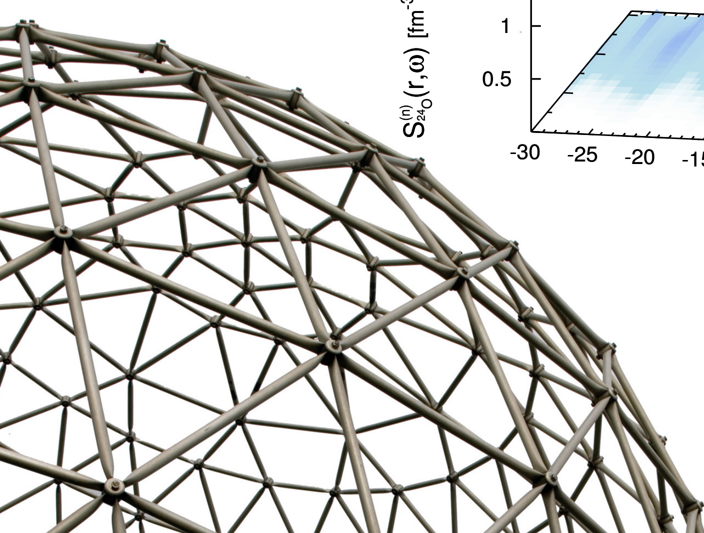
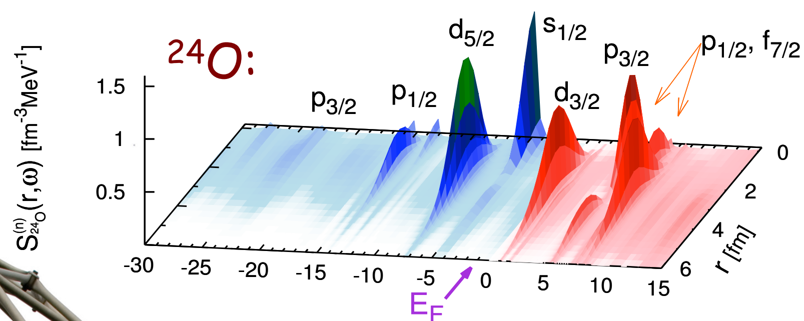
"Nuclear Physics, Compact Stars, and Compact Star Mergers 2016"
基礎物理学研究所, 京都, 28年 10月 25日

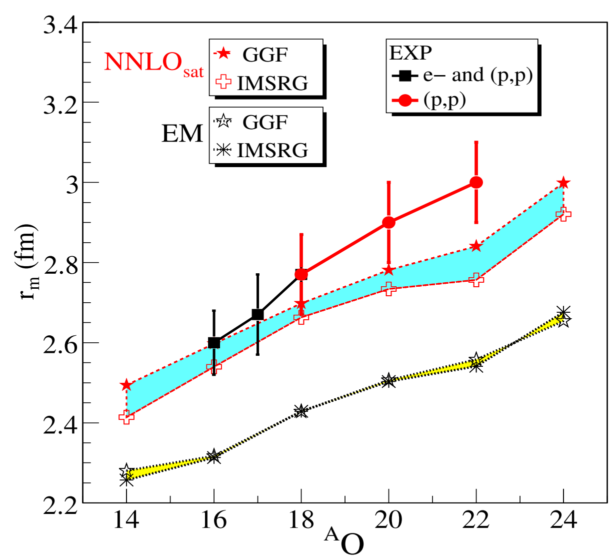
Neutron-rich nuclei from saturating chiral interactions

Carlo Barbieri — University of Surrey

Oct. 25th, 2016







Current Status of low-energy nuclear physics

Composite system of interacting fermions

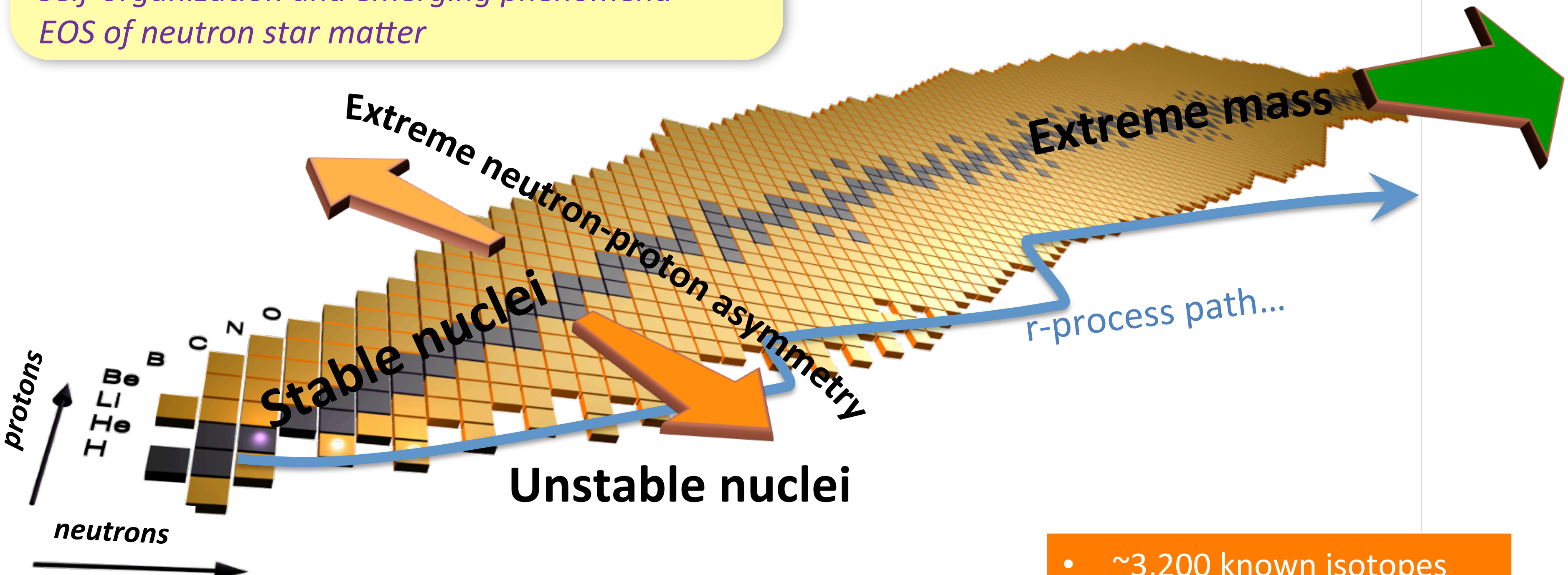
Binding and limits of stability

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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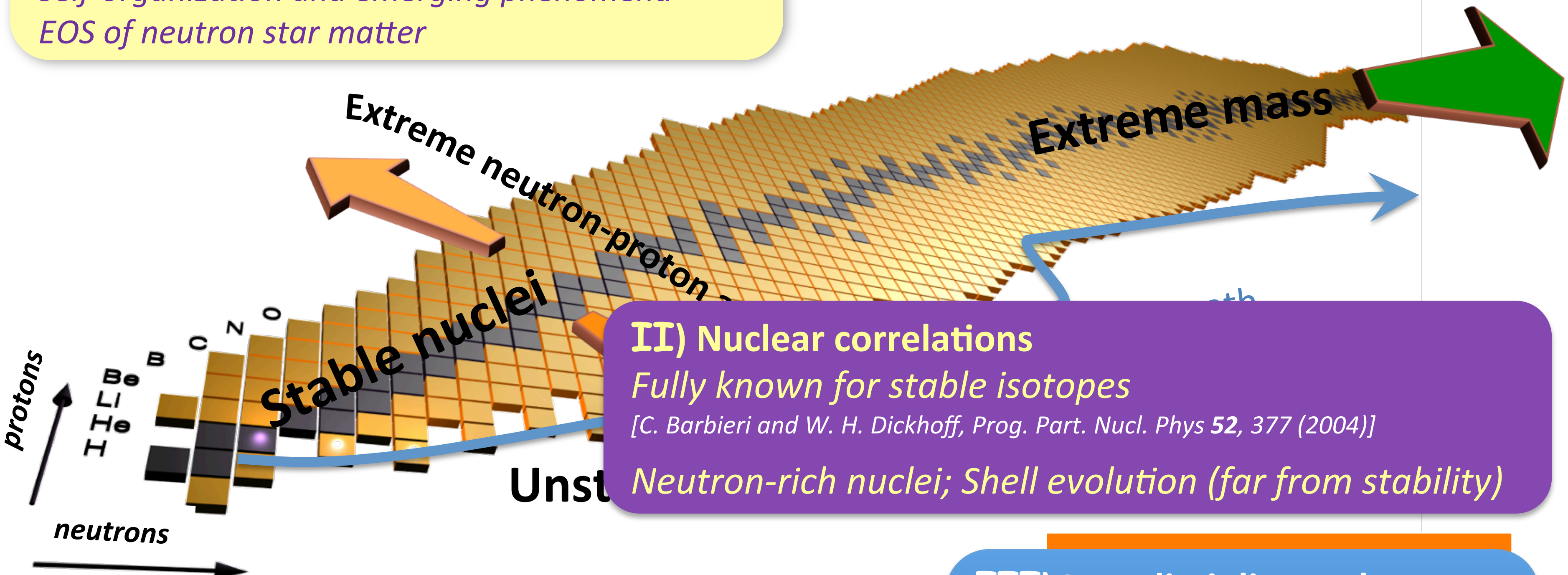


