TALENT Course no. 2: Many-Body Methods for Nuclear Physics

Self-consistent Green's function in Finite Nuclei and related things…
-
Lectures VI

The Gorkov-SCGF formalism for open shell nuclei; Applications to medium-mass nuclei

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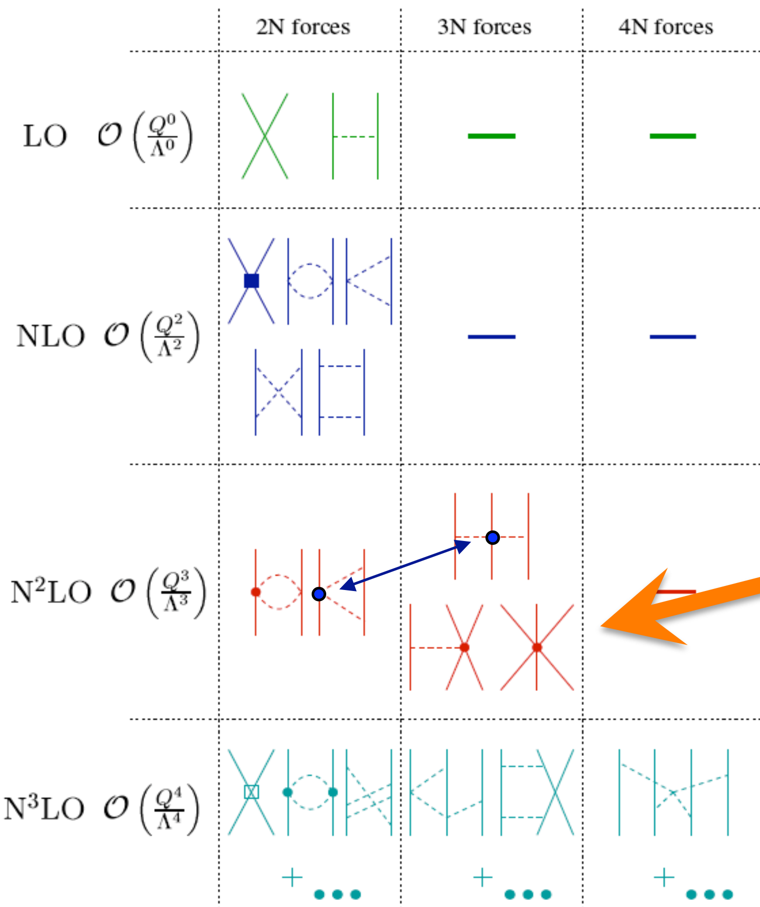
Adding 3-nucleon forces

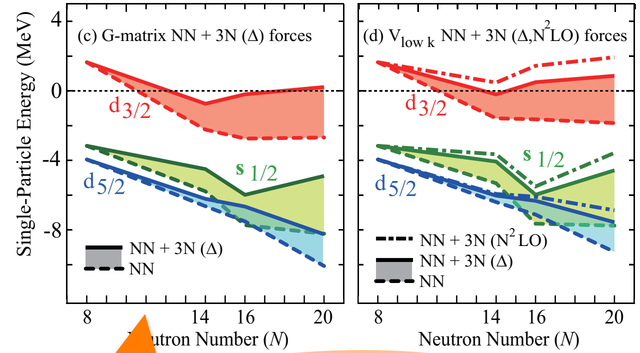
Modern realistic nuclear forces

Chiral EFT for nuclear forces:



(3NFs arise naturally at N2LO)

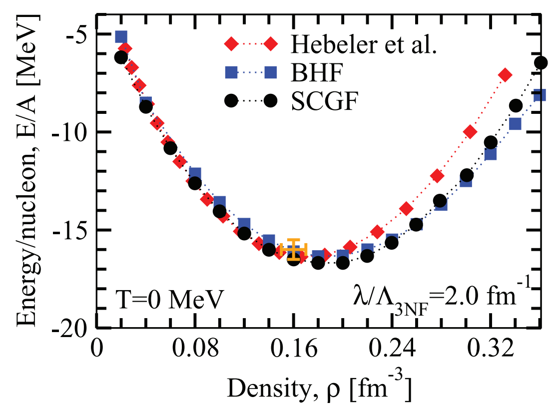
Single particle spectrum at E_{fermi}:



[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)]

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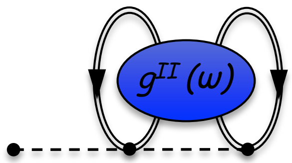
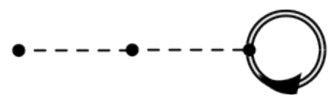
Inclusion of NNN forces

*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

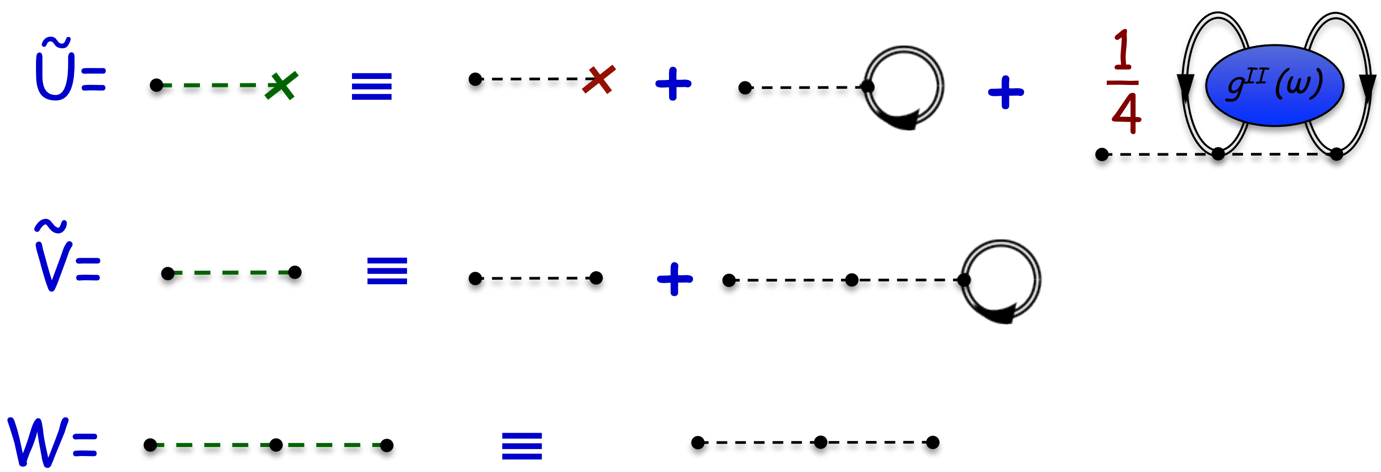
- Contractions are with *fully correlated density matrices* (BEYOND a normal ordering…)

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 *<u>fully correlated density matrices</u>*
(BEYOND a normal ordering…)

Inclusion of NNN forces

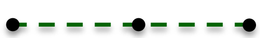
A. Carbone, CB, et al., Phys. Rev. C**88**, 054326 (2013)

- NNN forces can enter diagrams in three different ways:

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

$$\tilde{U} = \sum_{\alpha\beta} \left[-U_{\alpha\beta} - i\hbar \sum_{\delta\gamma} v_{\alpha\gamma,\beta\delta}\, g_{\delta\gamma}(\tau = 0^-) + \frac{i\hbar}{4} \sum_{\gamma\delta\mu\nu} g^{II}_{\mu\nu,\gamma\delta}(\tau = 0^-)\, w_{\alpha\gamma\delta,\beta\mu\nu} \right] a^\dagger_\alpha\, a_\beta$$

$$\tilde{V} = \sum_{\alpha\beta} \frac{1}{4} \left[v_{\alpha\beta,\gamma\delta} - i\hbar \sum_{\mu\nu} w_{\alpha\beta\mu,\gamma\delta\nu}\, g_{\nu\mu}(\tau = 0^-) \right] a^\dagger_\alpha a^\dagger_\beta\, a_\delta a_\gamma$$

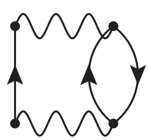
W=  $\equiv$ $W_{\alpha\beta\gamma,\mu\nu\lambda} a^\dagger_\alpha a^\dagger_\beta a^\dagger_\gamma a_\lambda a_\nu a_\mu$

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

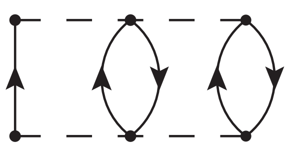
Inclusion of NNN forces

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

- *Second order* PT
diagrams with 3BFs:



(a)



(b)

effectively:

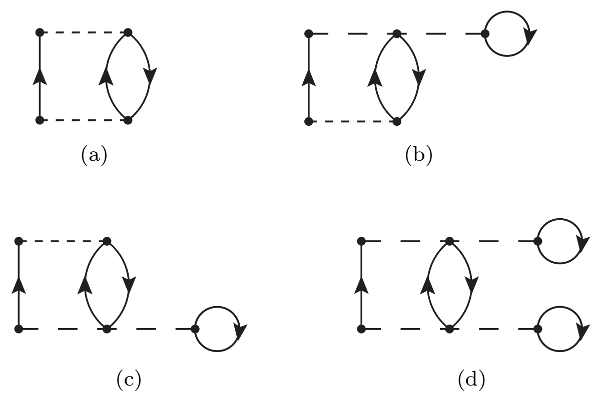
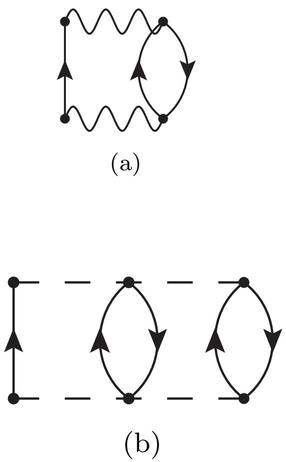


FIG. 4. The one *interaction irreducible* diagrams (a) and the three *interaction reducible* ones (b, c and d) that are contained in Fig. 3a.

Inclusion of NNN forces

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

- *Second order* PT diagrams with 3BFs:



- *Third order* PT diagrams with 3BFs:

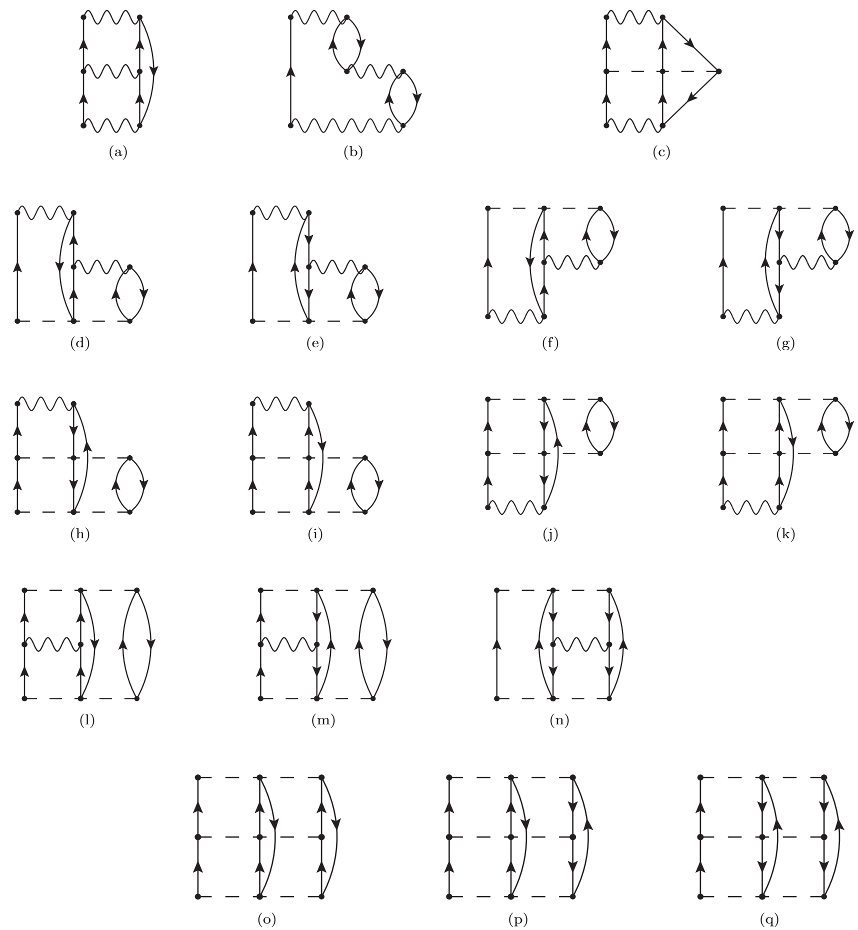
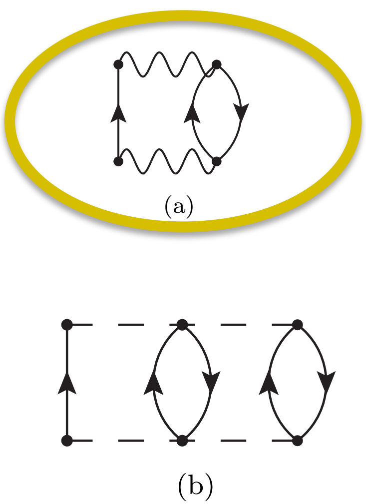


FIG. 5. 1PI, *skeleton* and *interaction irreducible* self-energy diagrams appearing at 3^{rd}-order in perturbative expansion (7), making use of the effective hamiltonian of Eq. (9).

Inclusion of NNN forces

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

- *Second order* PT diagrams with 3BFs:



- *Third order* PT diagrams with 3BFs:

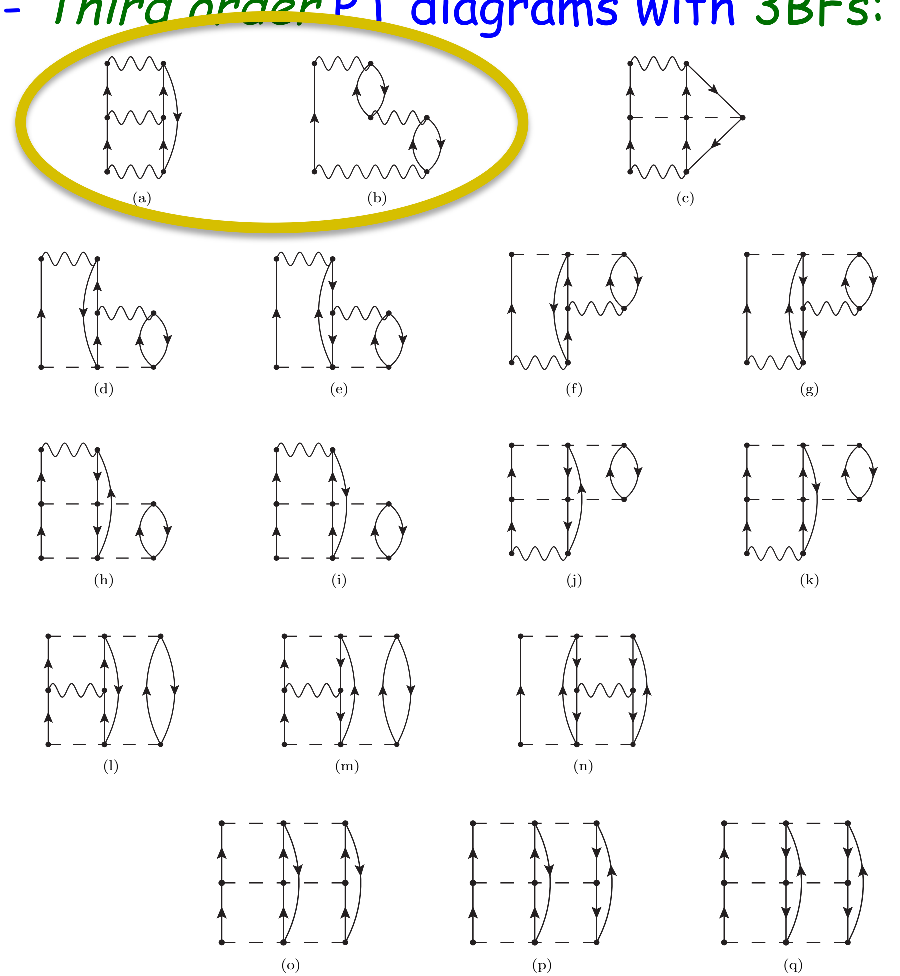


FIG. 5. 1PI, *skeleton* and *interaction irreducible* self-energy diagrams appearing at 3^{rd}-order in perturbative expansion (7), making use of the effective hamiltonian of Eq. (9).

