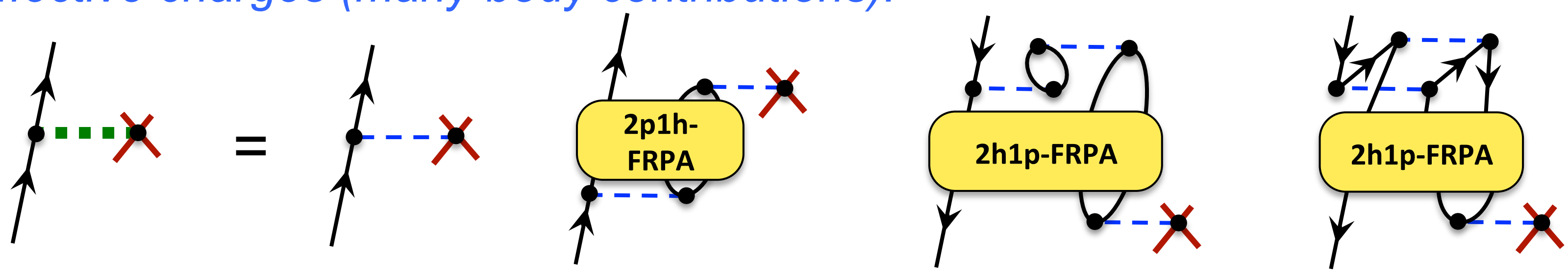


PT expansion of effective interactions:



but NO self-en insertions

Effective charges (many-body contributions):