II) Nuclear correlations

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

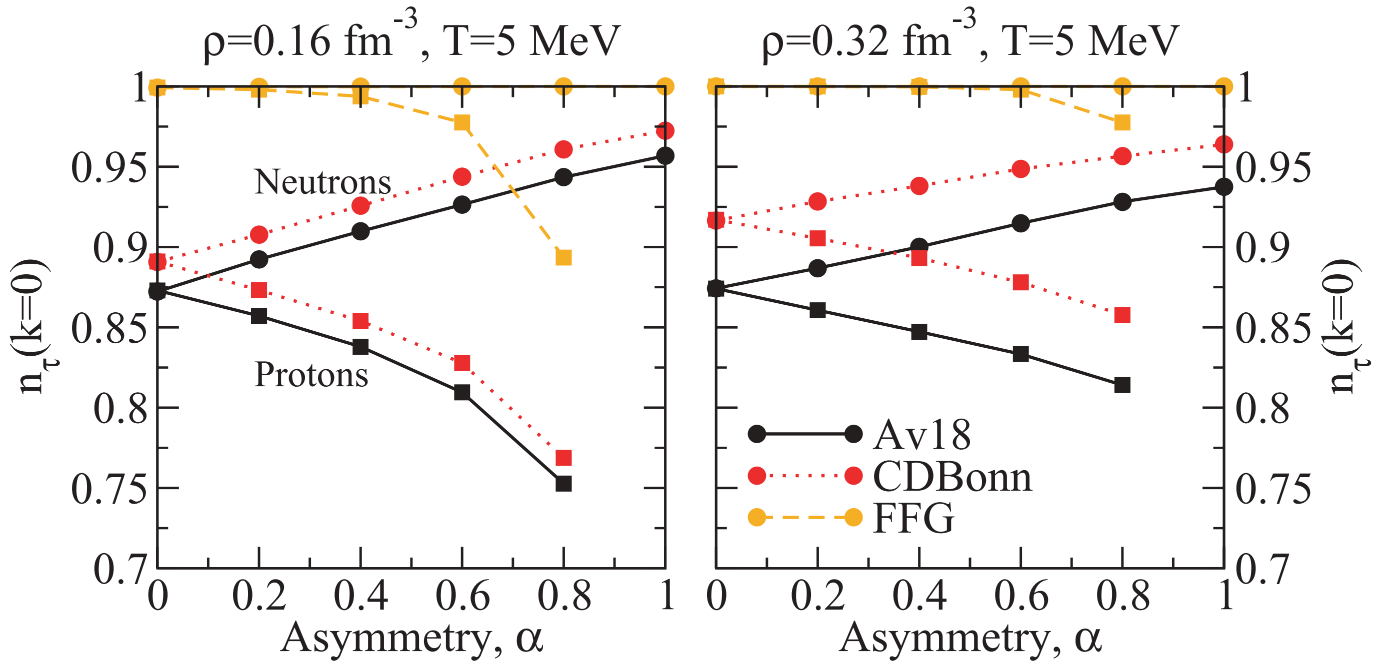
Tests of the standard model

Other fermionic systems:

ultracold gasses; molecules;

Correlations in asymmetric matter

- *Different correlations nuclear matter (stronger!) and in neutron matter*
- *3 nucleon forces not negligible at high asymmetry*

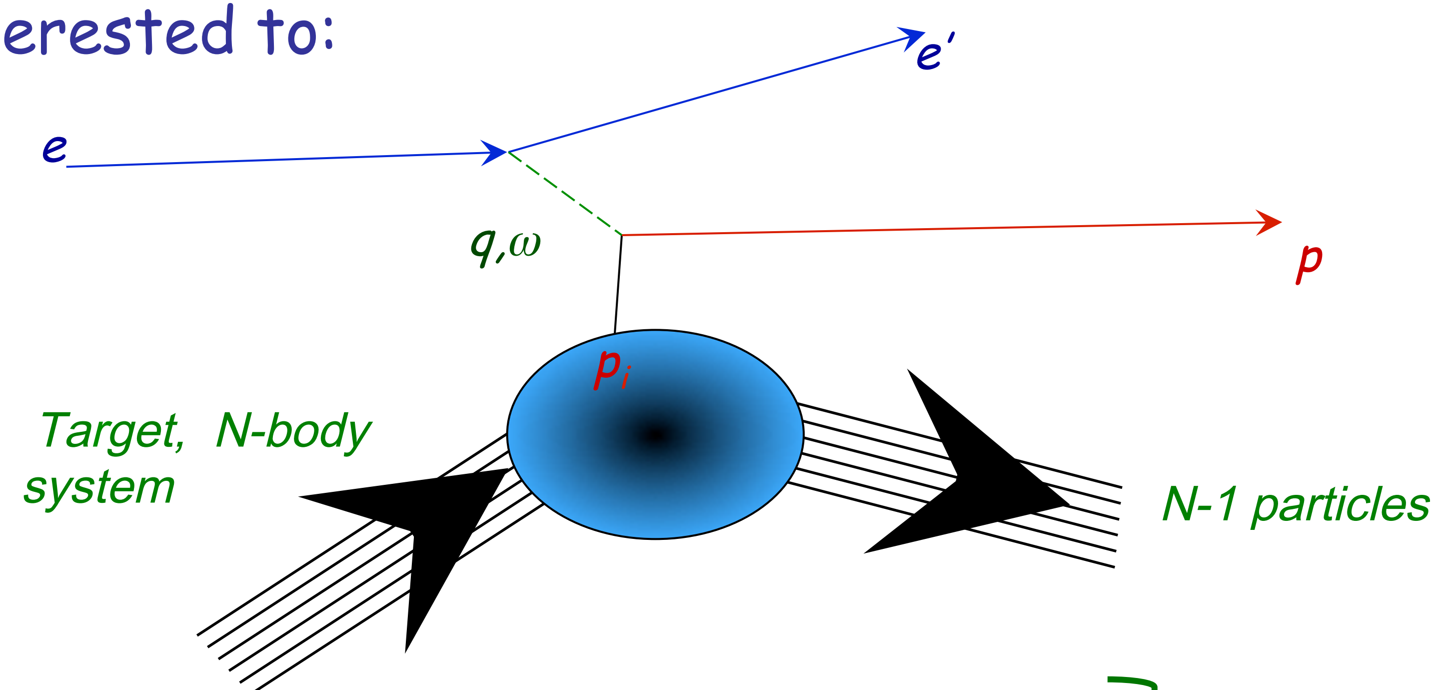


[Rios, Polls, Dickhoff, Phys Rev C 79, 064308 (2009)]

UNIVERSITY OF SURREY

Spectroscopy via knock out reactions-basic idea

Use a probe (ANY probe) to eject the particle we are interested to:



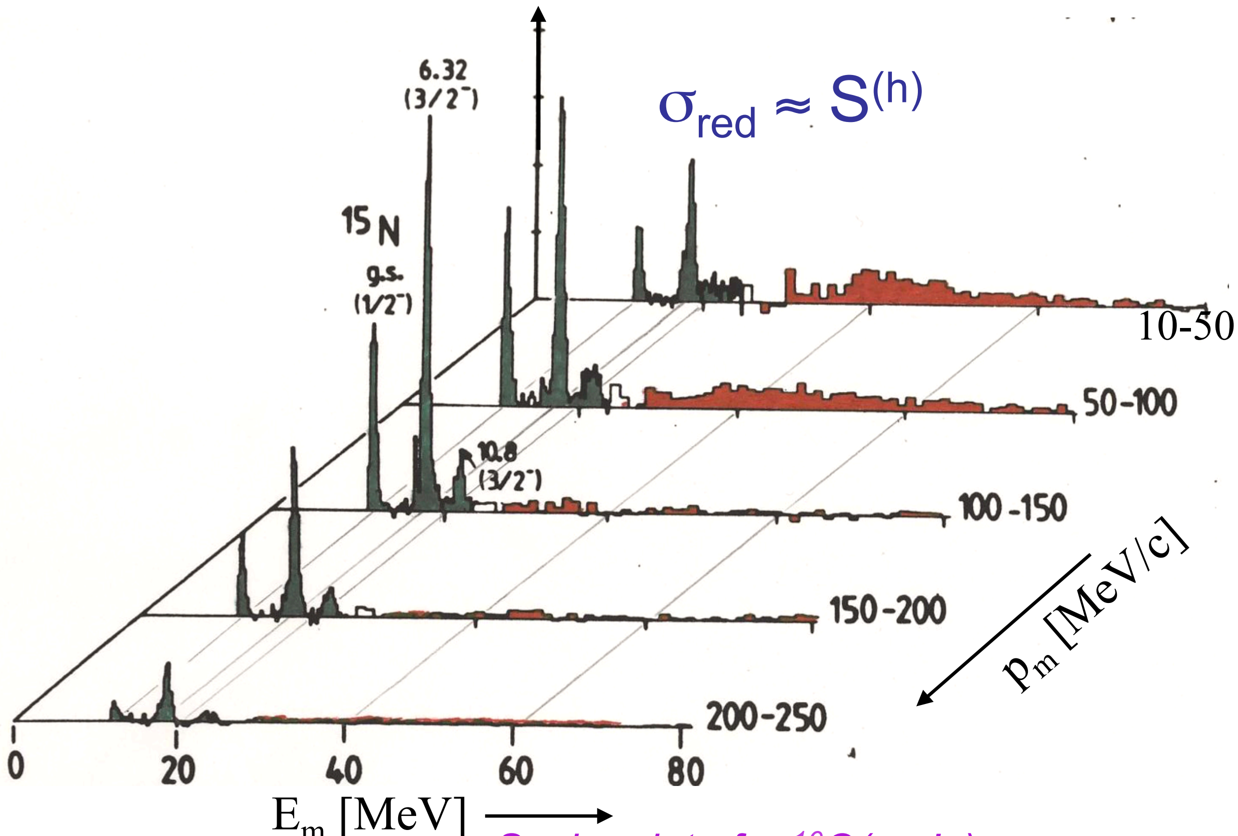
Basic idea:

- we know, e, e' and p
- "get" *energy and momentum* of p_i: $p_i = k_e' + k_p - k_e$
  $E_i = E_e' + E_p - E_e$

Better to choose large transferred momentum and weak probes!!!