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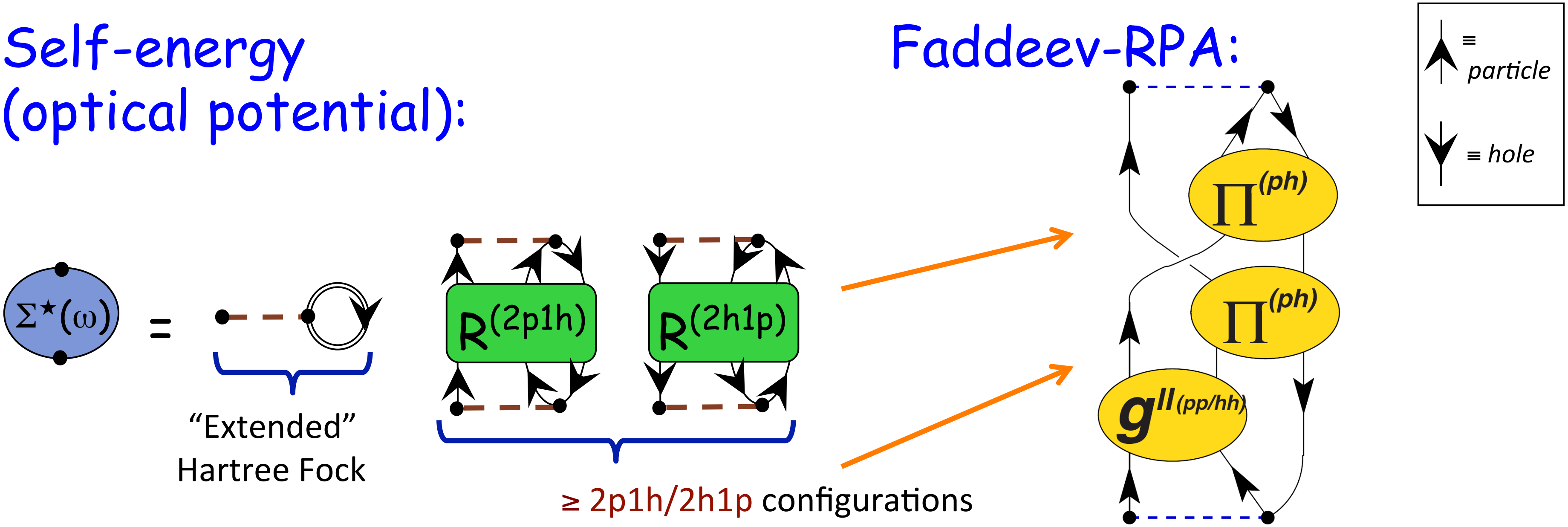
Gorkov method for the open-shells

Faddeev-RPA in two words…

Self-energy (optical potential):

Faddeev-RPA:



- A complete expansion requires <u>*all types*</u> of particle-vibration coupling:
  - ✓ $g^{II}(\omega)$ → pairing effects, two-nucleon transfer
  - ✓ $\Pi^{(ph)}(\omega)$ → collective motion, using RPA or beyond
  - ✓ Pauli exchange effects
- The Self-energy $\Sigma^\star(\omega)$ yields *both* single-particle states and scattering
- Finite nuclei:→ require high-performance computing

Phys. Rev. C63, 034313 (2001); Phys. Rev. C65, 064313 (2002)
Phys. Rev. A76, 052503 (2007); Phys. Rev. C79, 064313 (2009)

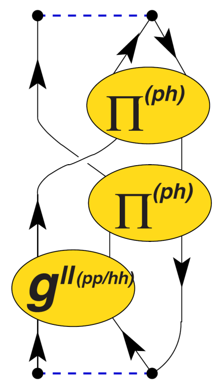
Applications to doubly-magic nuclei

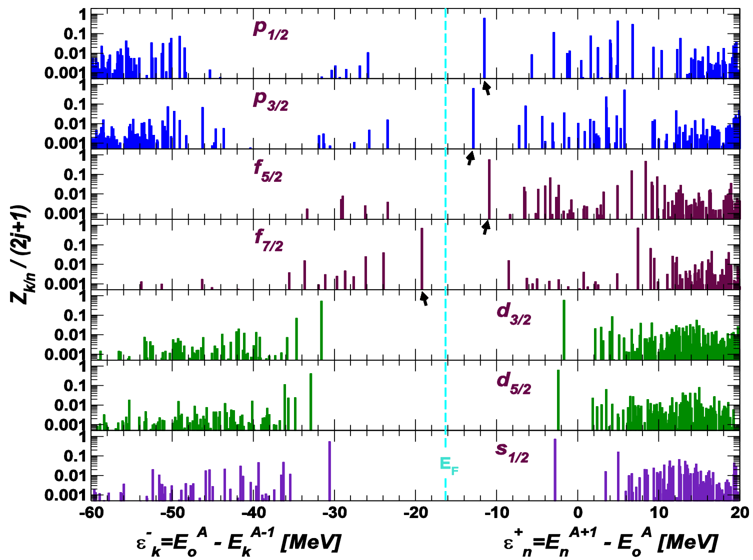
- Faddeev-RPA approximation for the self-energy

collective vibrations

particle-vibration coupling

[C.B. *et al*. 2001-2011]





- Successful in medium-mass doubly-magic systems

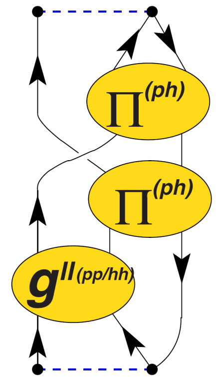
Applications to doubly-magic nuclei

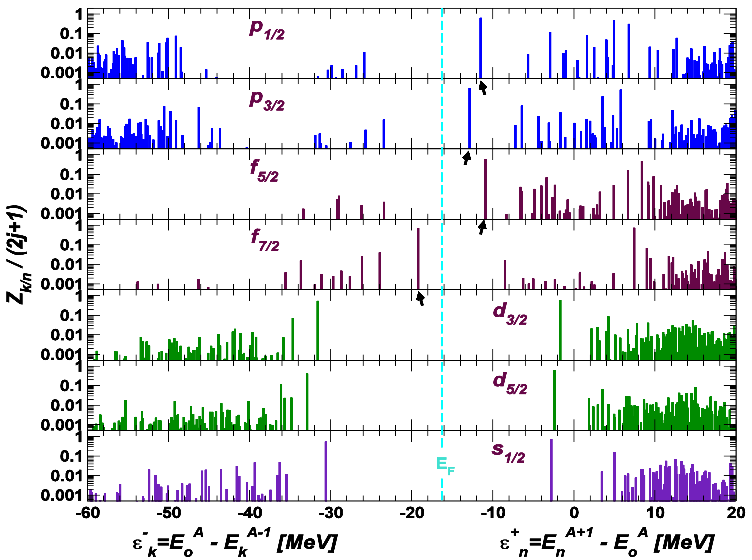
✳ Faddeev-RPA approximation for the self-energy

collective vibrations

particle-vibration coupling

[C.B. *et al*. 2001-2011]





✳ Successful in medium-mass doubly-magic systems

Expansion breaks down when pairing instabilities appear

Explicit configuration mixing

Single-reference: Bogoliubov (Gorkov)

Going to open-shells: Gorkov ansatz

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

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

✺ 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 $N = \langle\Psi_0|N|\Psi_0\rangle$

⇒ $$\Omega_0 = \sum_{N'} |c_{N'}|^2 \Omega_0^{N'} \approx E_0^N - \mu N$$

Gorkov Green's functions and equations

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

✵ Set of 4 Green's functions

$$i\,G^{11}_{ab}(t,t') \equiv \langle\Psi_0|T\left\{a_a(t)a^\dagger_b(t')\right\}|\Psi_0\rangle \quad \equiv$$

$$i\,G^{21}_{ab}(t,t') \equiv \langle\Psi_0|T\left\{\bar{a}^\dagger_a(t)a^\dagger_b(t')\right\}|\Psi_0\rangle \quad \equiv$$

$$i\,G^{12}_{ab}(t,t') \equiv \langle\Psi_0|T\left\{a_a(t)\bar{a}_b(t')\right\}|\Psi_0\rangle \quad \equiv$$

$$i\,G^{22}_{ab}(t,t') \equiv \langle\Psi_0|T\left\{\bar{a}^\dagger_a(t)\bar{a}_b(t')\right\}|\Psi_0\rangle \quad \equiv$$

[Gorkov 1958]

$$\mathbf{G}_{ab}(\omega) = \mathbf{G}^{(0)}_{ab}(\omega) + \sum_{cd}\mathbf{G}^{(0)}_{ac}(\omega)\,\mathbf{\Sigma}^{\star}_{cd}(\omega)\,\mathbf{G}_{db}(\omega)$$

Gorkov equations

$$\mathbf{\Sigma}^{\star}_{ab}(\omega) \equiv \begin{pmatrix} \Sigma^{\star\,11}_{ab}(\omega) & \Sigma^{\star\,12}_{ab}(\omega) \\ \Sigma^{\star\,21}_{ab}(\omega) & \Sigma^{\star\,22}_{ab}(\omega) \end{pmatrix}$$

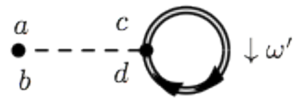
$$\mathbf{\Sigma}^{\star}_{ab}(\omega) \equiv \mathbf{\Sigma}_{ab}(\omega) - \mathbf{U}_{ab}$$

Open-shells: 1st & 2nd order Gorkov diagrams

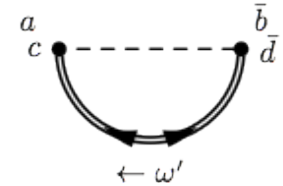
V. Somà, CB, T. Duguet, , Phys. Rev. C **89**, 024323 (2014)
V. Somà, CB, T. Duguet, Phys. Rev. C **87**, 011303R (2013)
V. Somà, T. Duguet, CB, Phys. Rev. C **84**, 064317 (2011)

✺ 1st order ➟ energy-independent self-energy

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

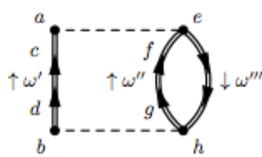


$\Sigma^{12\,(1)}_{ab} =$

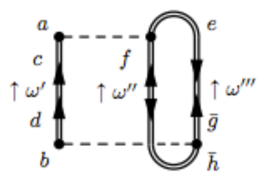


✺ 2nd order ➟ energy-dependent self-energy

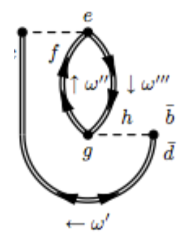
$\Sigma^{11\,(2)}_{ab}(\omega) =$



$+$



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



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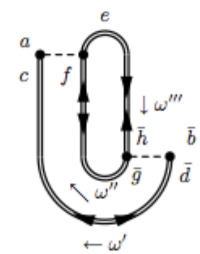


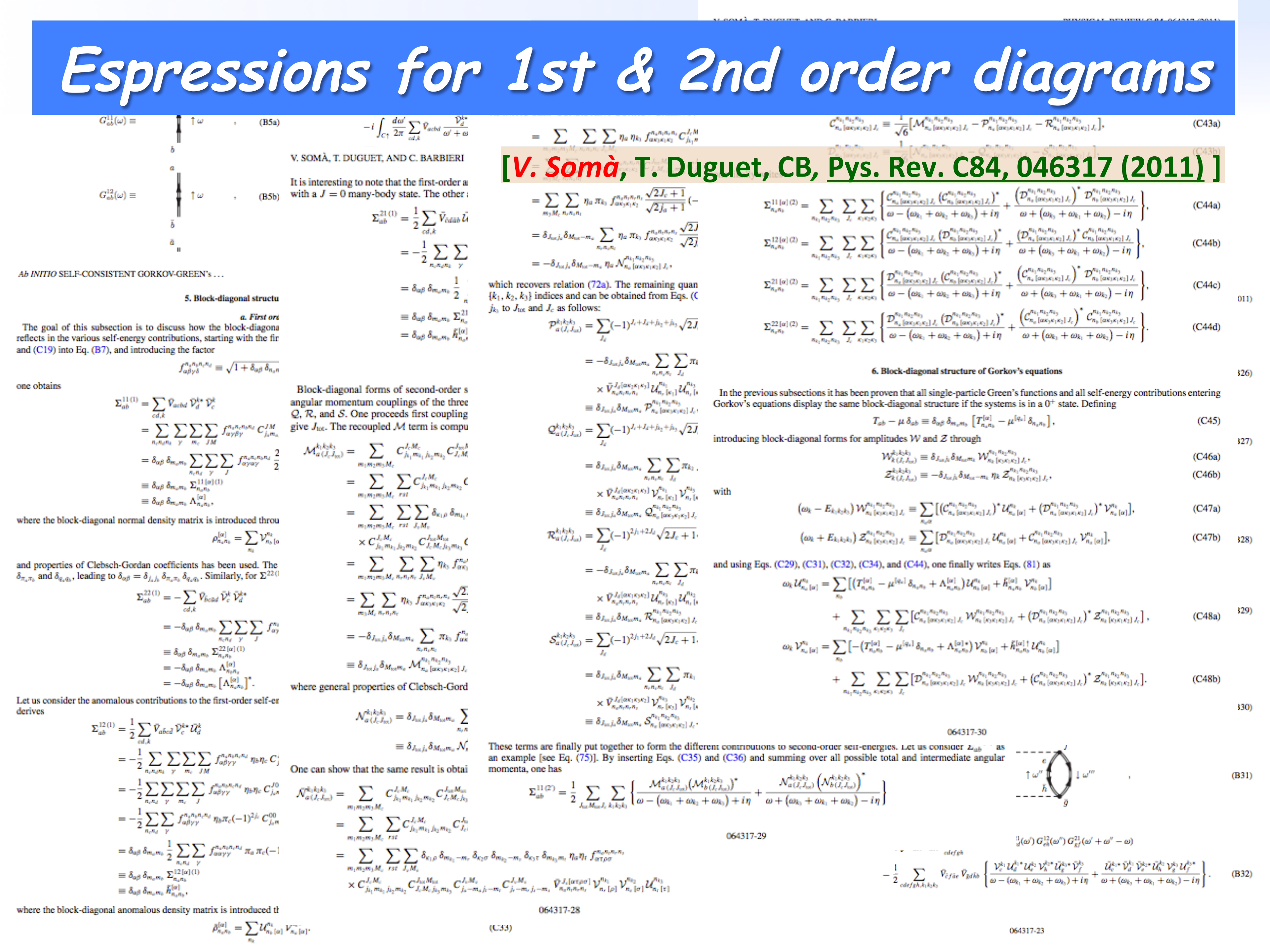
✺ Gorkov equations ⟶ eigenvalue problem

$$\sum_b \begin{pmatrix} t_{ab} - \mu_{ab} + \Sigma^{11}_{ab}(\omega) & \Sigma^{12}_{ab}(\omega) \\ \Sigma^{21}_{ab}(\omega) & -t_{ab} + \mu_{ab} + \Sigma^{22}_{ab}(\omega) \end{pmatrix}\Bigg|_{\omega_k} \begin{pmatrix} \mathcal{U}^k_b \\ \mathcal{V}^k_b \end{pmatrix} = \omega_k \begin{pmatrix} \mathcal{U}^k_a \\ \mathcal{V}^k_a \end{pmatrix}$$

$$\mathcal{U}^{k*}_a \equiv \langle \Psi_k | \bar{a}^\dagger_a | \Psi_0 \rangle$$
$$\mathcal{V}^{k*}_a \equiv \langle \Psi_k | a_a | \Psi_0 \rangle$$

Espressions for 1st & 2nd order diagrams

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



Gorkov equations

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

$$\sum_b \begin{pmatrix} t_{ab} - \mu_{ab} + \Sigma^{11}_{ab}(\omega) & \Sigma^{12}_{ab}(\omega) \\ \Sigma^{21}_{ab}(\omega) & -t_{ab} + \mu_{ab} + \Sigma^{22}_{ab}(\omega) \end{pmatrix}\Bigg|_{\omega_k} \begin{pmatrix} \mathcal{U}^k_b \\ \mathcal{V}^k_b \end{pmatrix} = \omega_k \begin{pmatrix} \mathcal{U}^k_a \\ \mathcal{V}^k_a \end{pmatrix}$$

$$\Downarrow$$

$$\begin{pmatrix} T-\mu+\Lambda & \tilde{h} & \mathcal{C} & -\mathcal{D}^\dagger \\ \tilde{h}^\dagger & -T+\mu-\Lambda & -\mathcal{D}^\dagger & \mathcal{C} \\ \mathcal{C}^\dagger & -\mathcal{D} & E & 0 \\ -\mathcal{D} & \mathcal{C}^\dagger & 0 & -E \end{pmatrix} \begin{pmatrix} \mathcal{U}^k \\ \mathcal{V}^k \\ \mathcal{W}_k \\ \mathcal{Z}_k \end{pmatrix} = \omega_k \begin{pmatrix} \mathcal{U}^k \\ \mathcal{V}^k \\ \mathcal{W}_k \\ \mathcal{Z}_k \end{pmatrix}$$

Energy *independent* eigenvalue problem

with the normalization condition $\sum_a \left[\left|\mathcal{U}^k_a\right|^2 + \left|\mathcal{V}^k_a\right|^2 \right] + \sum_{k_1 k_2 k_3} \left[\left|\mathcal{W}^{k_1 k_2 k_3}_k\right|^2 + \left|\mathcal{Z}^{k_1 k_2 k_3}_k\right|^2 \right] = 1$