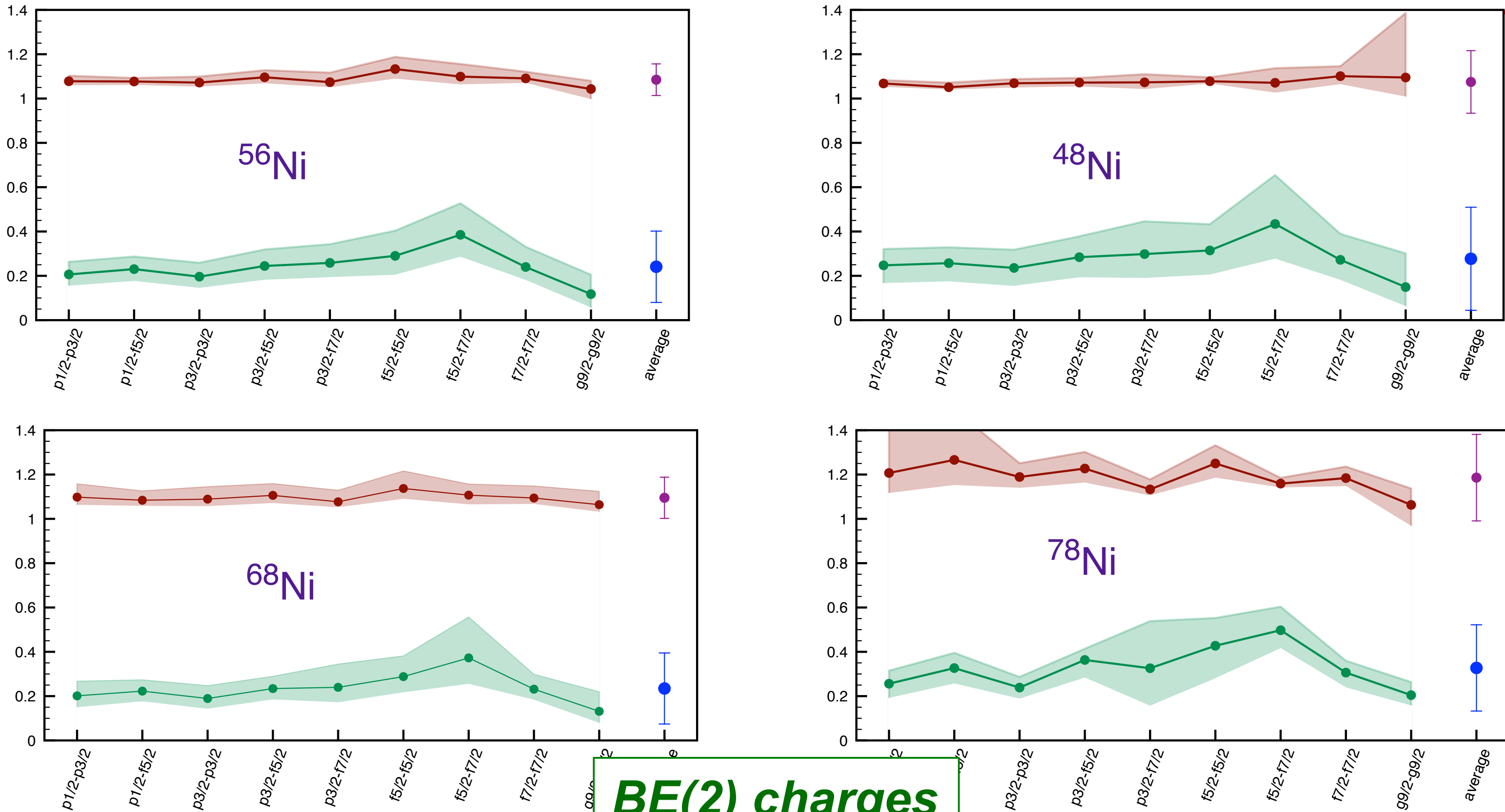
UNIVERSITY OF SURREY

Some results – ^{A}Ni chain in pf$g_{9/2}$ shell

Interaction: NNLO-opt, AV18 (+Gmatrix)

Single particle basis: HF

Preliminary



BE(2) charges

UNIVERSITY OF SURREY

CB, T. Otsuka, in preparation

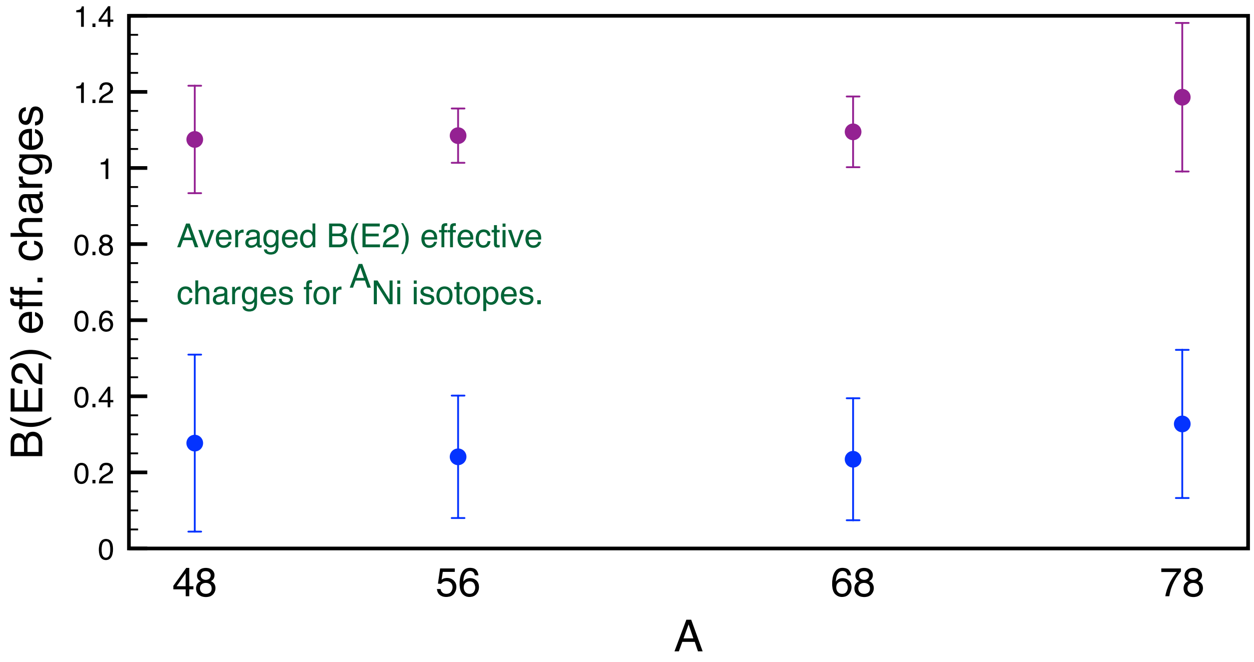
Some results – ^{A}Ni chain in pfg$_{9/2}$ shell