Concept of correlations

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

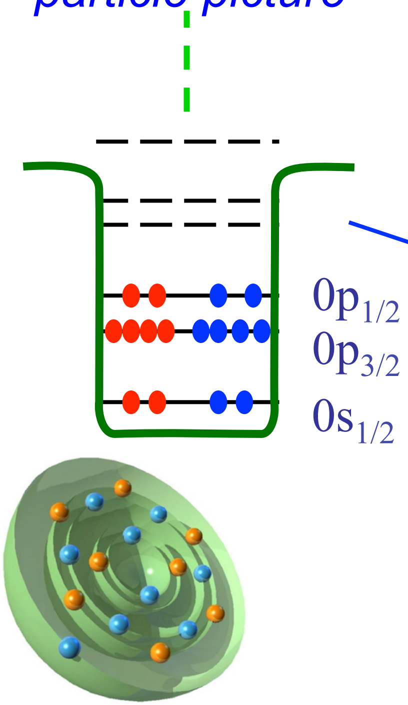


Saclay data for $^{16}O(e,e'p)$
[Mougey et al., Nucl. Phys. A335, 35 (1980)]

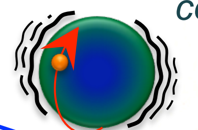
Understood for a few stable closed shells:
[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys ***52****, 377 (2004)]*

Concept of correlations

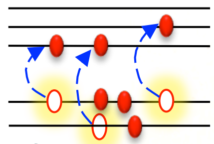
independent particle picture



Particle-vibration coupling (PV)



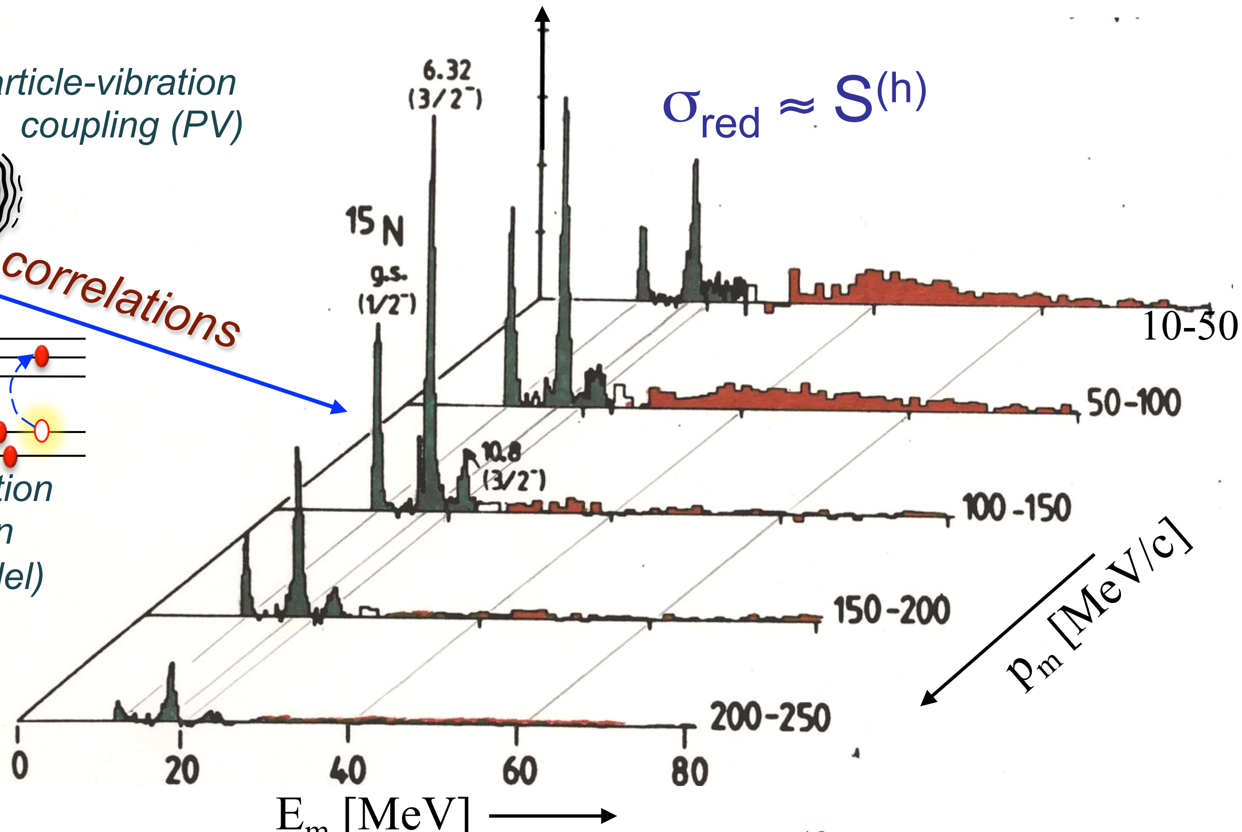
correlations



Configuration interaction (shell model)

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

$\sigma_{red} \approx S^{(h)}$



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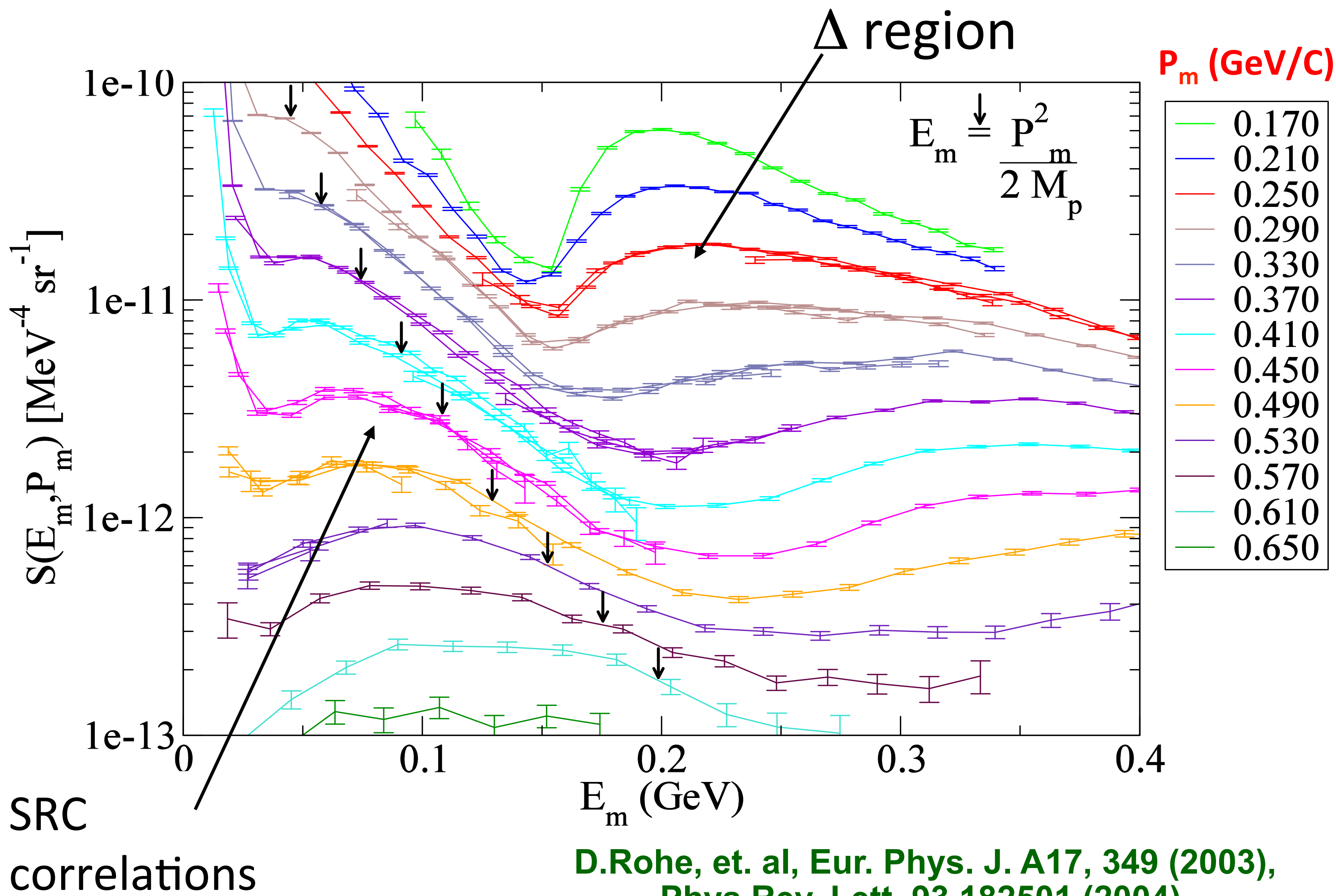
Spectral strength of ^{12}C from exp. E97-006

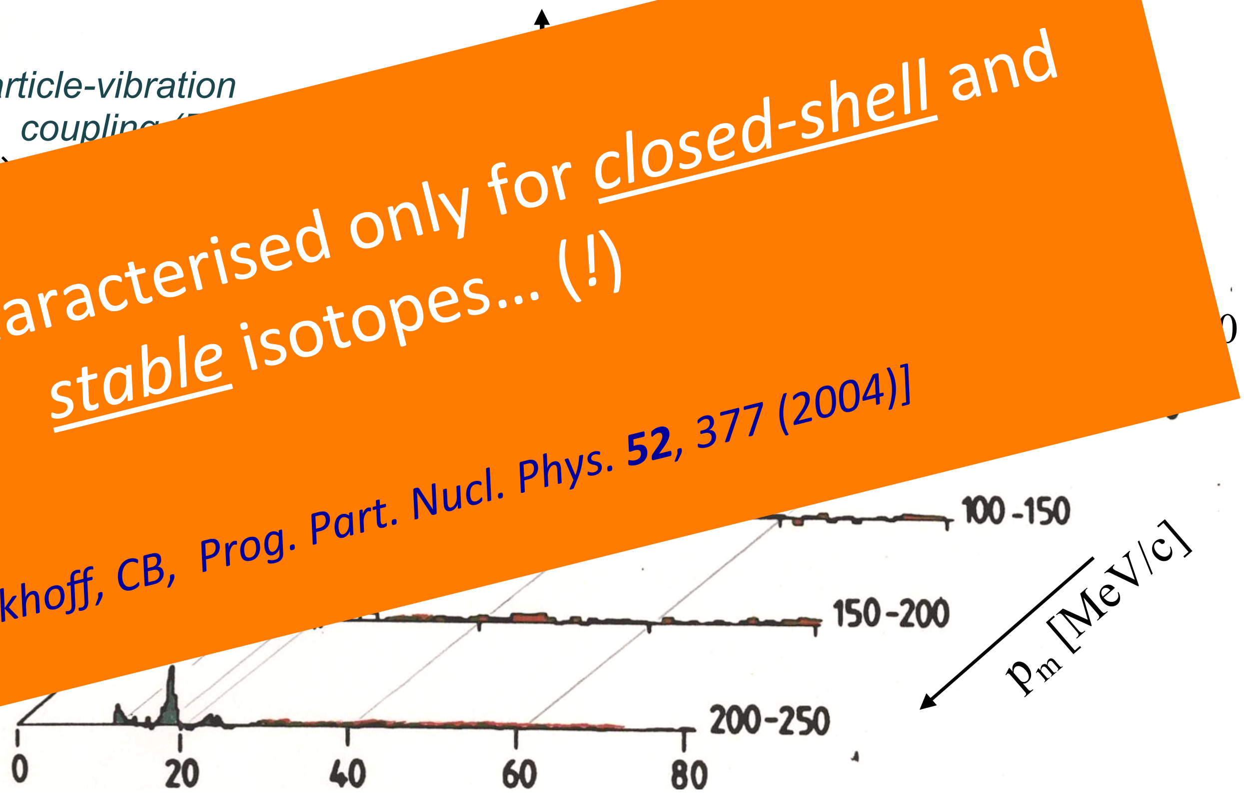


D.Rohe, et. al, Eur. Phys. J. A17, 349 (2003), Phys Rev. Lett. 93 182501 (2004).