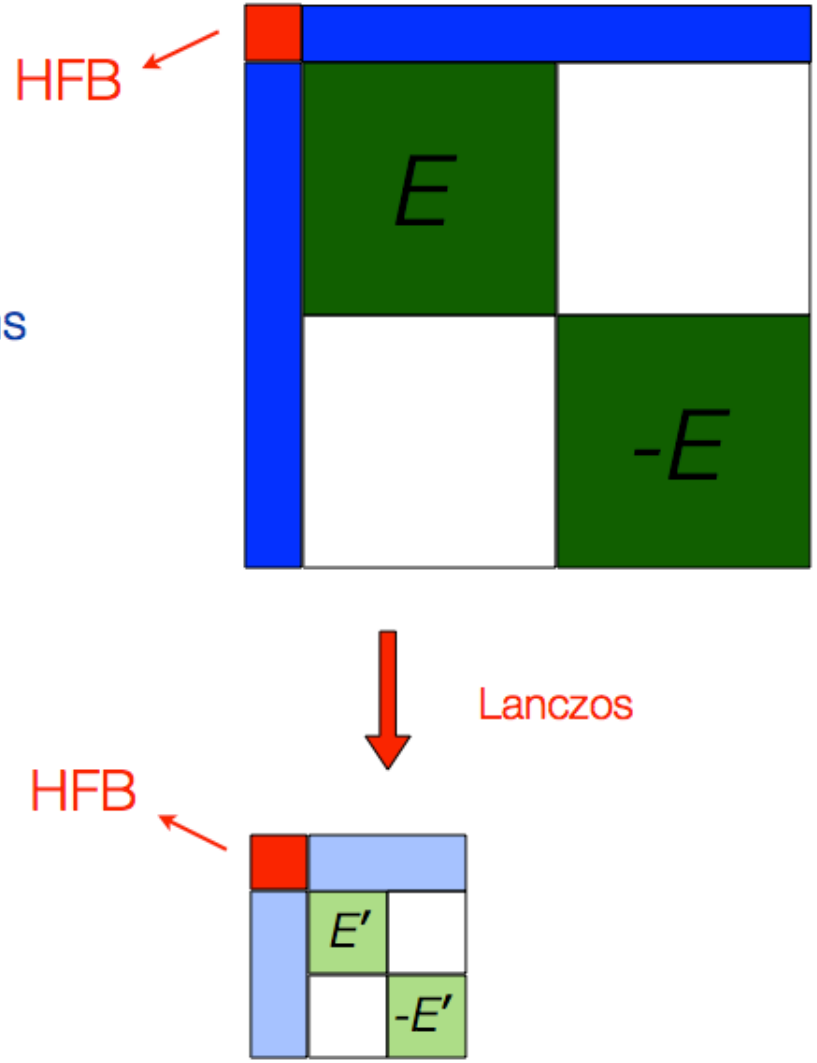
Lanczos reduction of self-energy

V. Somà, CB, T. Duguet, , Phys. Rev. C **89**, 024323 (2014)

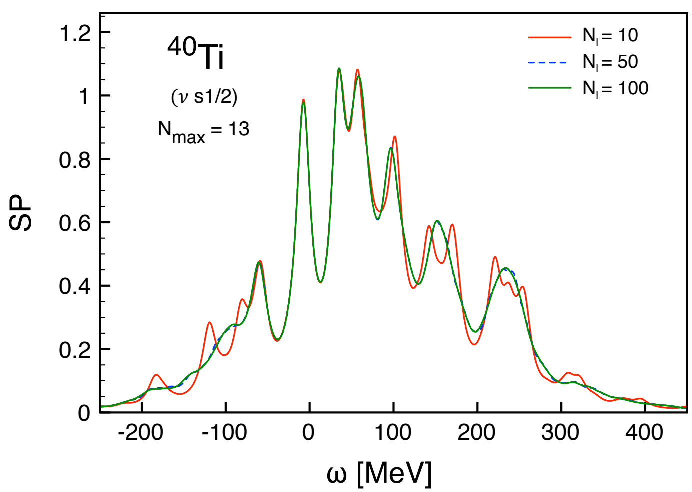
$$\begin{pmatrix} T-\mu+\Lambda & \tilde{h} & \mathcal{C} & -\mathcal{D}^\dagger \\ \tilde{h}^\dagger & -T+\mu-\Lambda & -\mathcal{D}^\dagger & \mathcal{C} \\ \mathcal{C}^\dagger & -\mathcal{D} & E & 0 \\ -\mathcal{D} & \mathcal{C}^\dagger & 0 & -E \end{pmatrix} \begin{pmatrix} \mathcal{U}^k \\ \mathcal{V}^k \\ \mathcal{W}_k \\ \mathcal{Z}_k \end{pmatrix} = \omega_k \begin{pmatrix} \mathcal{U}^k \\ \mathcal{V}^k \\ \mathcal{W}_k \\ \mathcal{Z}_k \end{pmatrix}$$

➡ Conserves moments of spectral functions

➡ Equivalent to exact diagonalization for $N_L \rightarrow \dim(E)$



Spectral strength



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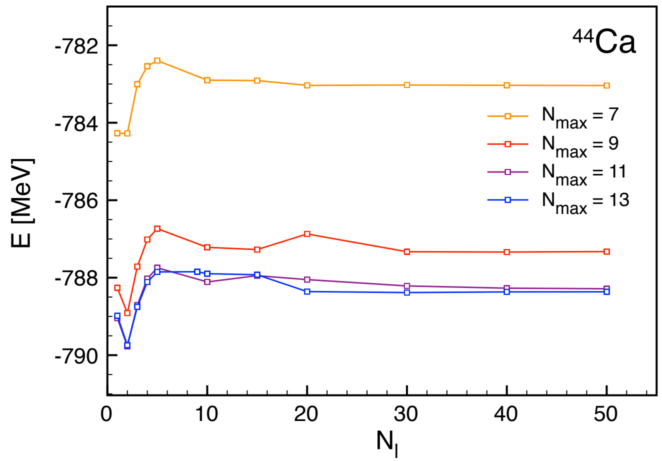
Testing Krylov projection

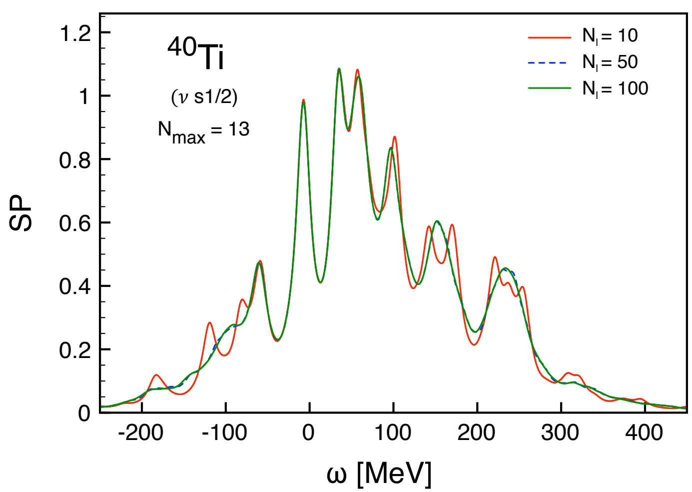
V. Somà, CB, T. Duguet, , Phys. Rev. C **89**, 024323 (2014)

- Energy and spectra independent of the projection
- Same behavior for all model spaces

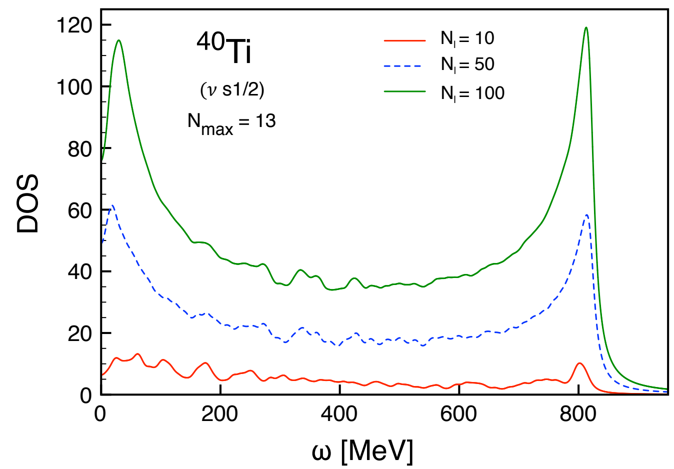
Favourable scaling



Spectral strength



Deinsity of states



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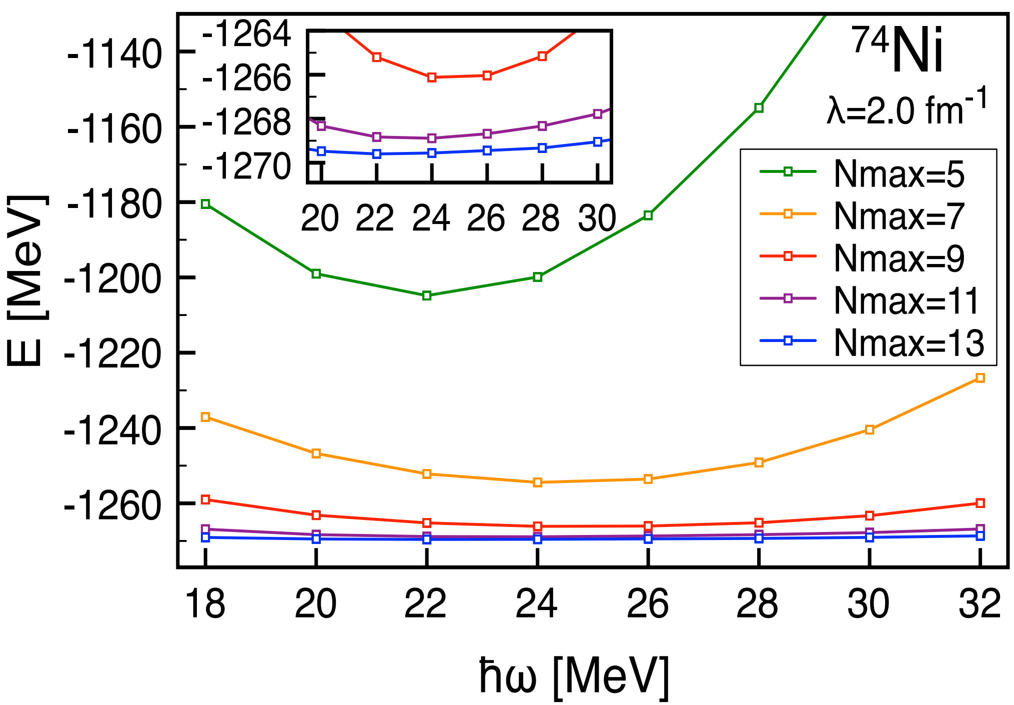
Binding energies

Somà, CB, Duguet, Phys. Rev. C **87**, 011303 (2013)



➟ NN interaction:
chiral N³LO SRG-evolved to 2.0 fm^{-1}

[Entem and Machleidt 2003]

➟ Very good convergence

➟ From N=13 to N=11 → 200 keV

E (N=13) = -1269.6 MeV

E (N=∞) = -1269.7(2) MeV

(Extrapolation to infinite model space from [Furnstahl, Hagen, Papenbrok 2012] and [Coon et al. 2012])

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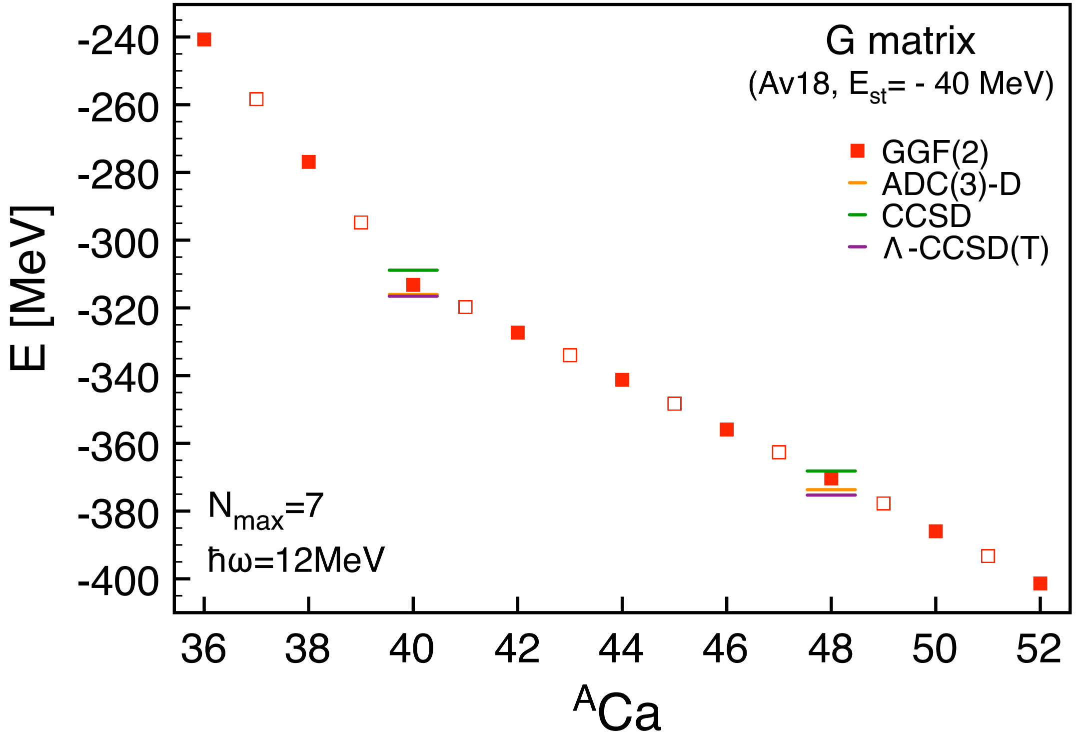
Binding energies

Somà, CB, Duguet, Phys. Rev. C **87**, 011303 (2013)

- Systematic along isotopic/isotonic chains has become available



➡ Accuracy is good (close to CCSD and FRPA) and improvable

➡ Systematic along isotopic/isotonic chains has become possible

➡ Of course, need proper interactions and (at least) NNN forces…

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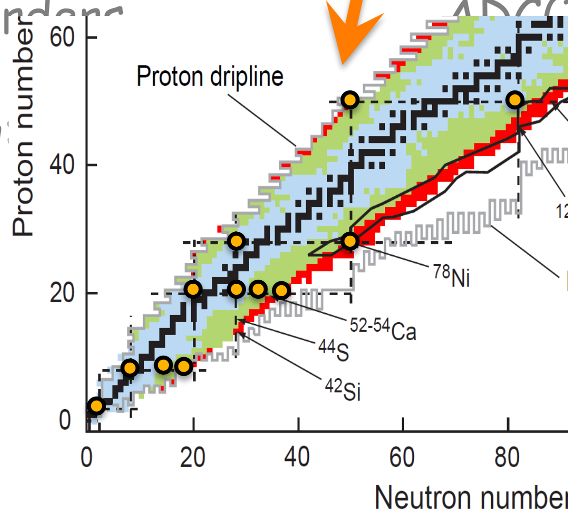
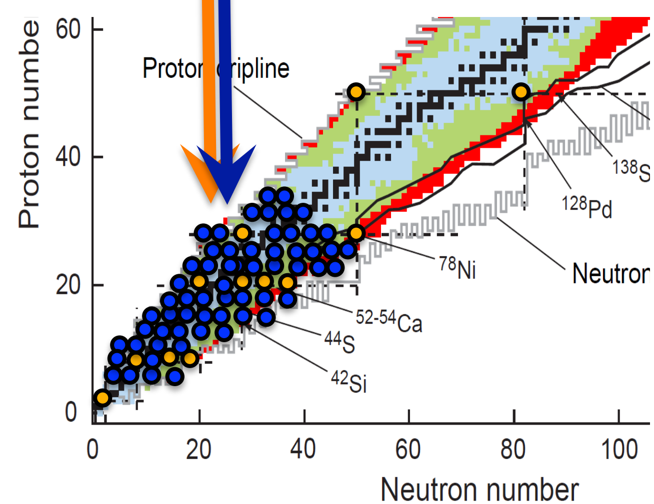
Approaches in GF theory

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

Approaches in GF theory

Truncation scheme:	Dyson formulation (closed shells)	Gorkov formulation (semi-magic)
1st order:	Hartree-Fock	HF-Bogolioubov
2nd order:	2nd order	2nd order (w/ pairing)
. . .	. . .	
3rd and all-orders sums, P-V coupling:	ADC(3)	



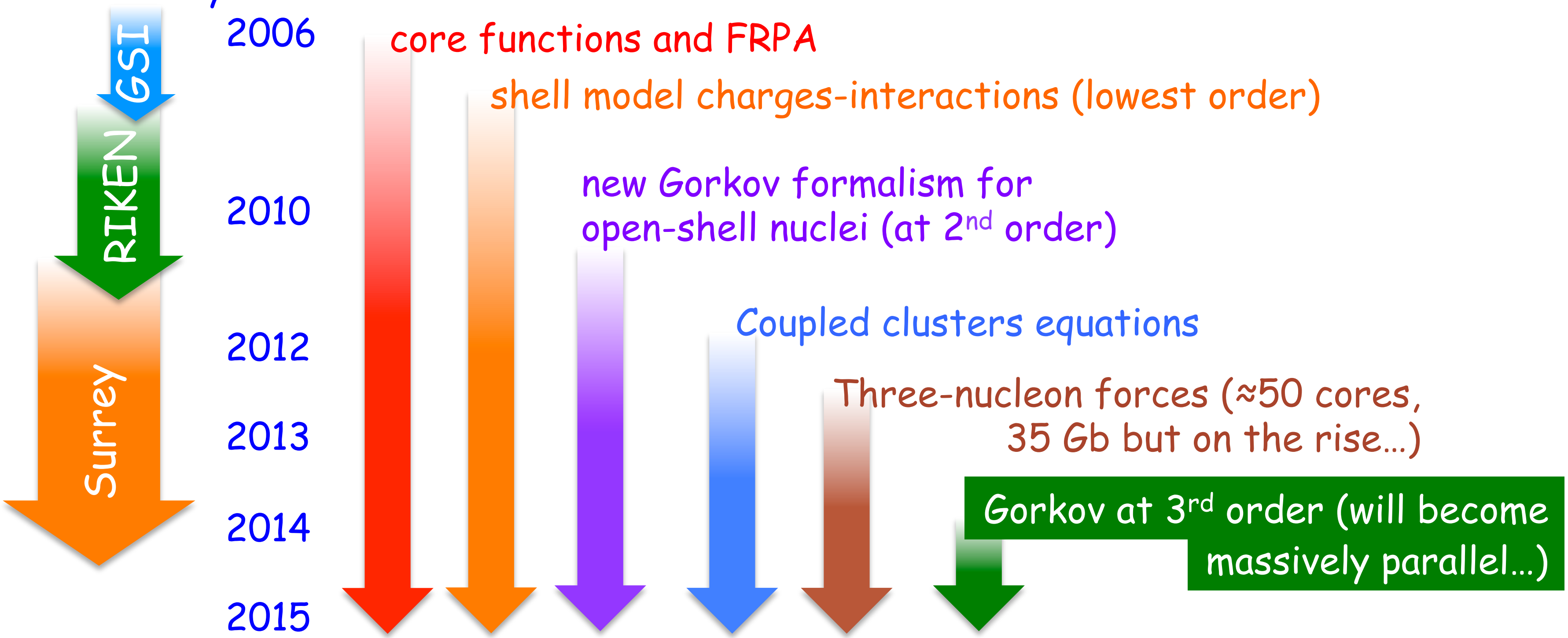


Ab-initio Nuclear Computation & BcDor code

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:

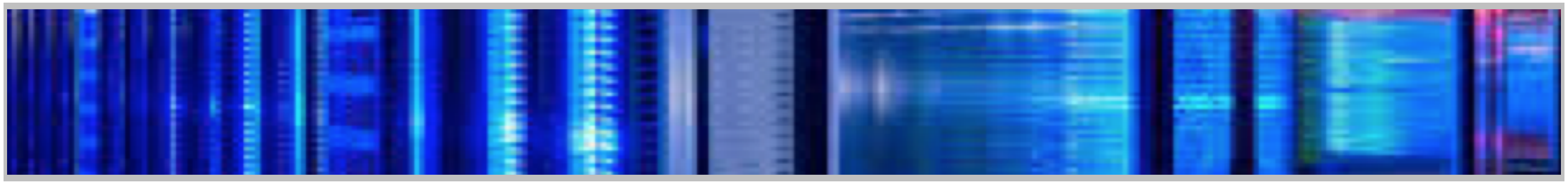


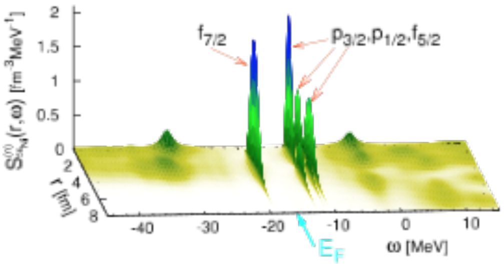
… applications …

Ab-initio Nuclear Computation & BcDor code

http://personal.ph.surrey.ac.uk/~cb0023/bcdor/

Computational Many-Body Physics





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Documentation

Welcome

From here you can download a public version of my self-consistent Green's function (SCGF) code for nuclear physics. This is a code in J-coupled scheme that allows the calculation of the single particle propagators (a.k.a. one-body Green's functions) and other many-body properties of spherical nuclei.