Interaction: NNLO-opt, AV18 (+Gmatrix)

Single particle basis: HF

Preliminary

Averaged charges



BE(2) charges

➔ "predicted" charges are smaller than usual phenomenological ones

➔ NO higher order currents here -- just the many-body correction…

CB, T. Otsuka, in preparation

Some results – O and C chains

Preliminary

Interaction: N3LO(500) (+Gmatrix)

Single particle basis: HF or HFB

BE(2) charges

	C10	C22	O14	O16	O20
$\nu_{s1/2}$-$\nu_{d3/2}$:	0.142	0.094	-0.751	0.160	0.128
$\nu_{s1/2}$-$\nu_{d5/2}$:	0.226	0.125	0.261	0.214	0.181
$\nu_{d3/2}$-$\nu_{d3/2}$:	0.278	0.121	0.198	0.082	0.155
$\nu_{d3/2}$-$\nu_{d5/2}$:	0.320	0.137	0.249	0.274	0.214
$\nu_{d5/2}$-$\nu_{d5/2}$:	0.278	0.151	0.294	0.250	0.232
$\pi_{s1/2}$-$\pi_{d3/2}$:	1.131	1.051	0.594	1.105	1.078
$\pi_{s1/2}$-$\pi_{d5/2}$:	1.155	1.094	1.161	1.142	1.134
$\pi_{d3/2}$-$\pi_{d3/2}$:	1.061	1.054	1.441	0.976	1.070
$\pi_{d3/2}$-$\pi_{d5/2}$:	1.141	1.107	1.042	1.091	1.170
$\pi_{d5/2}$-$\pi_{d5/2}$:	1.161	1.077	1.139	1.107	1.099
$\nu_{p1/2}$-$\nu_{p3/2}$:	0.359	0.319	0.344	0.401	0.404
$\nu_{p3/2}$-$\nu_{p3/2}$:	0.315	0.247	0.367	0.316	0.307
$\pi_{p1/2}$-$\pi_{p3/2}$:	1.102	1.134	1.183	1.179	1.198
$\pi_{p3/2}$-$\pi_{p3/2}$:	1.128	1.103	1.075	1.056	1.082

➔ *"predicted" charges are smaller than usual phenomenological ones*

➔ *NO higher order currents here -- just the many-body correction…*

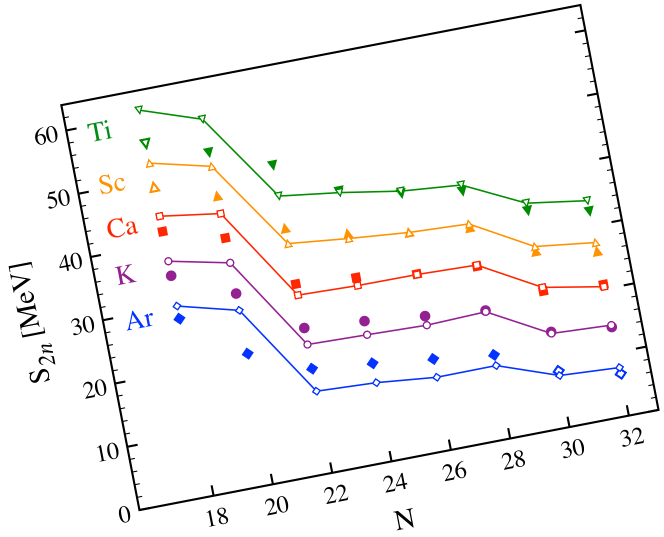
Conclusions

- 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.*

→ *more short-range repulsion or fitting to mid masses will help [see NNLOsat talk, atc…].*



Thank you for your attention!!!

Collaborators

A. Cipollone, A. Rios

V. Somà, T. Duguet

A. Carbone

P. Navratil

A. Polls

W.H. Dickhoff, S. Waldecker

D. Van Neck, M. Degroote

M. Hjorth-Jensen