Concept of correlations

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

independent particle picture



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

Understood for a few stable closed shells:

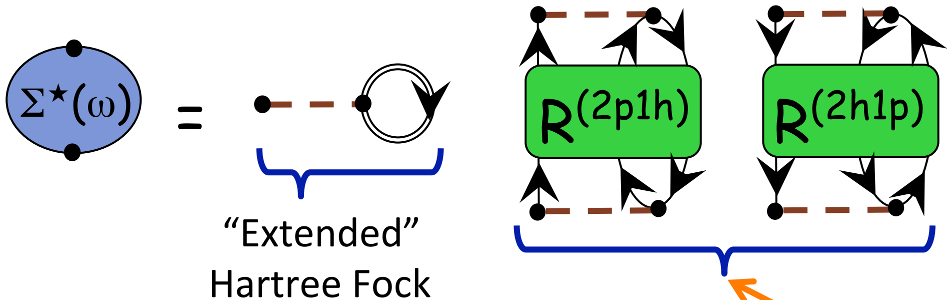
[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys ***52****, 377 (2004)]*

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…

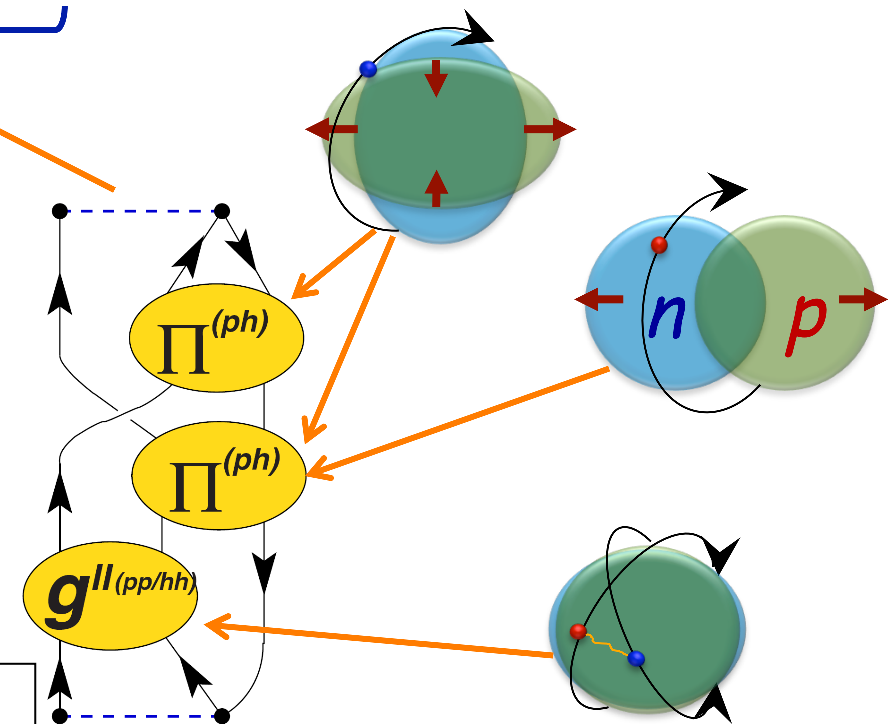
CB et al.,
Phys. Rev. C**63**, 034313 (2001)
Phys. Rev. A**76**, 052503 (2007)
Phys. Rev. C**79**, 064313 (2009)

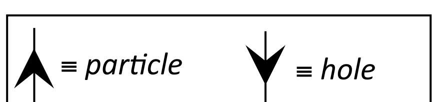


•*A* complete expansion requires *__all__* *__types__* of particle-vibration coupling

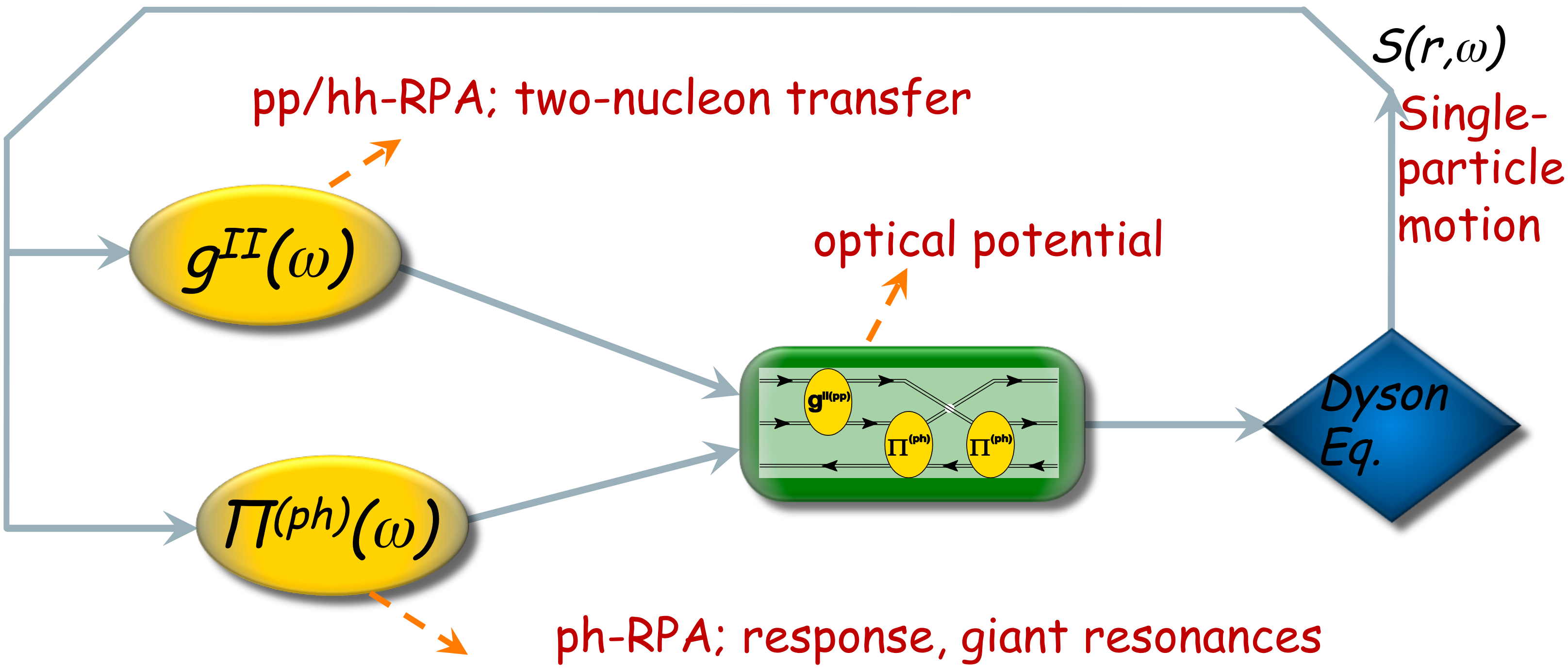
…these modes are all resummed exactly and to all orders in a *ab-initio* many-body expansion.

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



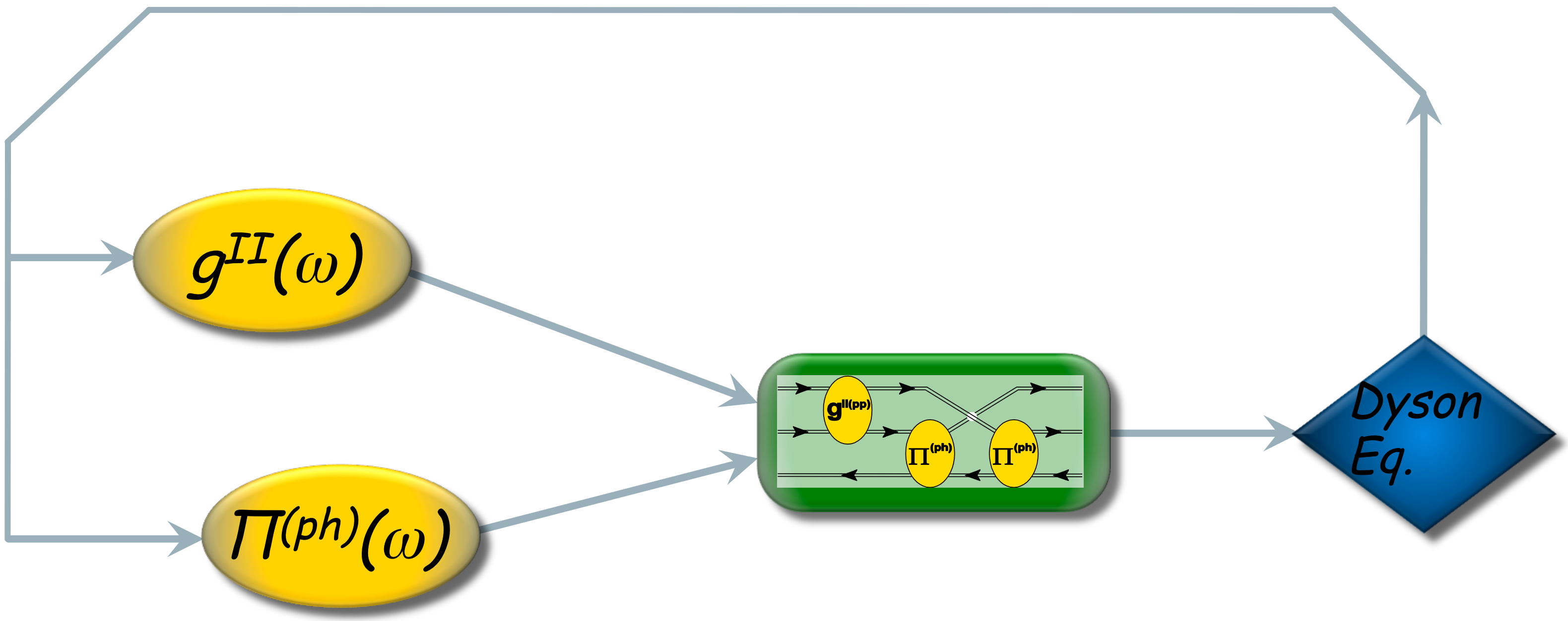


Self-Consistent Green's Function Approach



- Global picture of nuclear dynamics
- Reciprocal correlations among effective modes
- Guaranties *macroscopic conservation laws*