This version allows to:

- Perform Hartree-Fock calculations.
- Calculate the the correlation energy at second order in perturbation theory (MBPT2).
- Solve the Dyson equation for propagators (self consistently) up to second order in the self-energy.
- Solve coupled cluster CCD (doubles only!) equations.

When using this code you are kindly invited to follow the creative commons license agreement, as detailed at the weblinks below. In particular, we kindly ask you to refer to the publications that led the development of this software.

Relevant references (which can also help in using this code) are:

Prog. Part. Nucl. Phys. 52, p. 377 (2004),
Phys. Rev. A76, 052503 (2007),
Phys. Rev. C79, 064313 (2009),
Phys. Rev. C89, 024323 (2014)

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Results

Spectroscopic Factors

Quenching of absolute spectroscopic factors

Overall quenching of *spectroscopic factors* is driven by:

SRC → *~10%*

part-vibr. coupling → *dominant*

"shell-model" → *in open shell*

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

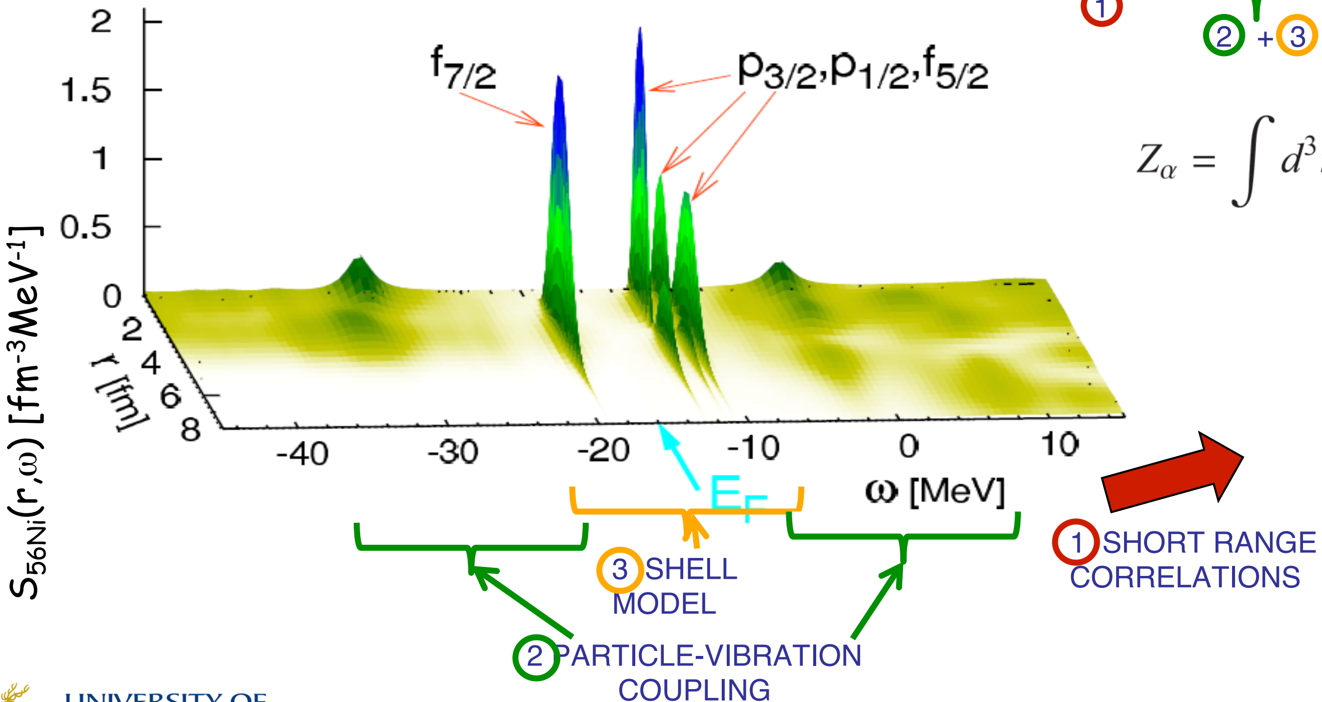
...with analogous conclusions for ^{48}Ca

	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
	①	② + ③			③		

^{57}Ni

^{55}Ni

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



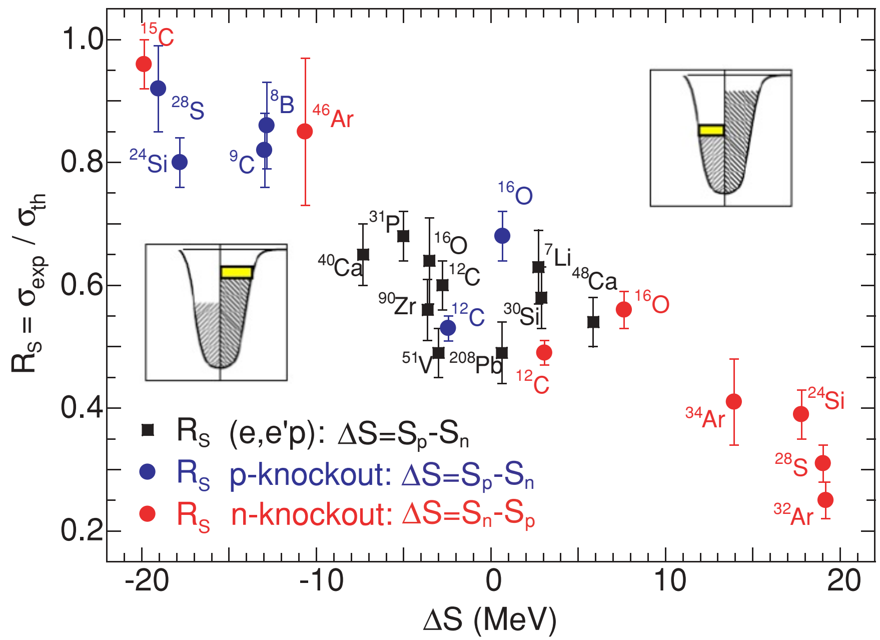
^{56}*Ni*

NN-N3LO(500)

Spectroscopic factors @ limits of stability

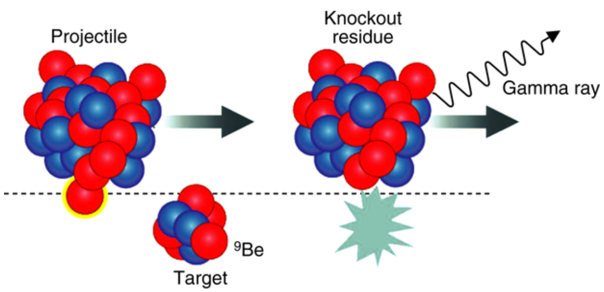
Weakling bound nucleons

Strongly bound nucleons



[Phys. Rev. C77, 044306 (2008)]

High energy knock-out in inverse kinematics



? ? ORIGIN UNCLEAR ?

- *Challenged* by recent experiments

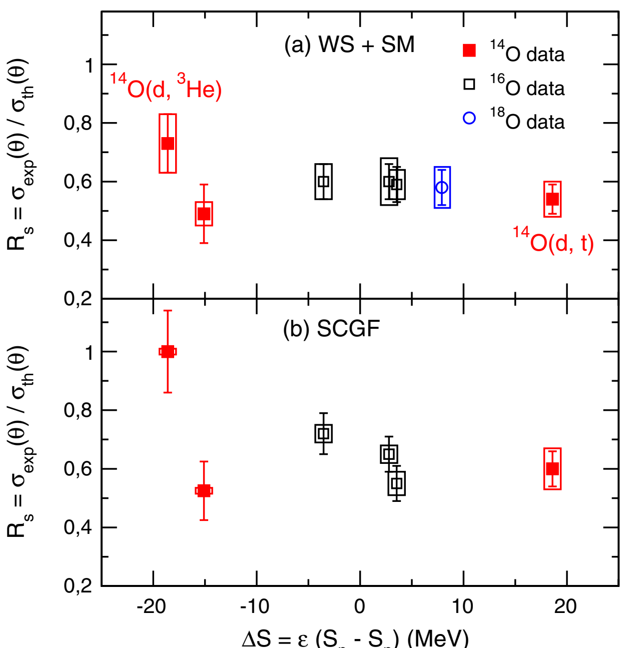
- May be correlations or scattering analysis

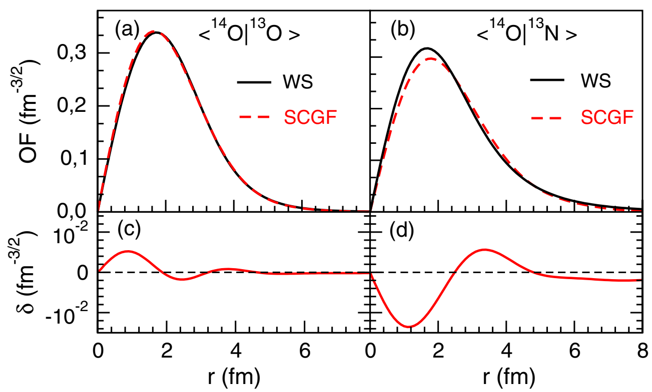
Single nucleon transfer in the oxygen chain

[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

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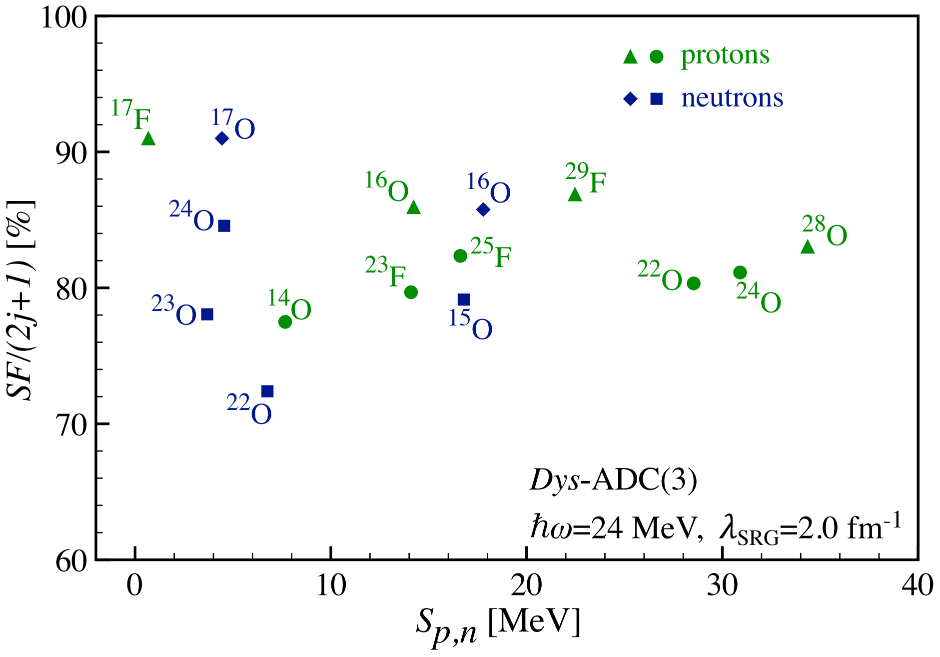
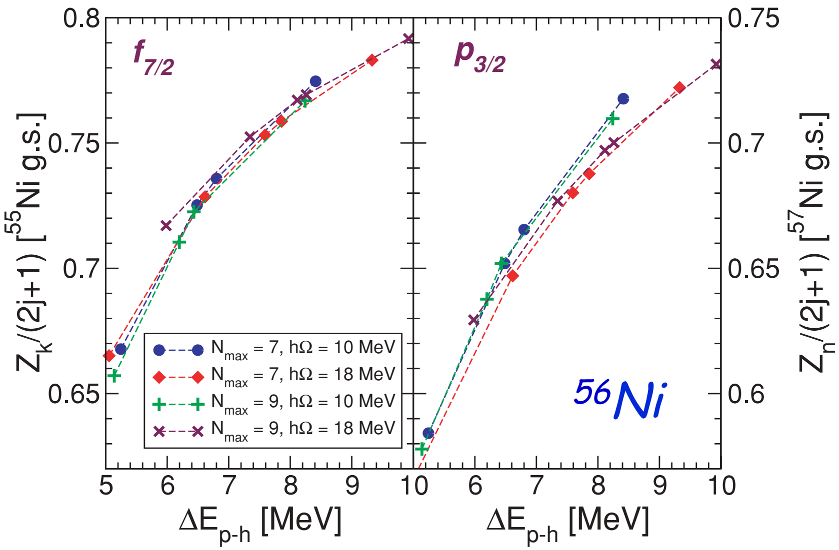
Z/N asymmetry dependence of SFs - Theory

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



Spectroscopic factor are strongly correlated to p-h gaps:



Knockout & transfer experiments

- Neutron removal from proton- and neutron- Ar isotopes @ NSCL:

Isotopes	lj^{π}	Sn(MeV)	ΔS (MeV)	(theo.) SF(LB-SM)	(expt.) SF(JLM + HF)	(expt.) Rs(JLM + HF)	(expt.) SF(CH89)	(expt.) Rs(CH89)
^{34}Ar	$s1/2^+$	17.07	12.41	1.31	0.85 ± 0.09	0.65 ± 0.07	1.10 ± 0.11	0.84 ± 0.08
^{36}Ar	$d3/2^+$	15.25	6.75	2.10	1.60 ± 0.16	0.76 ± 0.08	2.29 ± 0.23	1.09 ± 0.11
^{46}Ar	$f7/2^-$	8.07	−10.03	5.16	3.93 ± 0.39	0.76 ± 0.08	5.29 ± 0.53	1.02 ± 0.10

[Lee *et al.* 2010]

Gorkov GF NN

	Sn (MeV)	ΔS (MeV)	SF
^{34}Ar	33.0	18.6	1.46
^{36}Ar	27.7	7.5	1.46
^{46}Ar	16.0	-22.3	5.88

Gorkov GF NN + 3N

	Sn (MeV)	ΔS (MeV)	SF
^{34}Ar	22.4	15.5	1.56
^{36}Ar	15.3	7.2	1.54
^{46}Ar	6.5	-15.7	6.64

$\Delta S = Sn - Sp$

V.Somà, CB, et al, Eur. Phys. Jour.: Web. of Conf. **66**, 02005 (2014).