Self-Consistent Green's Function Approach



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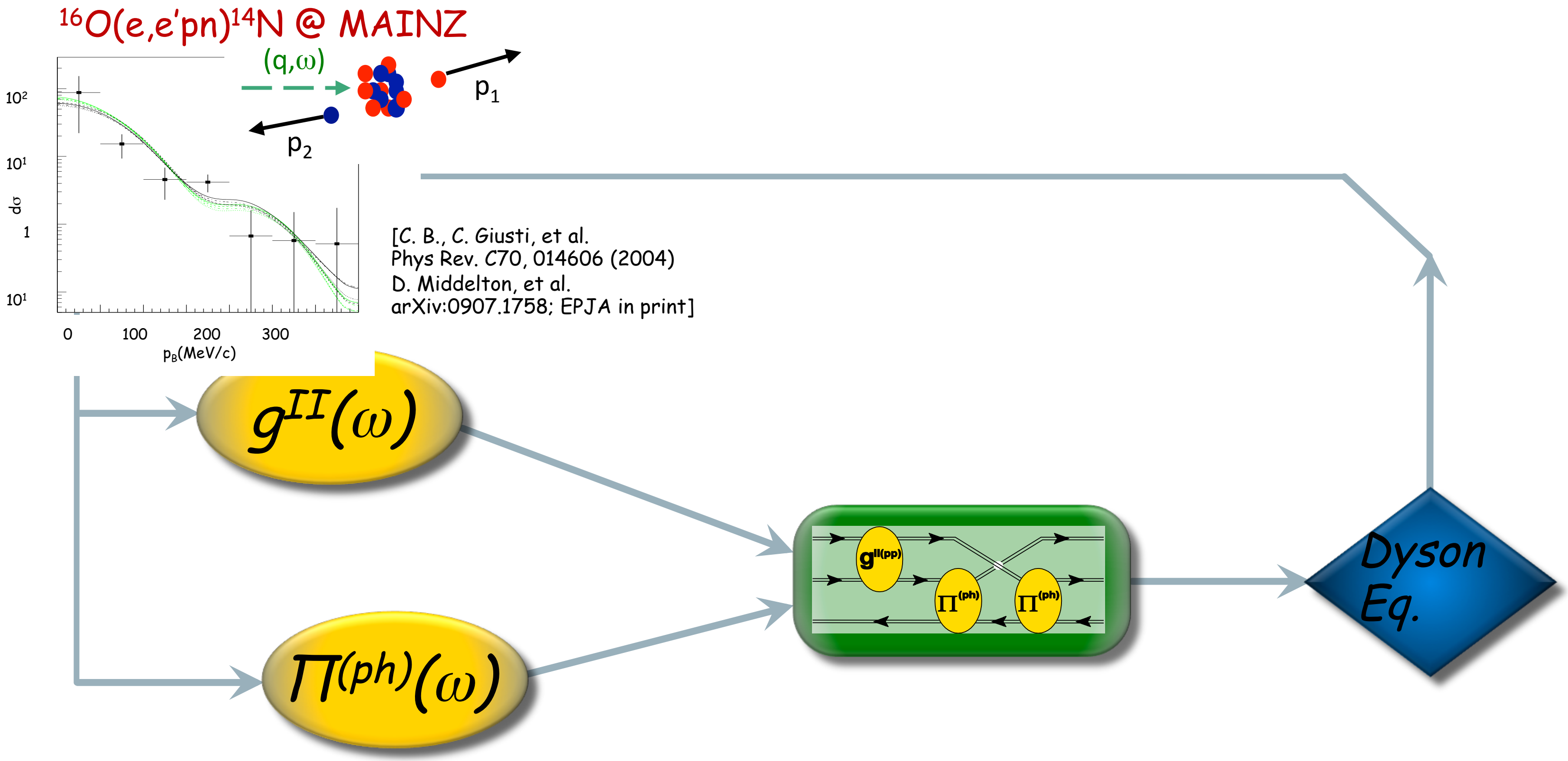
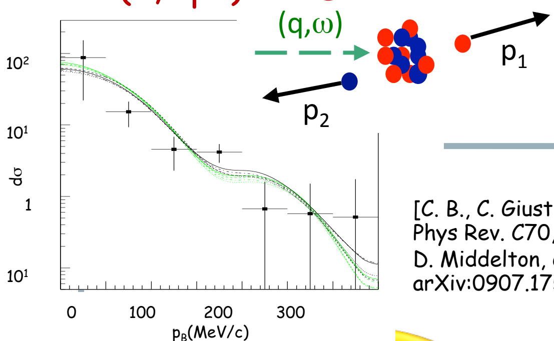


[C. B., C. Giusti, et al.
Phys Rev. C70, 014606 (2004)
D. Middelton, et al.
arXiv:0907.1758; EPJA in print]

Self-Consistent Green's Function Approach

$^{16}O(e,e'pn)^{14}N$ @ MAINZ



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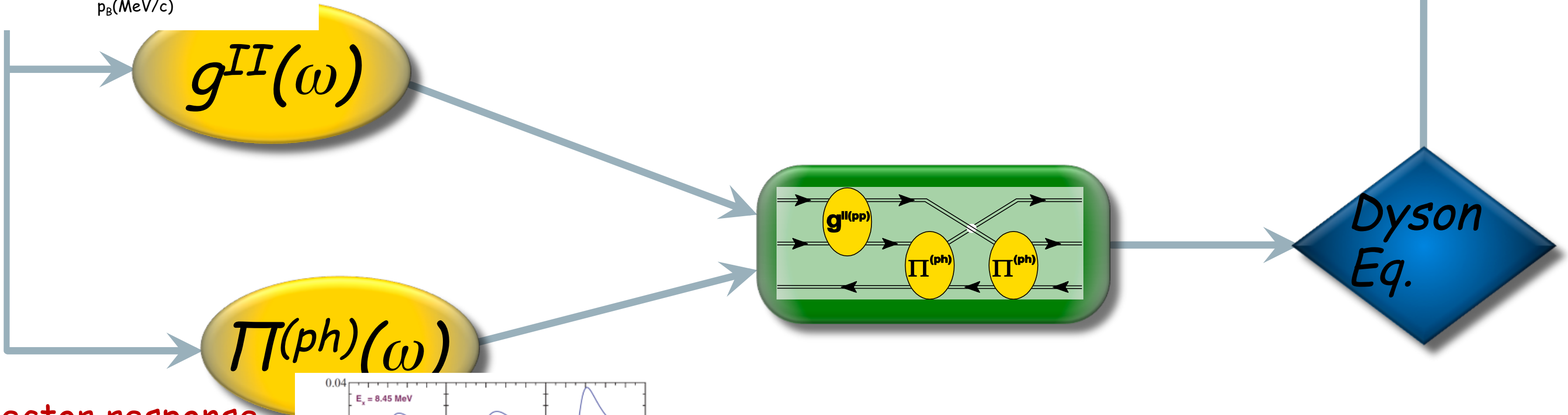
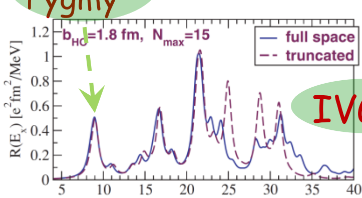
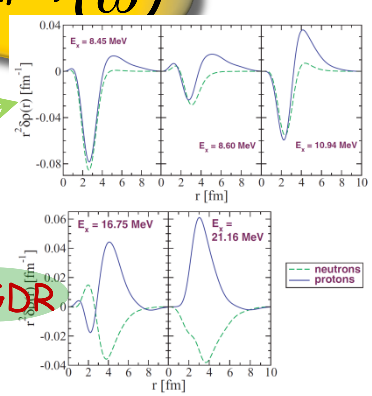


Isovector response for ^{32}Ar, ^{34}Ar

Proton Pygmy





[C. B., K. Langanke, et al., Phys Rev. C77, 024304 (2008)]

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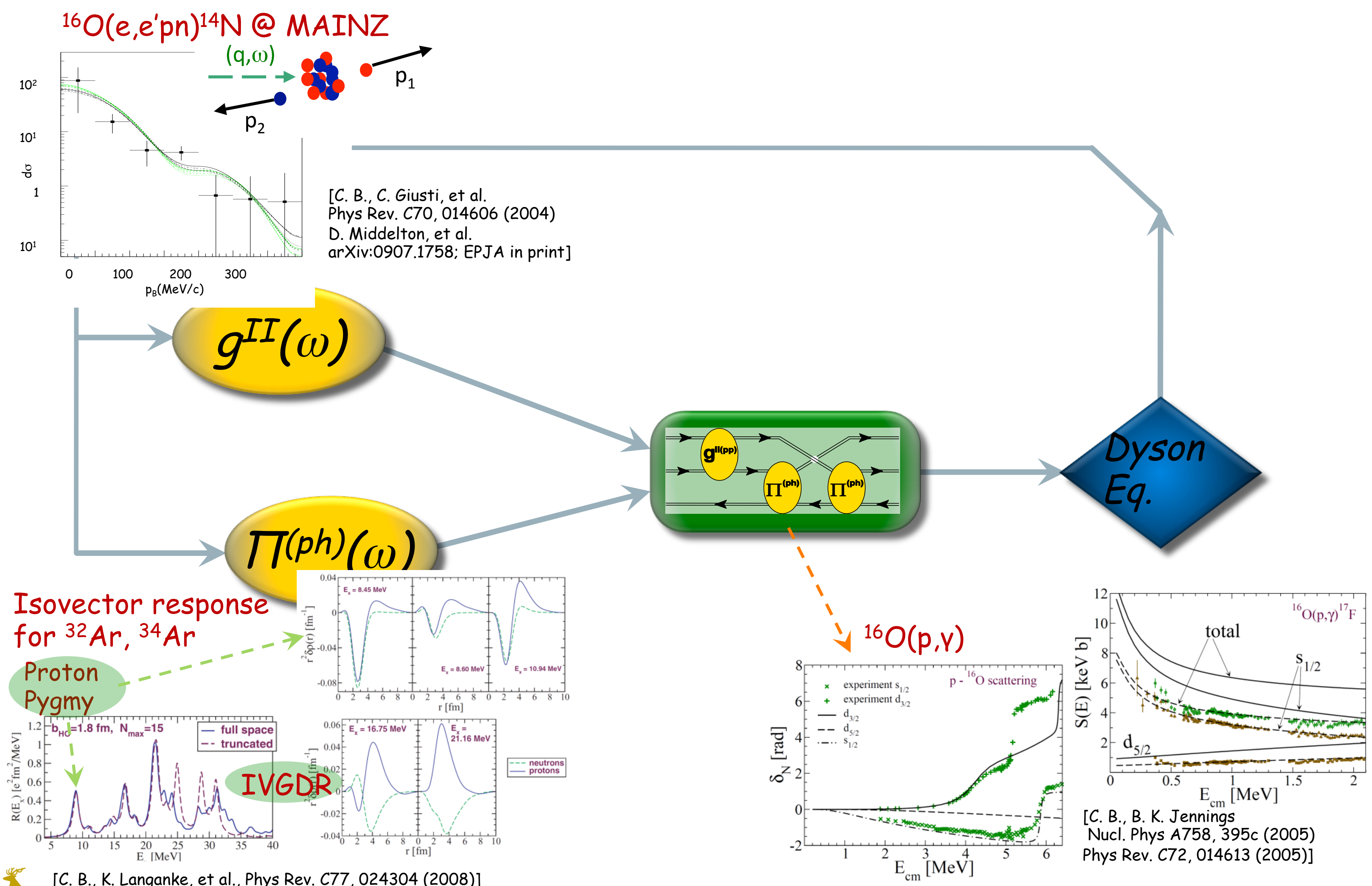

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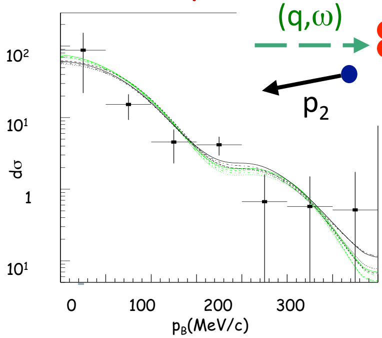

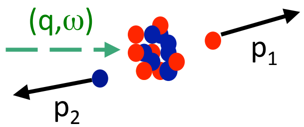

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Ionization energies/ affinities, in atoms

[CB, D. Van Neck,
AIP Conf.Proc.1120,104 ('09) & in prep]

		Hartree-Fock	FRPAc	Experiment [16, 17]
He:	1s	0.918 (+14)	0.9008 (-2.9)	0.9037
Be^{2+}:	1s	5.6672 (+116)	5.6551 (-0.5)	5.6556
Be:	2s	0.3093 (-34)	0.3224 (-20.2)	0.3426
	1s	4.733 (+200)	4.5405 (+8)	4.533
Ne:	2p	0.852 (+57)	0.8037 (+11)	0.793
	1s	1.931 (+149)	1.7967 (+15)	1.782
Mg^{2+}:	2p	3.0068 (+56.9)	2.9537 (+3.8)	2.9499
	1s	4.4827	4.3589	
Mg:	3s	0.253 (-28)	0.280 (-1)	0.281
	2p	2.282 (+162)	2.137 (+17)	2.12
Ar:	3p	0.591 (+12)	0.579 (≈0)	0.579
	3s	1.277 (+202)	1.065 (-10)	1.075
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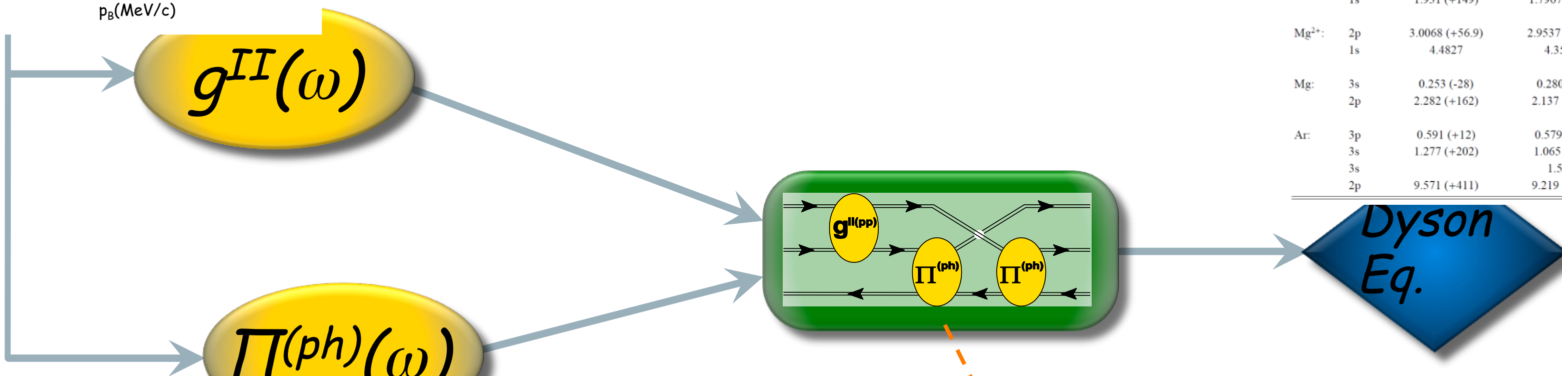

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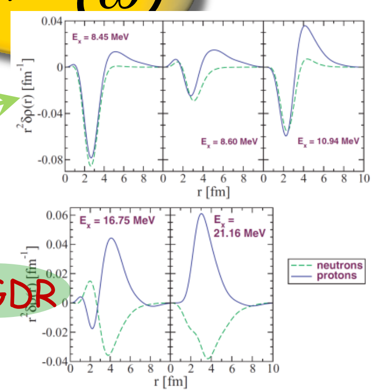
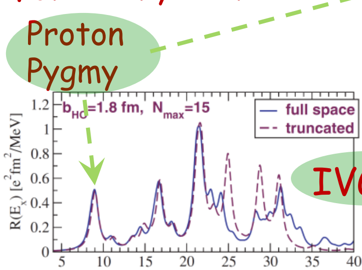
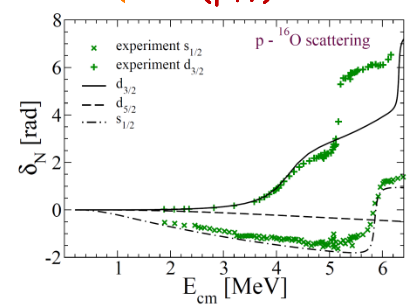
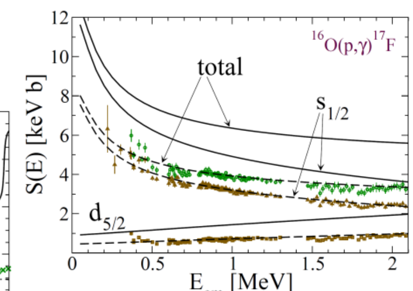




$^{16}O(p,\gamma)$





[C. B., B. K. Jennings
Nucl. Phys A758, 395c (2005)
Phys Rev. C72, 014613 (2005)]

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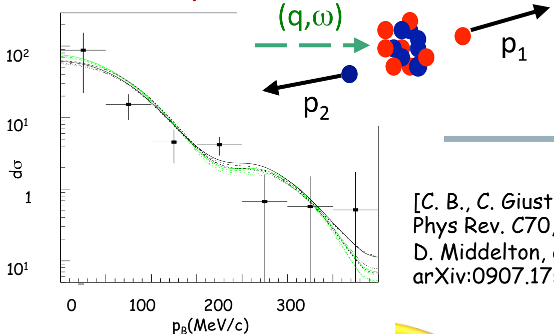

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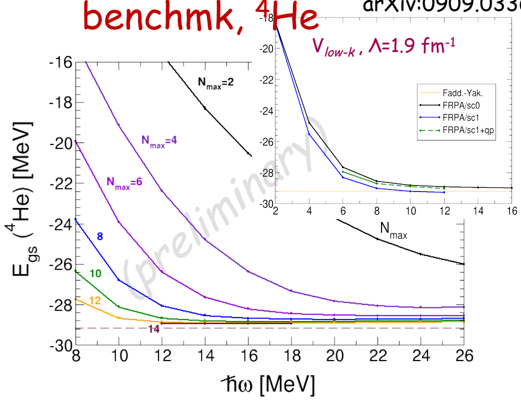
Binding energy benchmk, ^4He

[C. B., arXiv:0909.0336]