Knockout & transfer experiments

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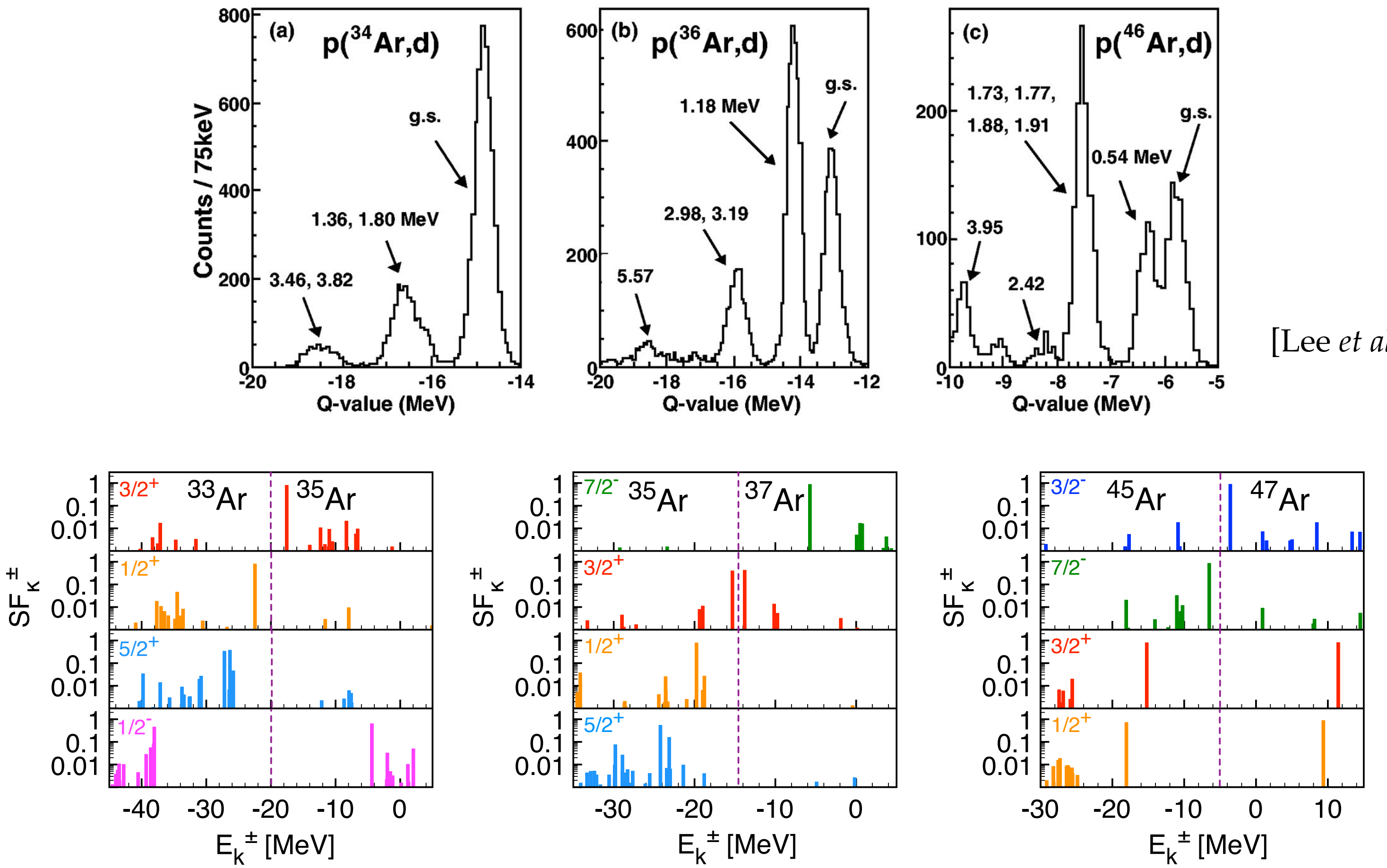
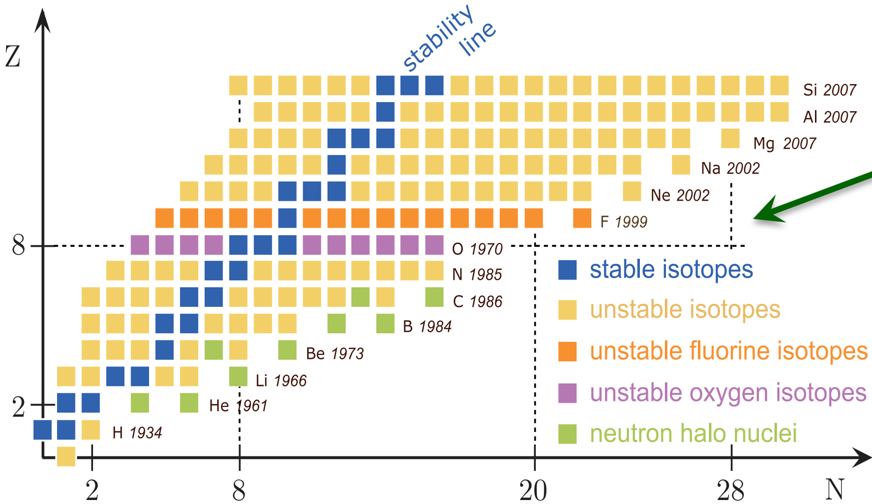


[Lee *et al.* 2010]

V.Somà, CB, et al, Eur. Phys. Jour.: Web. of Conf. **66**, 02005 (2014).

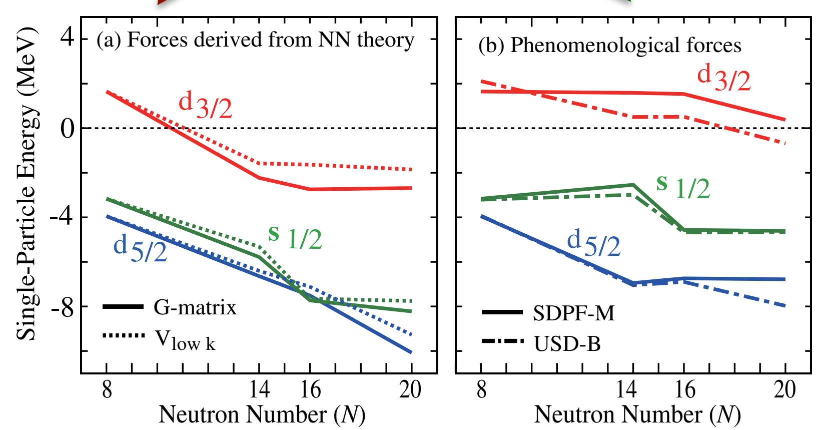
Chiral Hamiltonian and 3NF

Oxygen puzzle...

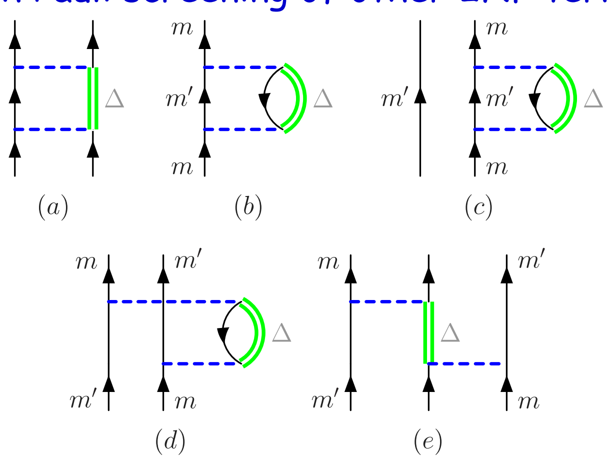


The oxygen dripline is at ^{24}O, at odds with other neighbor isotope chains.

Phenomenological shell model interaction reflect this in the s.p. energies but no realistic NN interaction alone is capable of reproducing this...

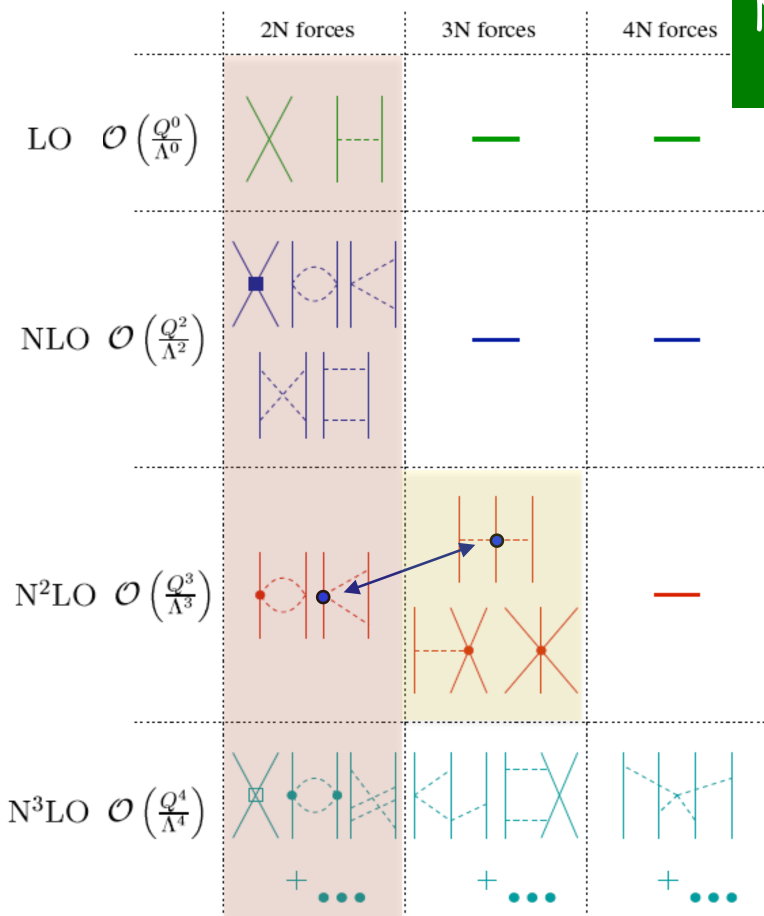


The fujita-Miyazawa 3NF provides repulsion through Pauli screening of other 2NF terms:

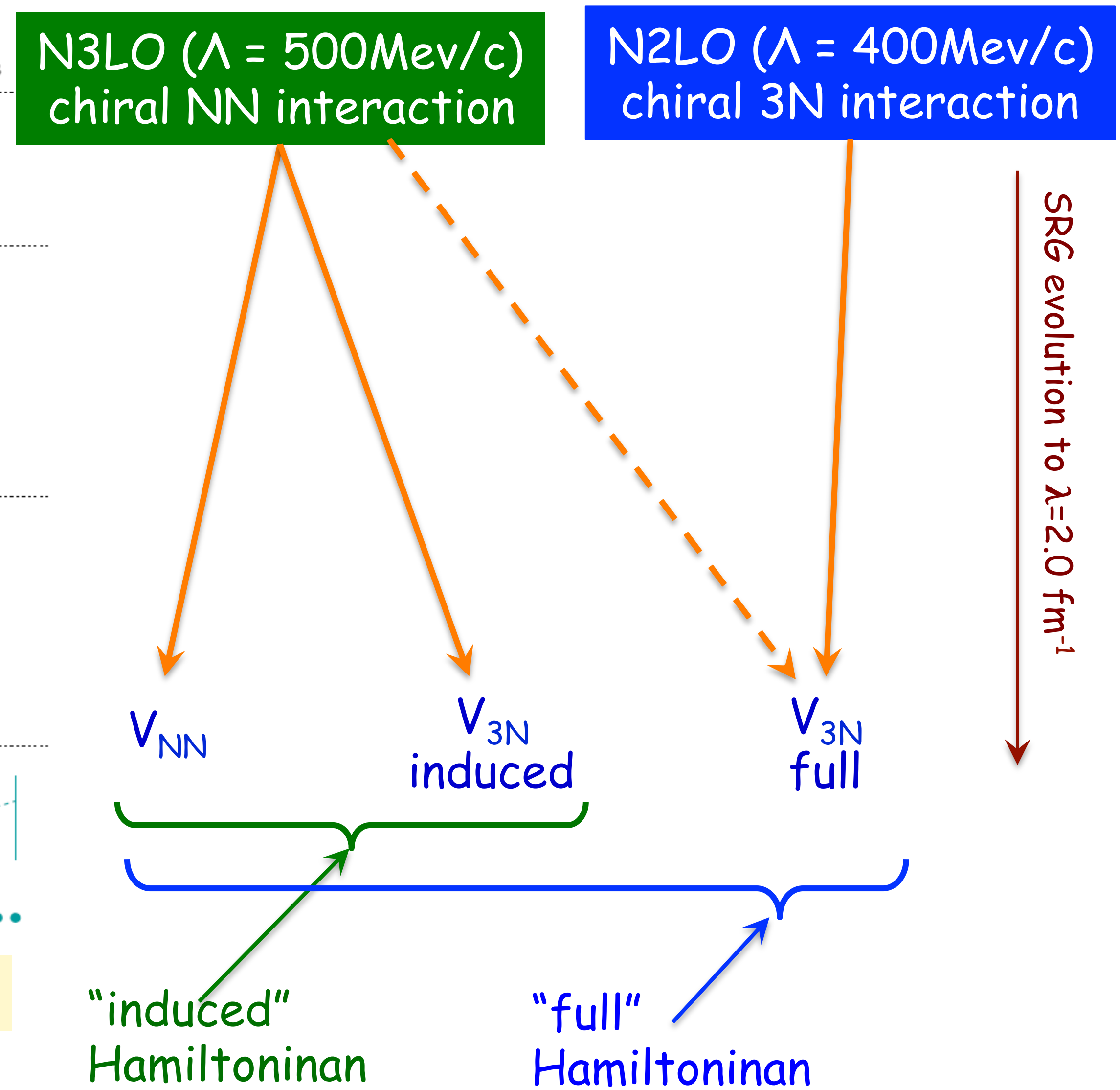


[T. Otsuka et al., Phys Rev. Lett **105**, 32501 (2010)]

Chiral Nuclear forces - SRG evolved



(3NFs arise naturally at N2LO)



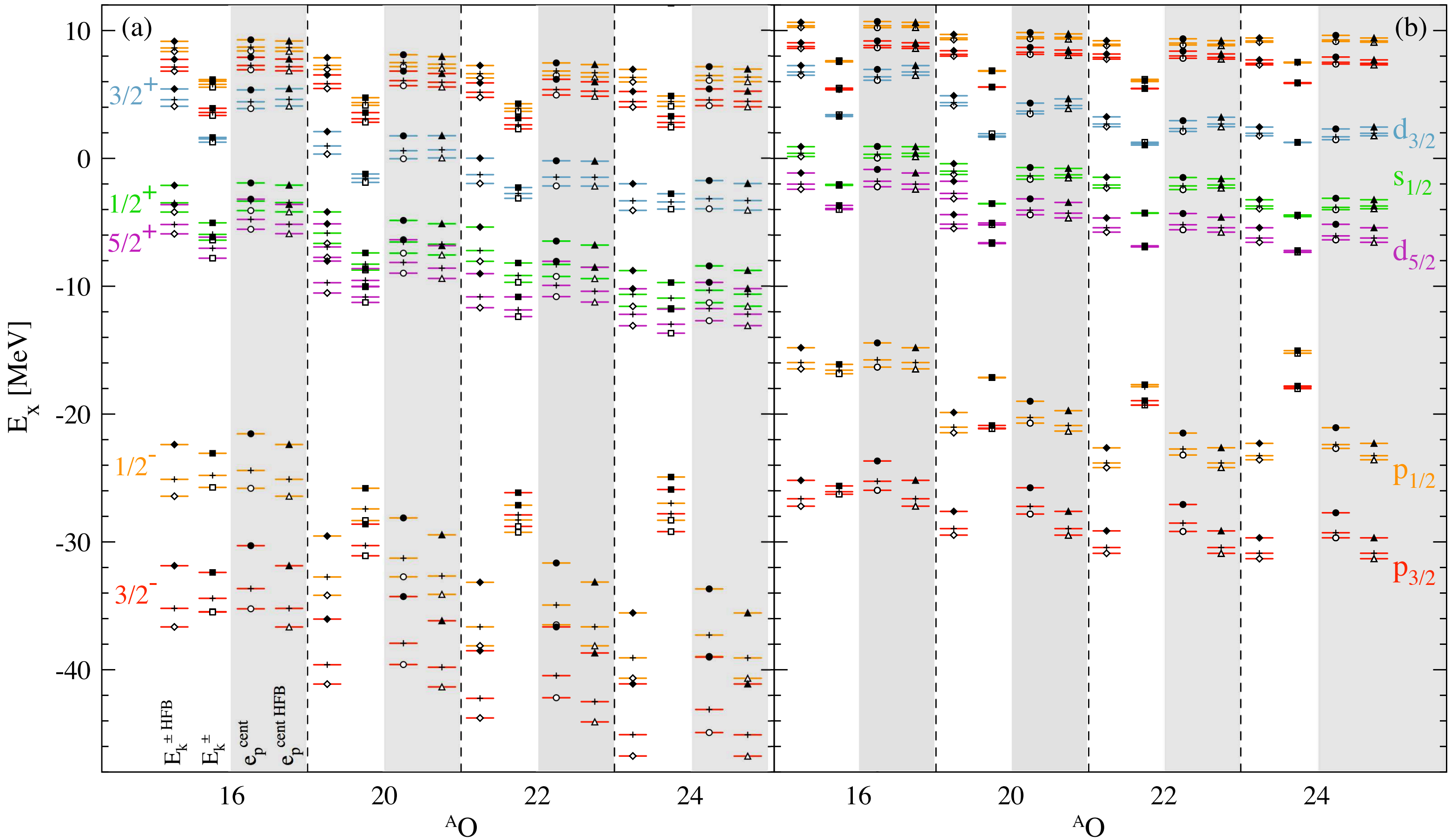
[Jurgenson, Navrátil, Furnstahl, Phys. Rev. Lett. **103**, 082501 (2009); Hebeler, Phys. Rev. C 85, 021002 (2012)]