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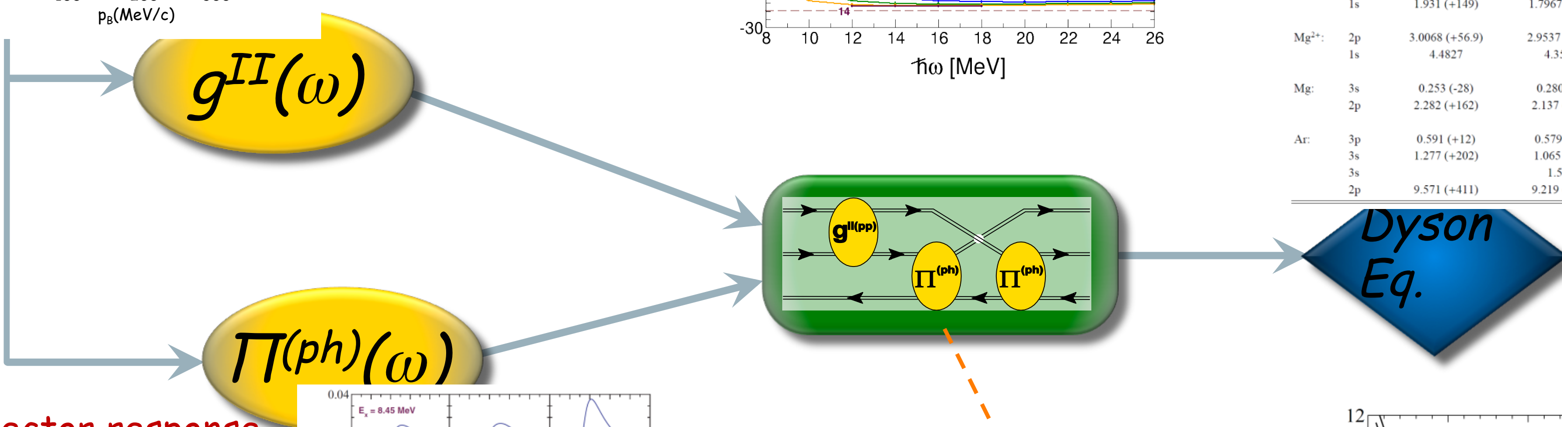

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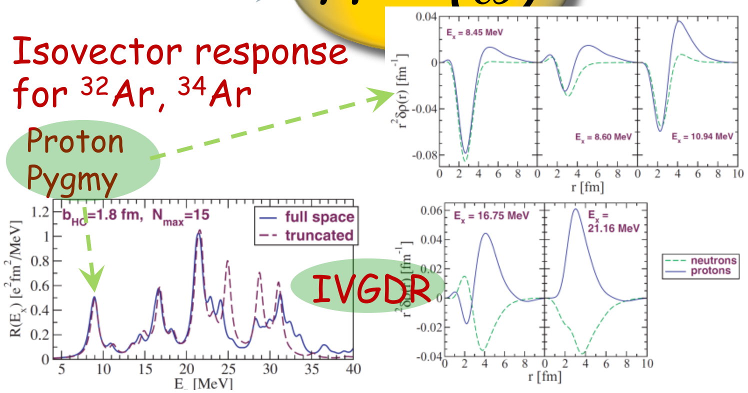

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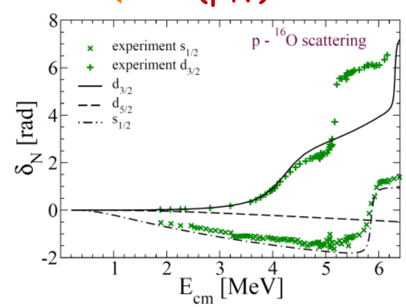
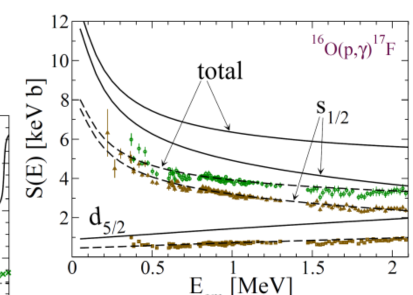
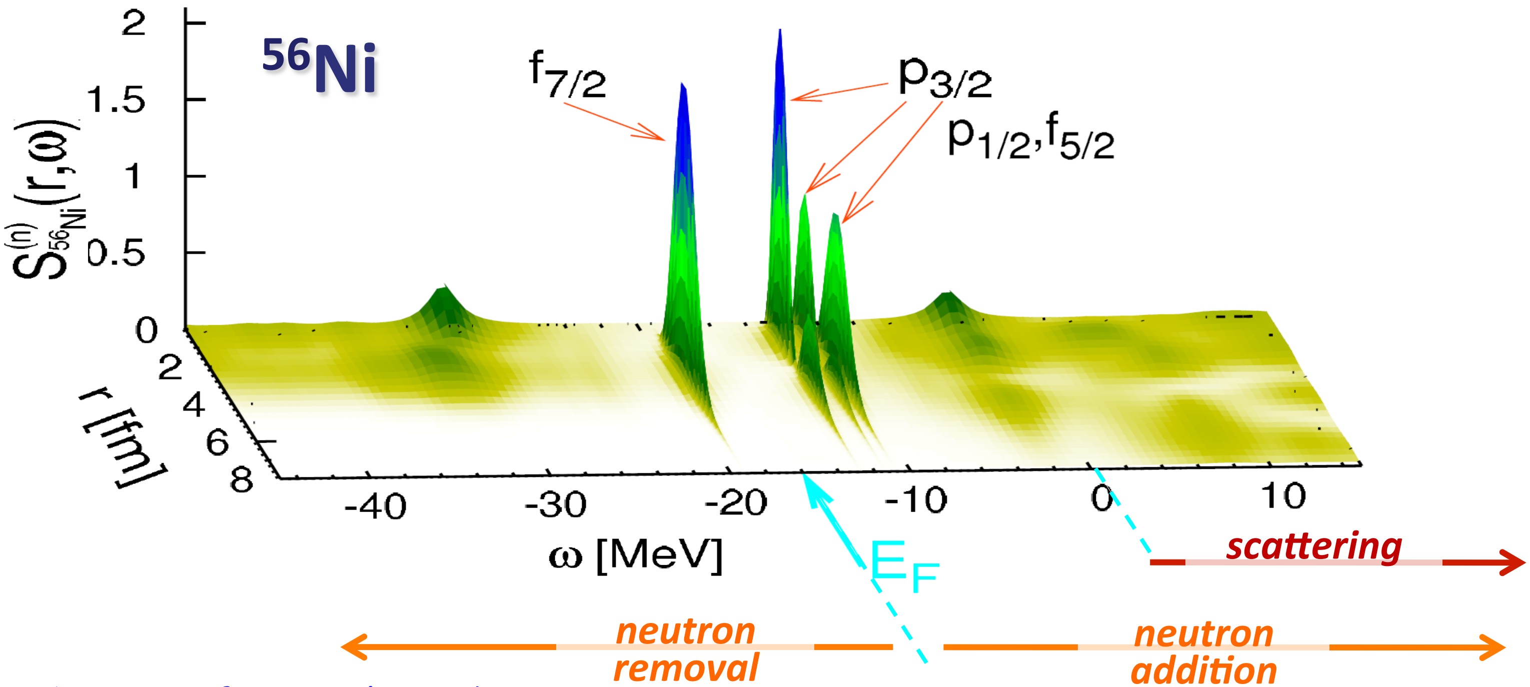




[C. B., B. K. Jennings
Nucl. Phys A758, 395c (2005)
Phys Rev. C72, 014613 (2005)]

One-nucleon spectral function

$$S^{p,h}(r,\omega) = \mp\frac{1}{\pi}\,\mathrm{Im}\,g(r=r';\omega)$$



Distribution of particle and hole neutron states in ^{56}Ni

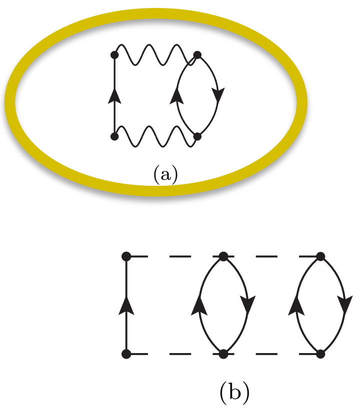
W. Dickhoff, CB, Prog. Part. Nucl. Phys. 53, 377 (2004)
CB, M.Hjorth-Jensen, Pys. Rev. C**79**, 064313 (2009)

Gorkov
and
3-nucleon forces

Inclusion of NNN forces

A. Carbone, CB, et al., Phys. Rev. C**88**, 054326 (2013)
and F. Raimondi, CB, in preparation (2016).

- Second order PT diagrams with 3BFs:



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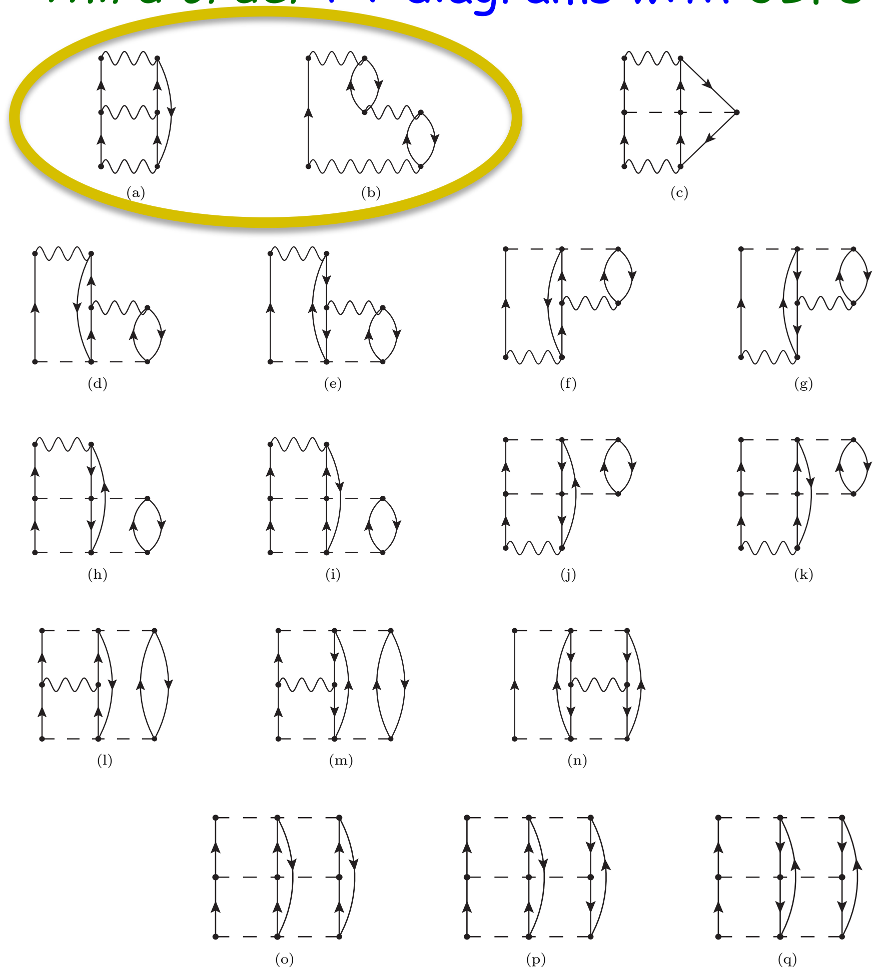