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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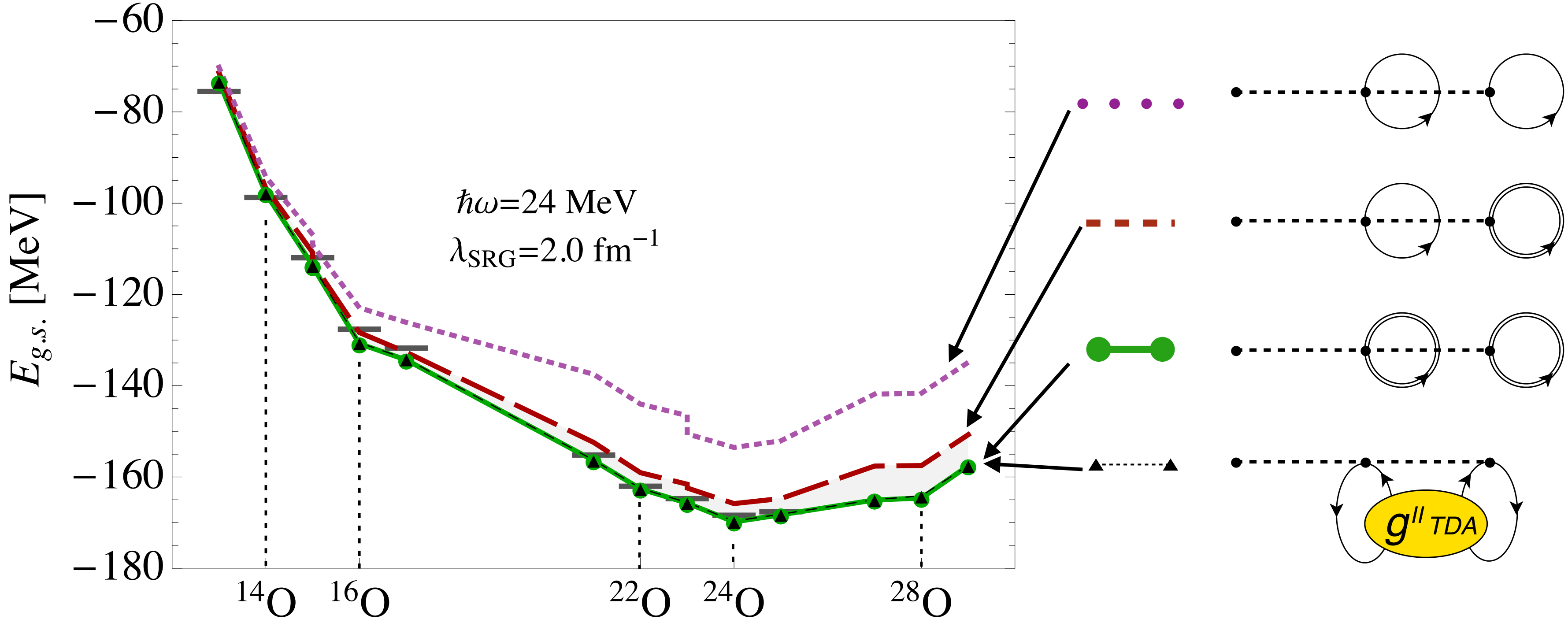
3N forces in FRPA/FTDA formalism

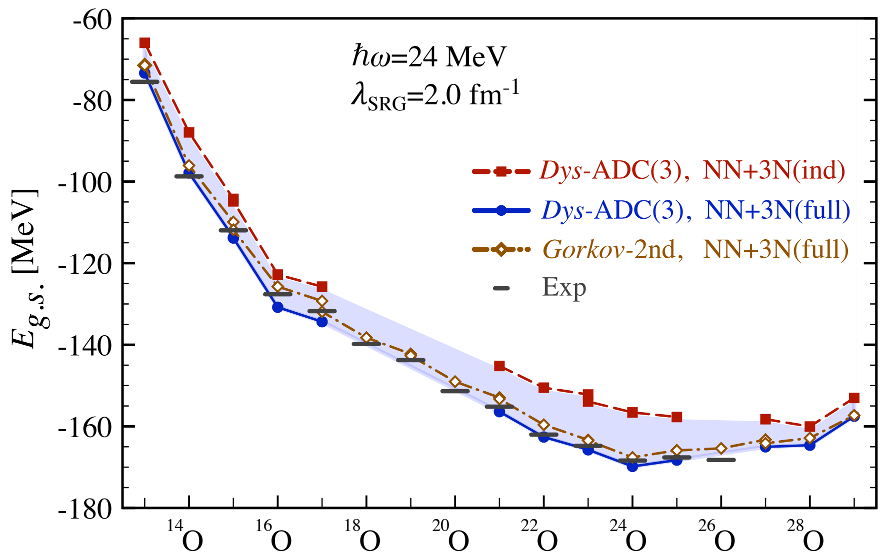
→ Ladder contributions to static self-energy are negligible (in oxygen)

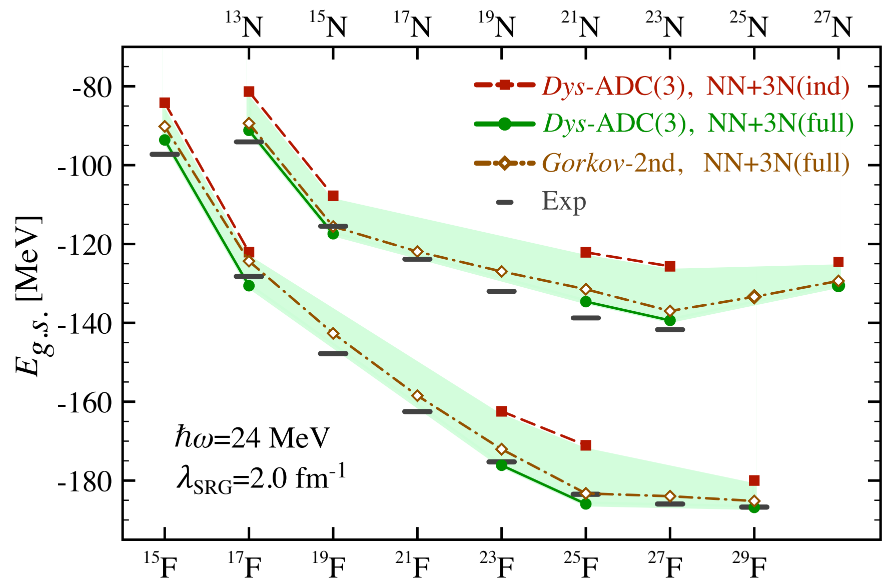


CB, *arXiv:1405.3002v2 [nucl-th]* (2014)

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)





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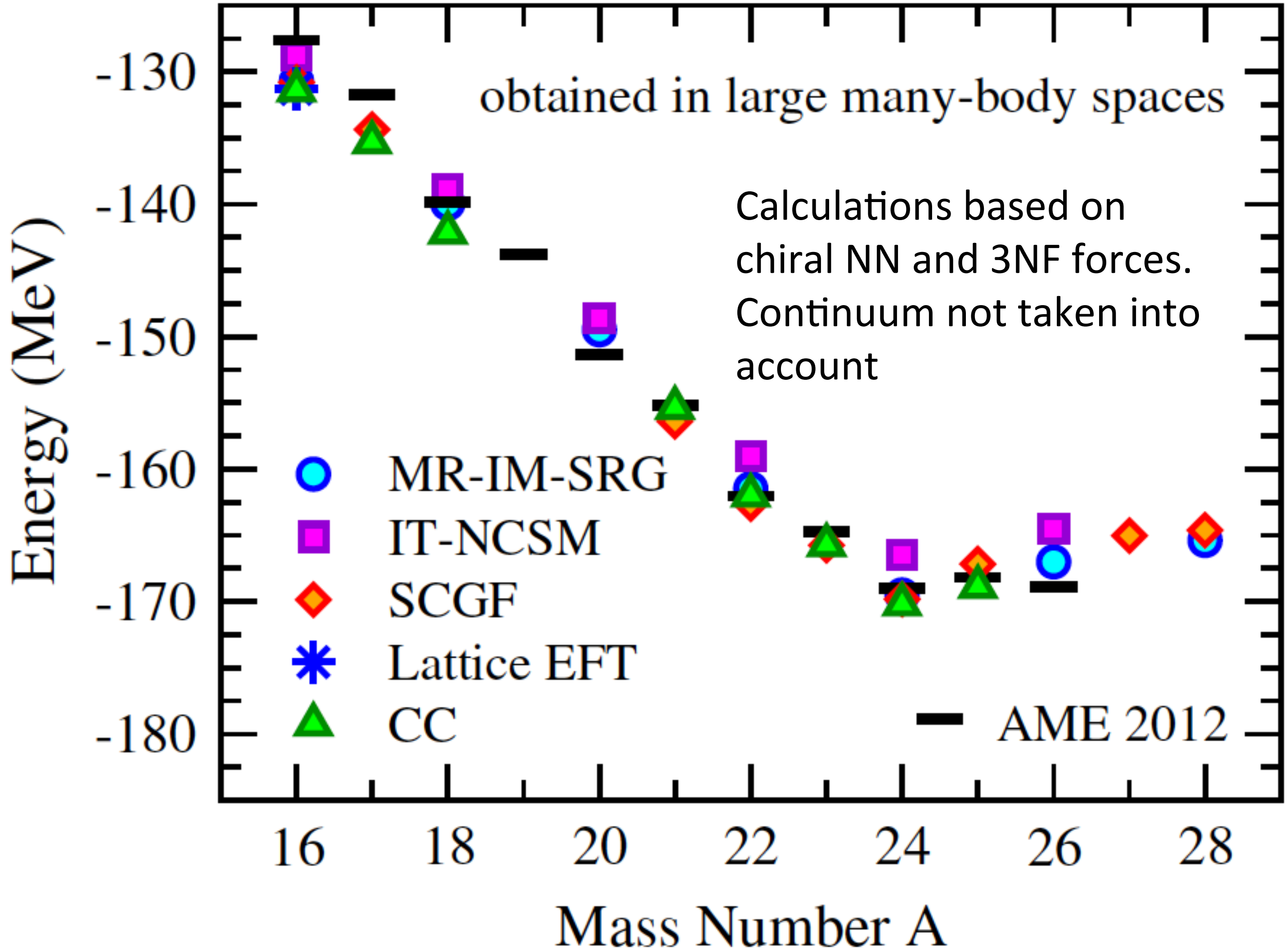
N3LO (Λ = 500Mev/c) chiral NN interaction evolved to 2N + 3N forces (2.0fm^{-1})
N2LO (Λ = 400Mev/c) chiral 3N interaction evolved (2.0fm^{-1})

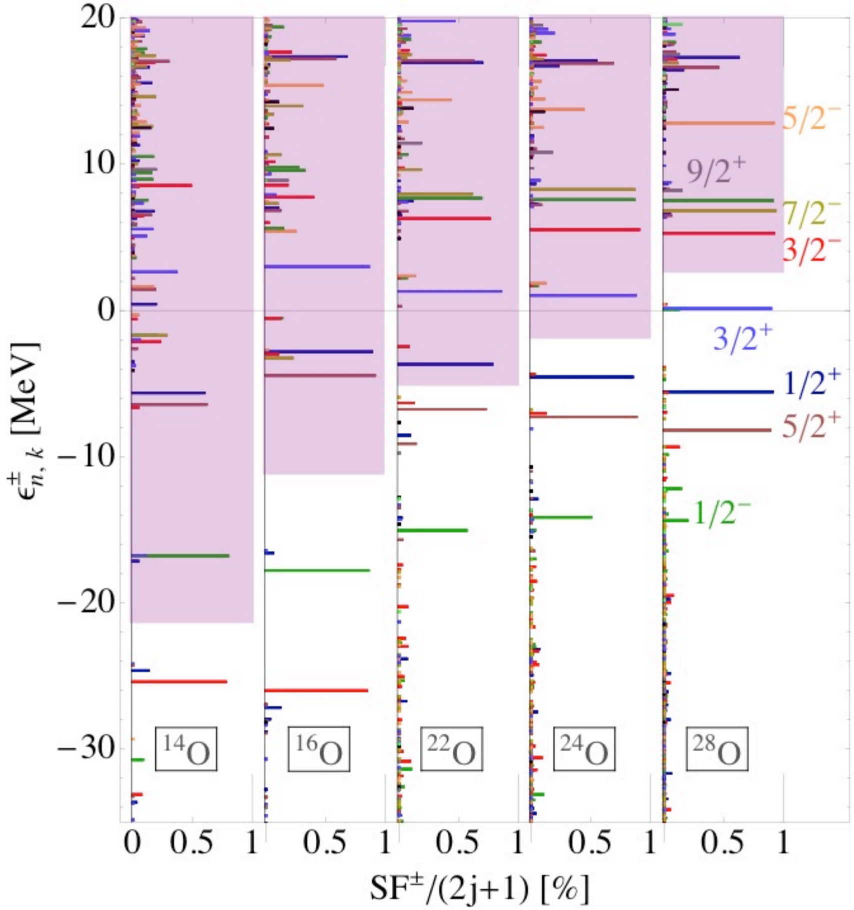
Benchmark of ab-initio methods in the oxygen isotopic chain

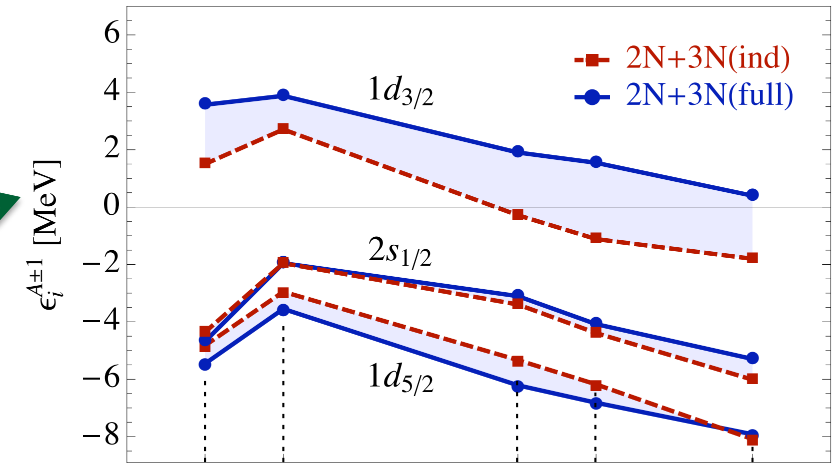


Hebeler, Holt, Menendez, Schwenk, Ann. Rev. Nucl. Part. Sci. in press (2015)

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).]

Results for the N-O-F chains

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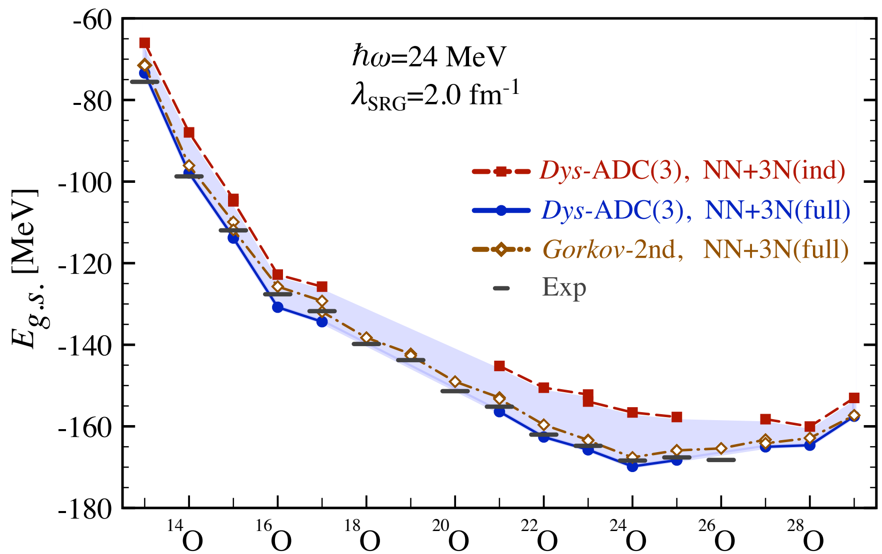

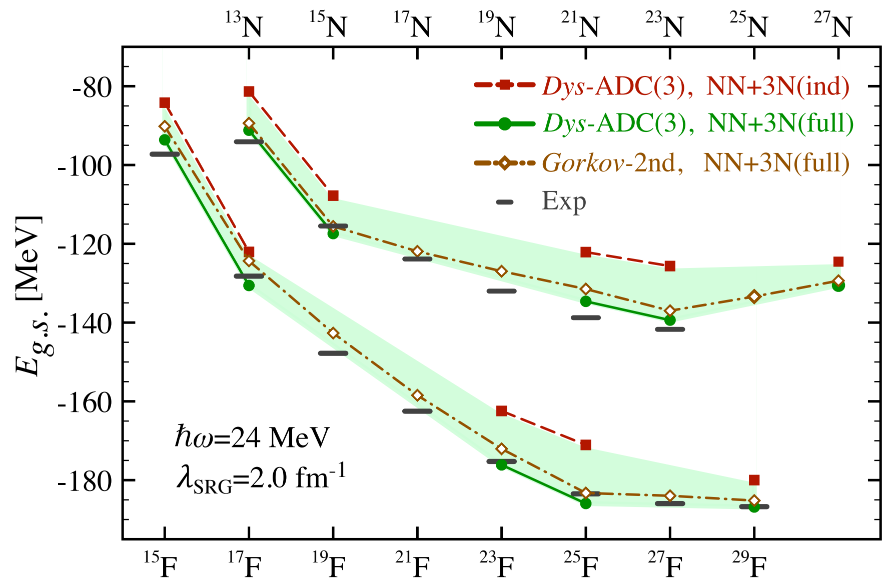

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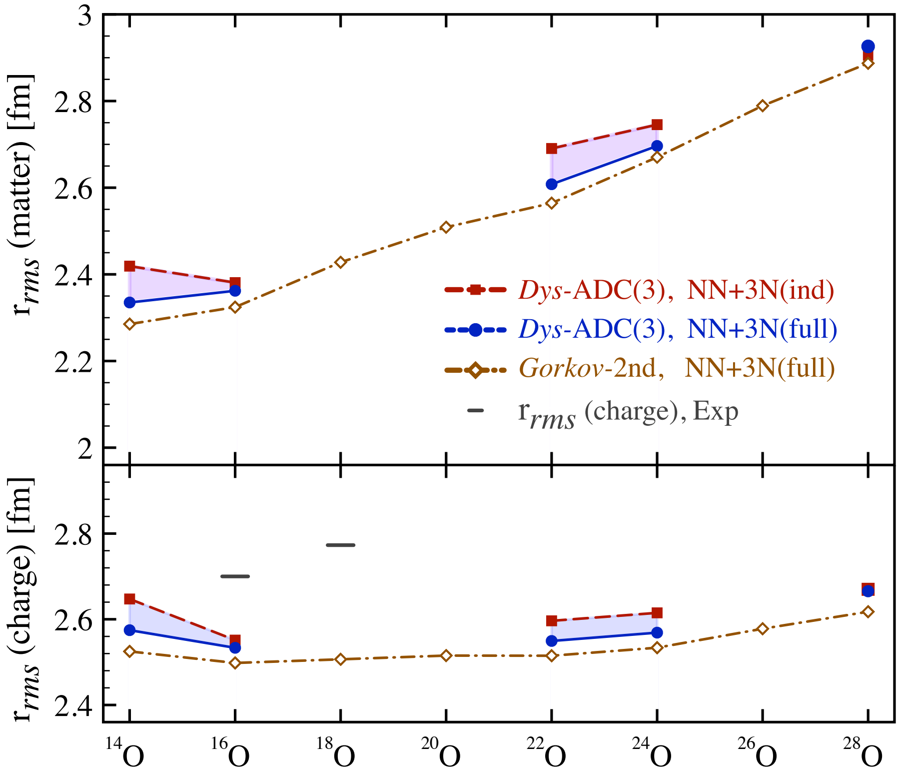
A. Cipollone, CB, P. Navrátil, arXiv:1412.3002 [nucl-th] (2014)

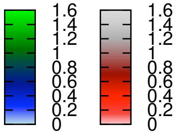


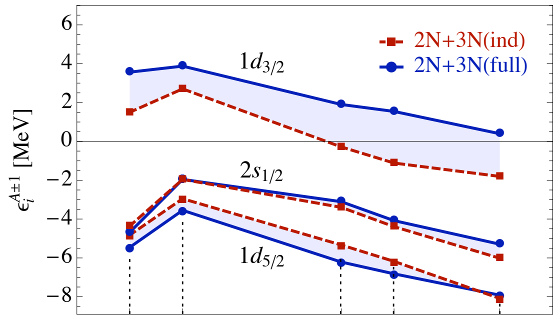
→ Single particle spectra slightly to spread and

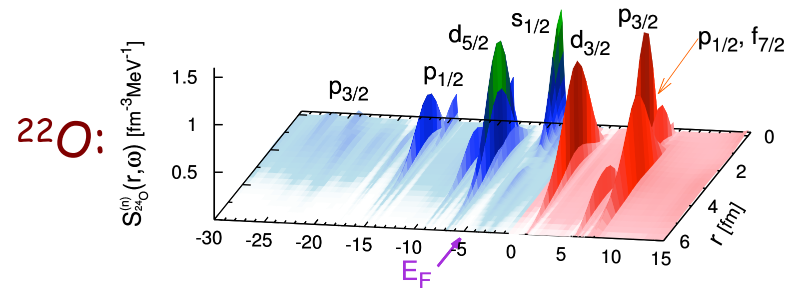
→ systematic underestimation of radii

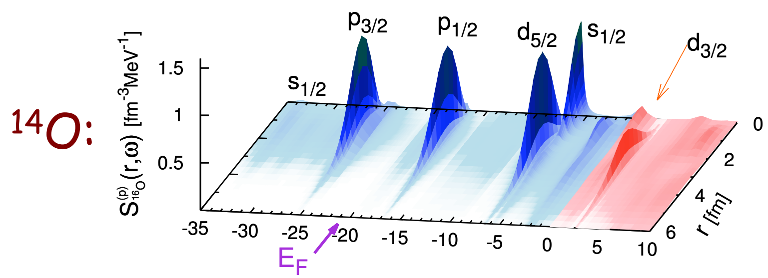
Neutron spectral function of Oxygens

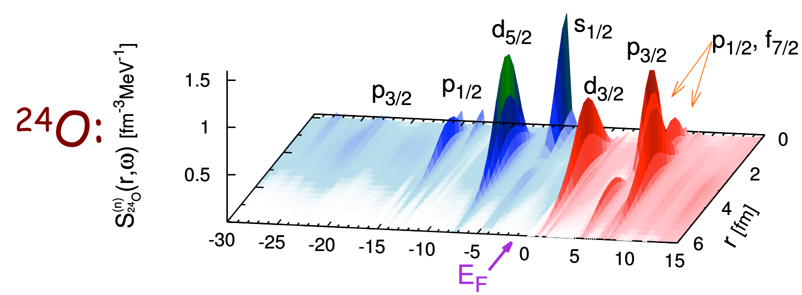
A. Cipollone, CB P. Navrátil, *PRC submitted* (2014)

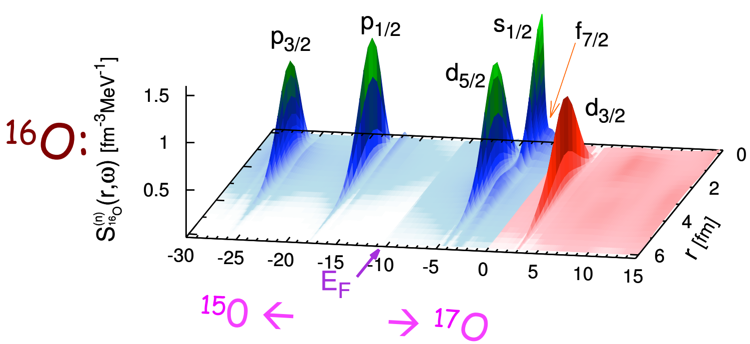


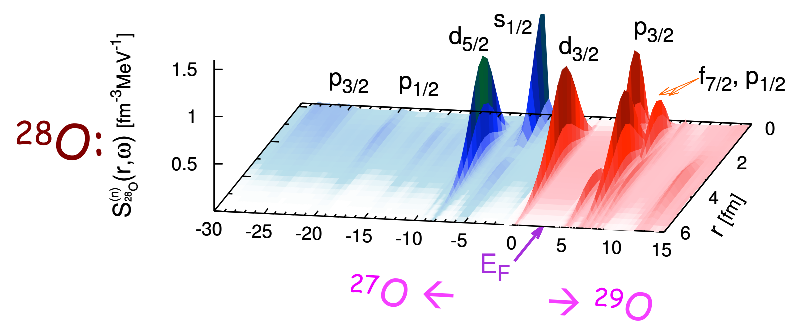












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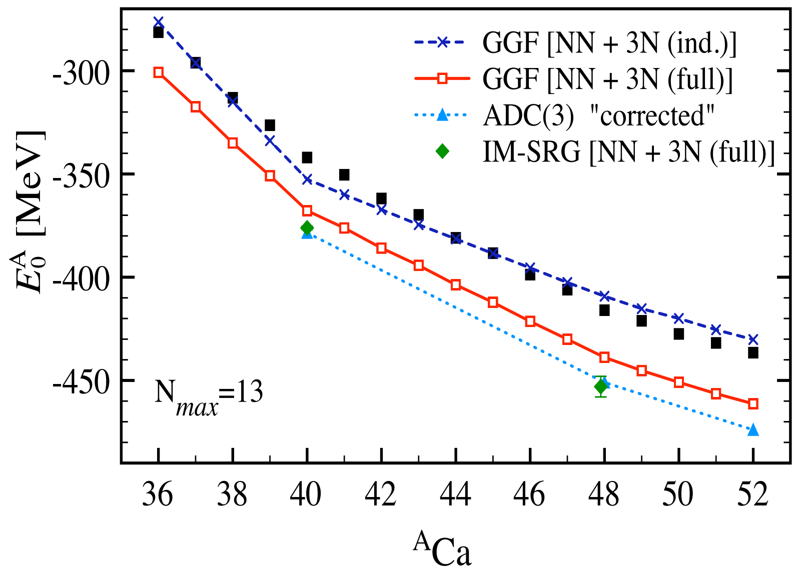
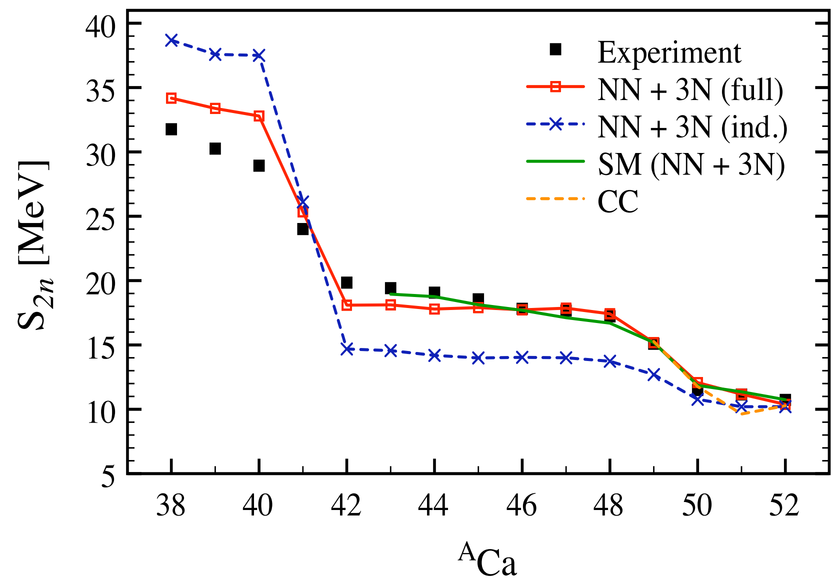
Calcium isotopic chain

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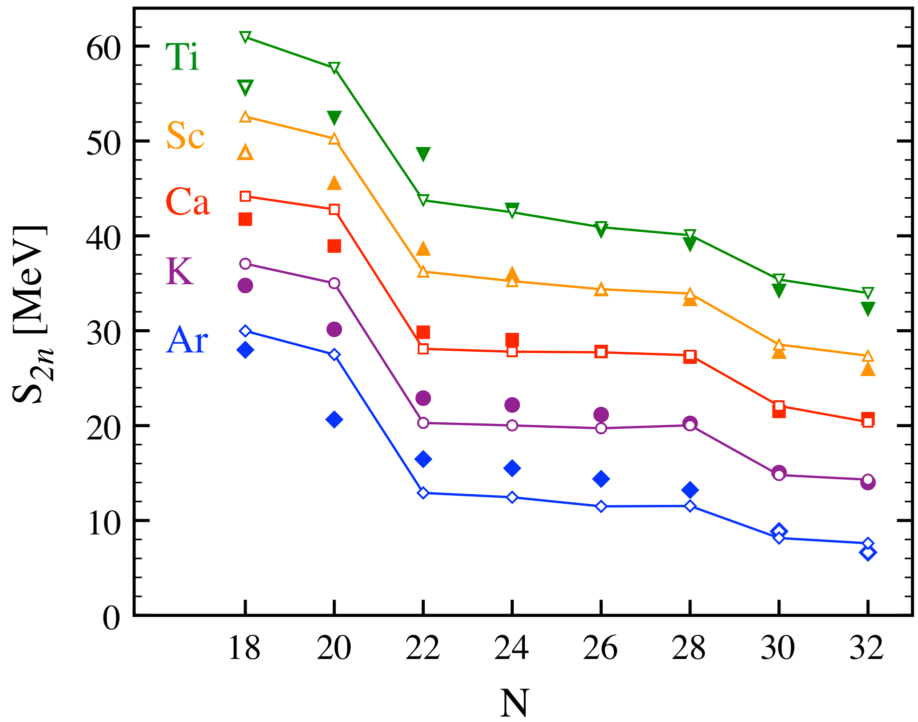
V. Somà, CB *et al.* Phys. Rev. C**89**, 061301R (2014)

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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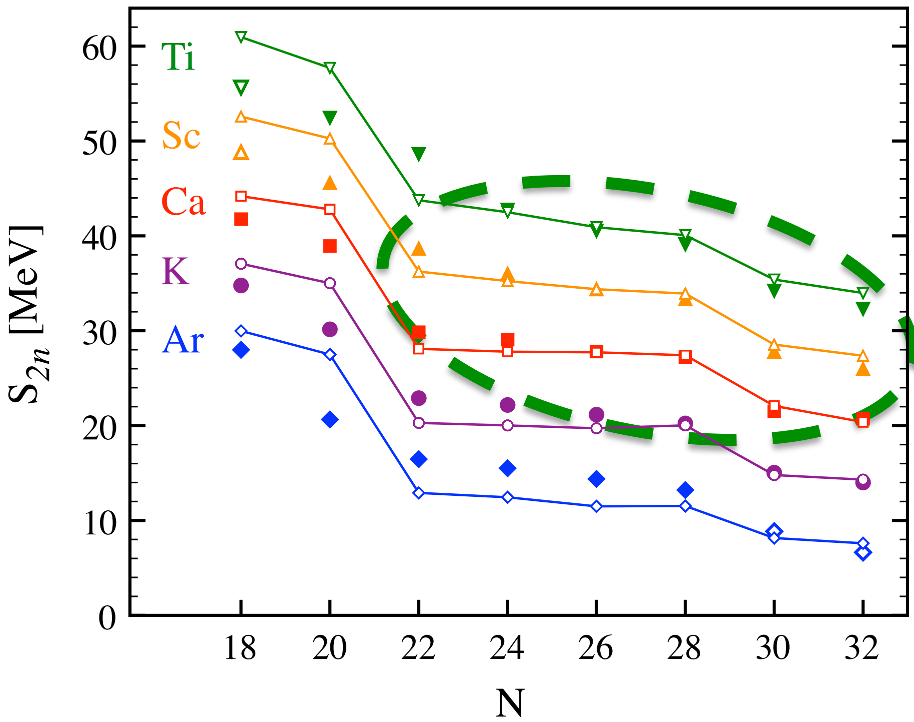

Works well in the *pf* shell

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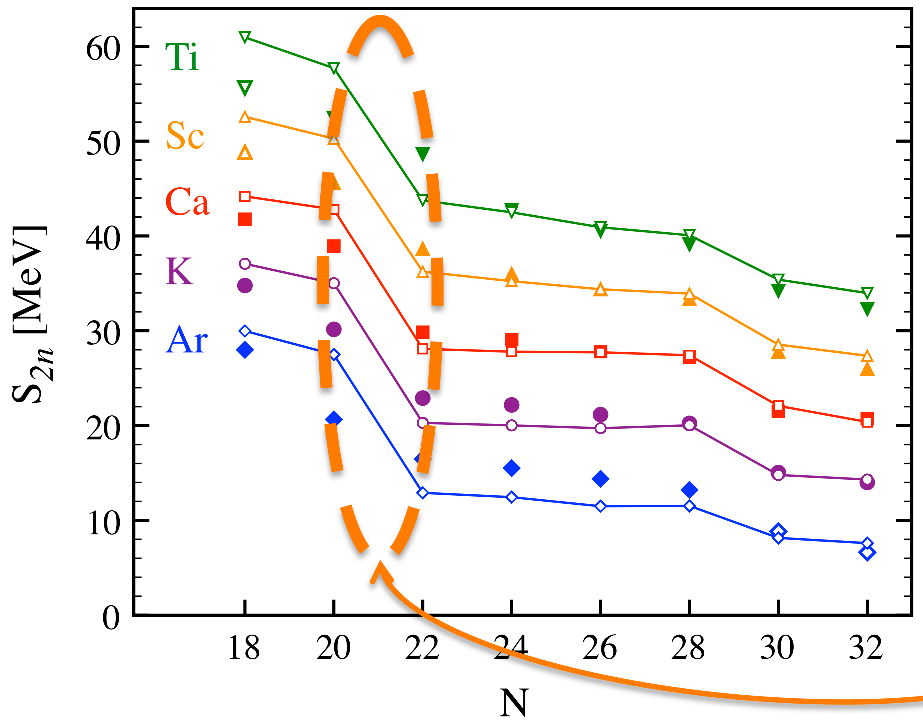

Over estimated
N=20 and Z=20 gaps

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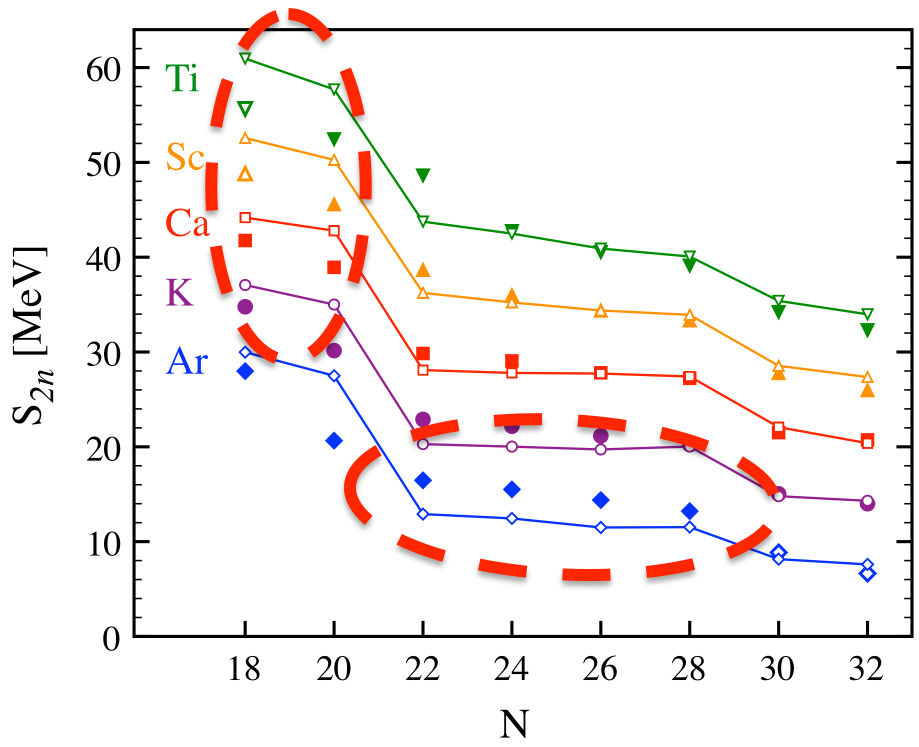
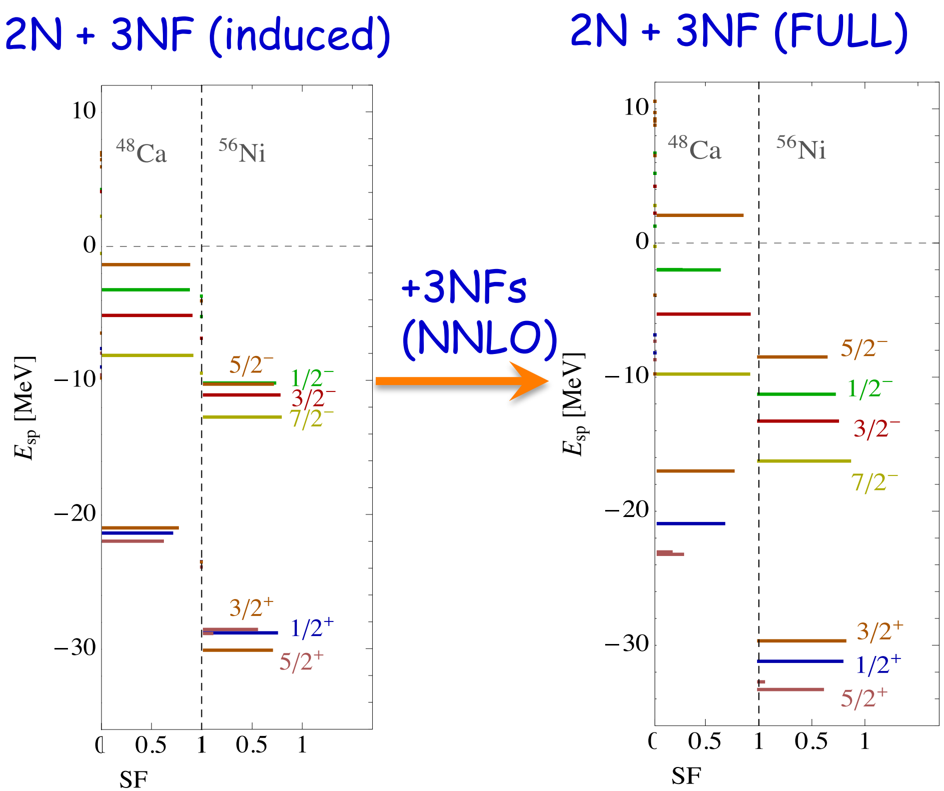


Lack of deformation due to quenched cross-shell quadrupole excitations

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

The sd-pf shell gap

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

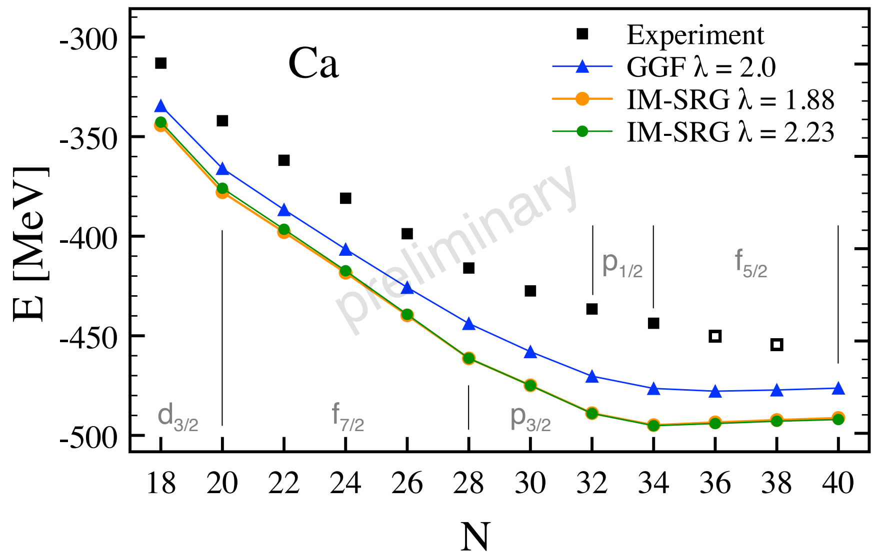


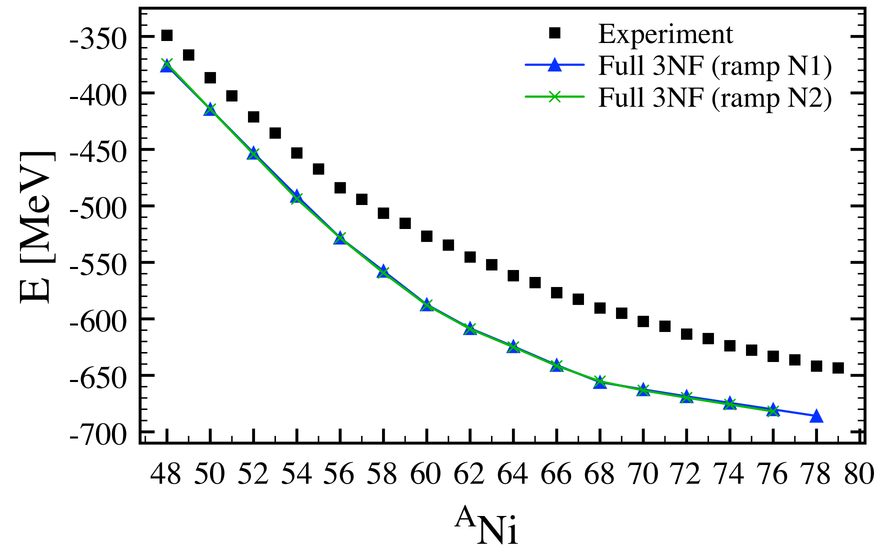
- *sd-pf separation is overestimated* even with leading order N2LO 3NF
- Correct increase of $p_{3/2}$-$f_{7/2}$ splitting (see Zuker 2003)

	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]

Ca and Ni isotopic chains





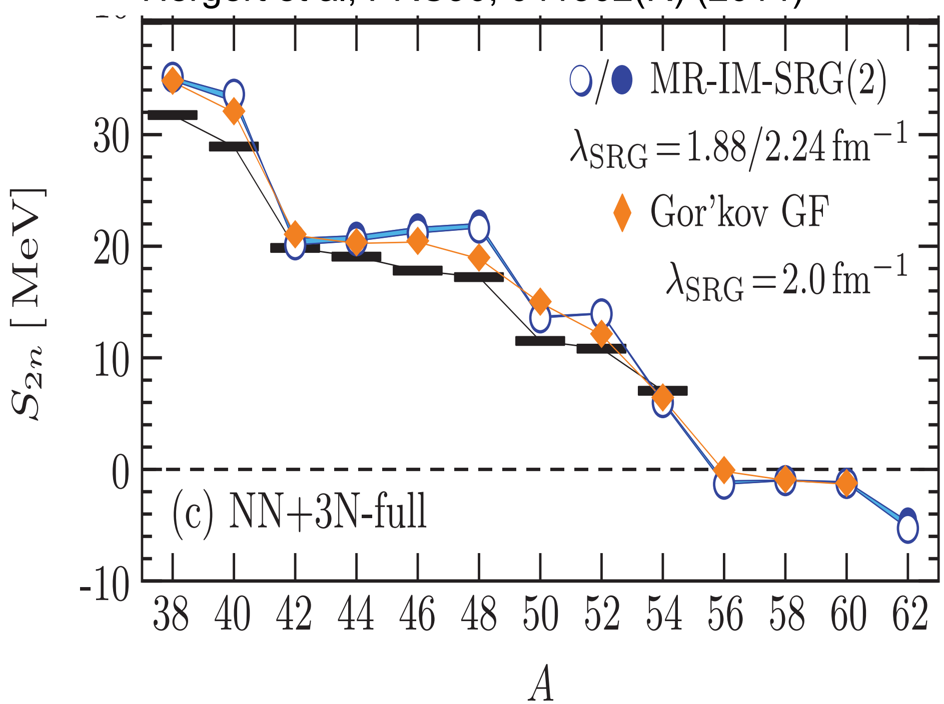
→ Large J in free space SRG matter (must pay attention to its convergence)

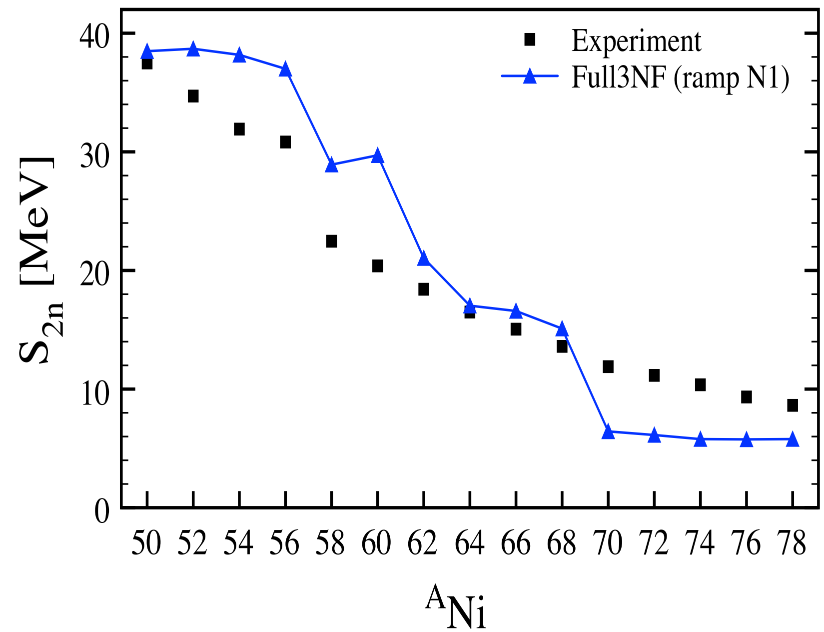
→ Overall conclusions regarding over binding and S_{2n} remain but details change

IM-SRG results from H. Hergert

Ca and Ni isotopic chains

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



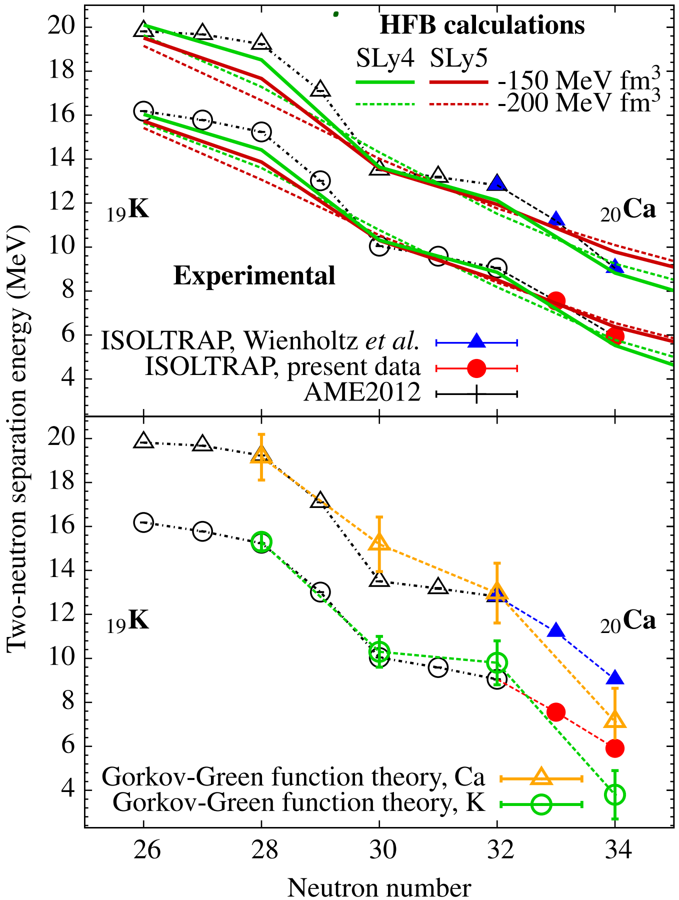


→ Large J in free space SRG matter (must pay attention to its convergence)

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

Two-neutron separation energies for neutron rich K isotopes

*M. Rosenbusch, et al., PRL**114**, 202501 (2015)*



Measurements
@ ISOLTRAP

Theory tend to overestimate the gap at N=34, but overall good

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

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

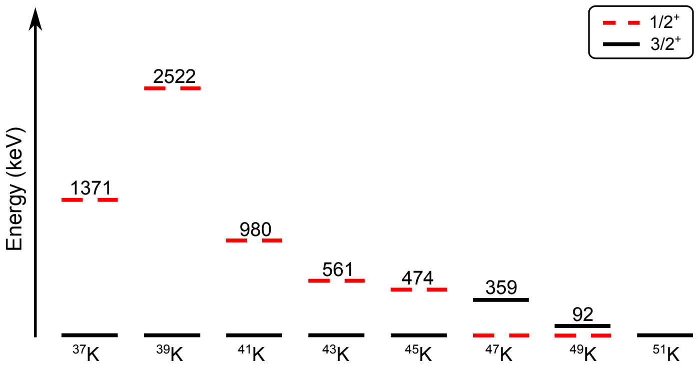


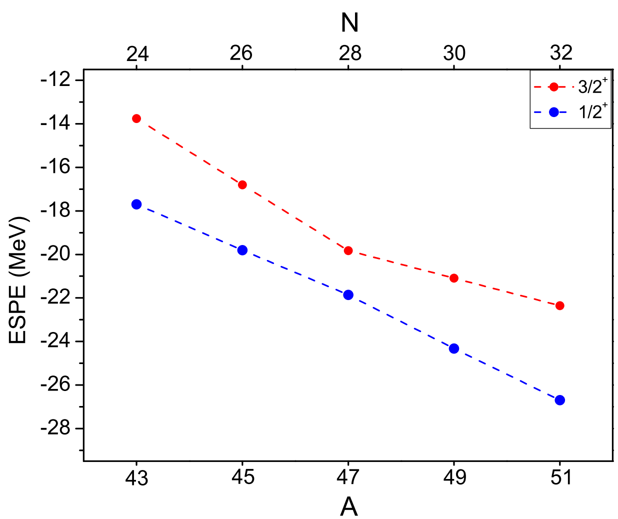
FIG. 1. (color online) Experimental energies for $1/2^+$ and $3/2^+$ states in odd-A K isotopes. Inversion of the nuclear spin is obtained in ^{47,49}K and reinversion back in ^{51}K. Results are

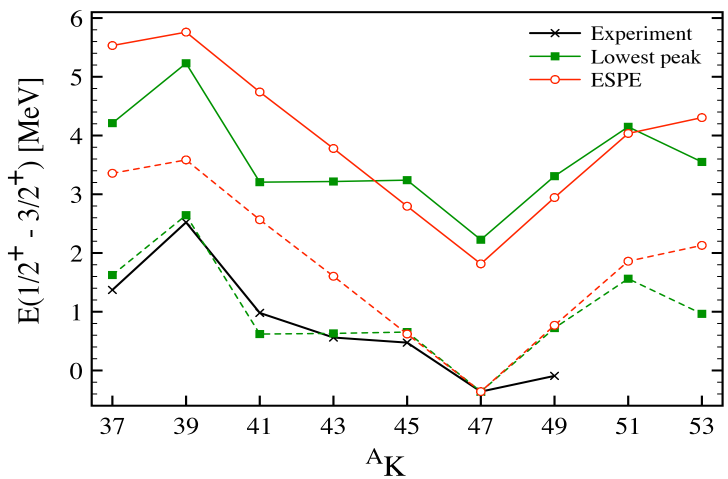
J. Papuga, et al., Phys. Rev. Lett. **110**, 172503 (2013);
Phys. Rev. C **90**, 034321 (2014)

^{A}K isotopes

Laser spectroscopy @ ISOLDE

Change in separation described by chiral NN+3NF:



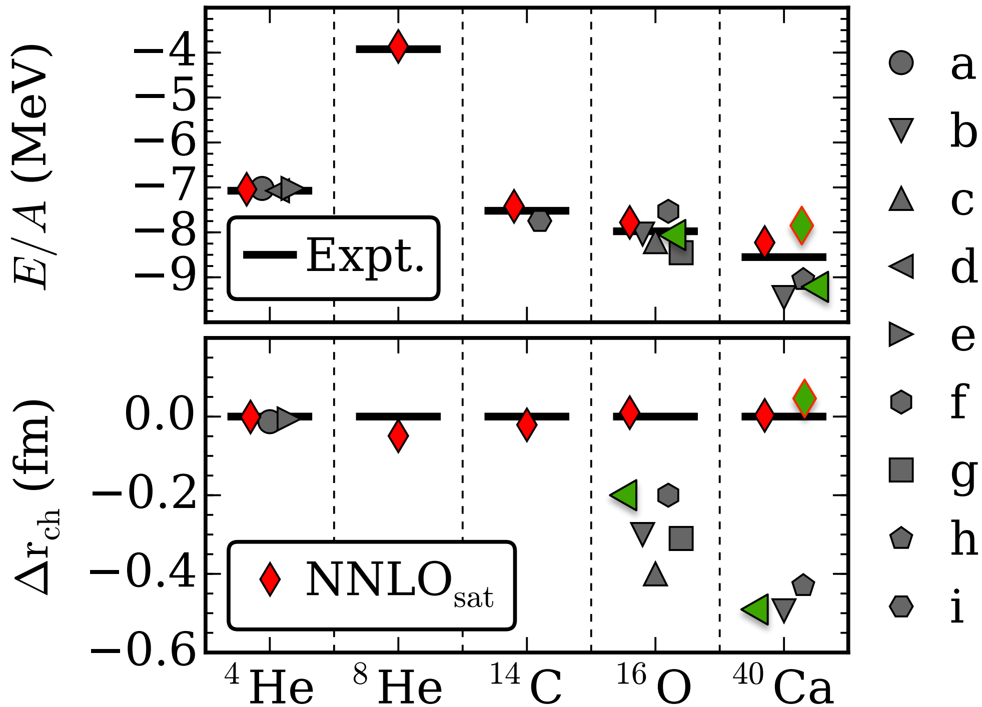


ESPE: "centroid" energies

(Gorkov calculations at 2nd order)

NNLO-sat : a global fit up to A≈24

A. Ekström *et al.* Phys. Rev. C**91**, 051301(R) (2015)



- Constrain NN phase shifts

- Constrain radii and energies up to A≲24

➔ Provides saturation up to large masses!

NNLOsat (V2 + W3) -- *Grkv 2nd ord.*

From **SCGF:**

V2-N3LO(500) + W3-NNLO(400MeV/c) w/ SRG at 2.0 fm^{-1}

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

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

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