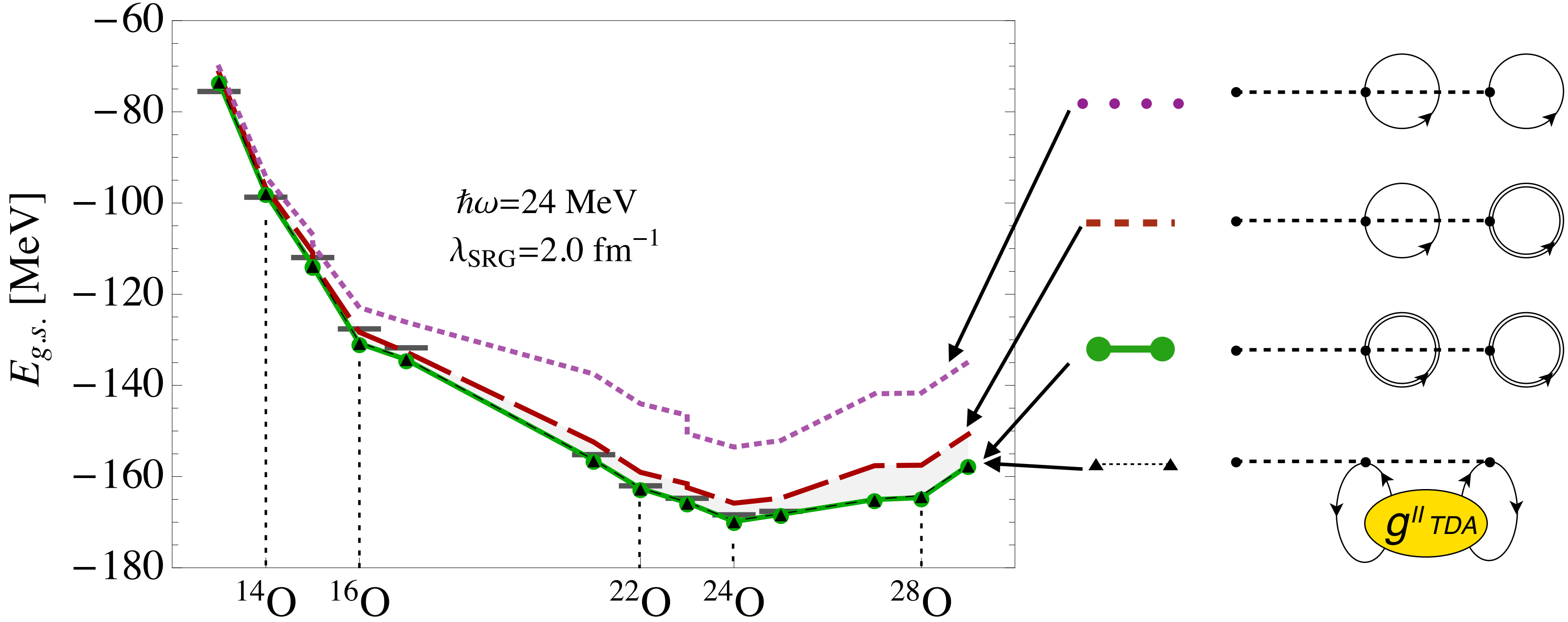
FIG. 5. 1PI, *skeleton* and *interaction irreducible* self-energy diagrams appearing at 3^{rd}-order in perturbative expansion (7), making use of the effective hamiltonian of Eq. (9).

➔ Use of irreducible 2-body interactions

➔ Need to correct the Koltun sum rule (for energy)

3N forces in FRPA/FTDA formalism

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



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

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

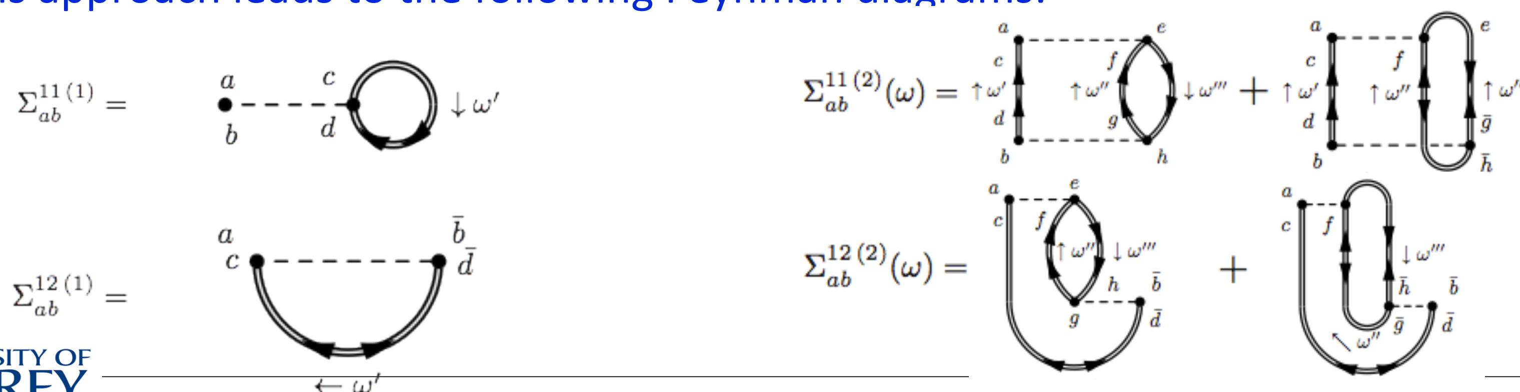
- Auxiliary many-body state $|\Psi_0\rangle \equiv \sum_N^{\text{even}} c_N \, |\psi_0^N\rangle$

  → 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-/doubly-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

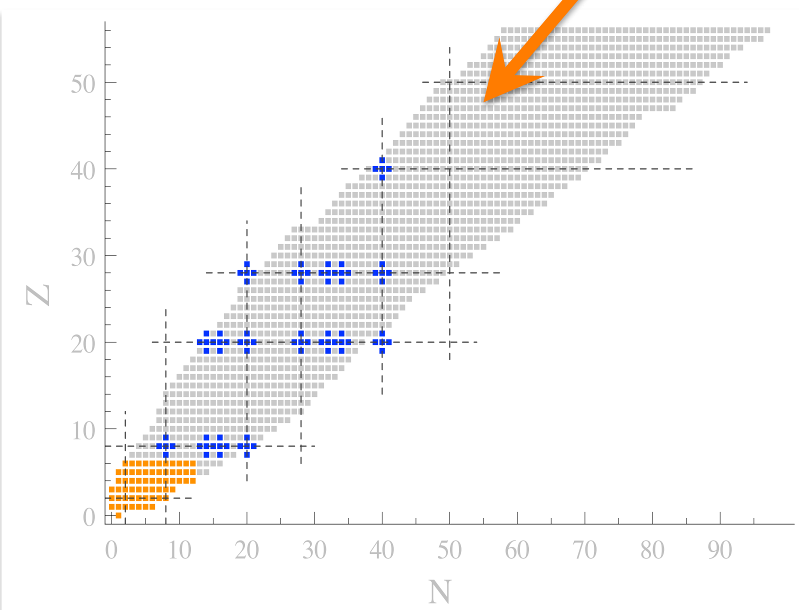
Approaches in GF theory

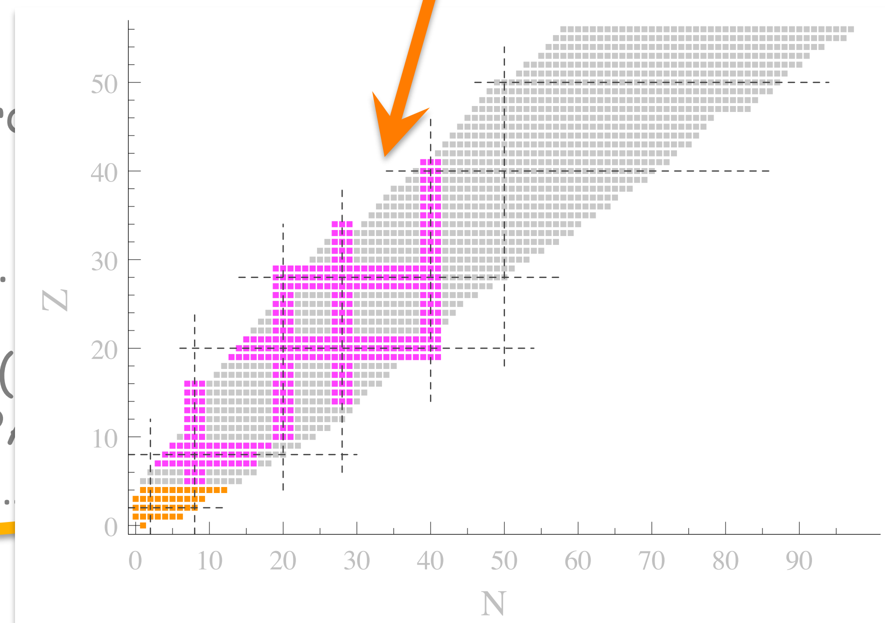
Truncation scheme:

Dyson formulation (closed shells)

Gorkov formulation (semi-/doubly-magic)

1^{st} order: Hartree-Fock HF-Bogolioubov





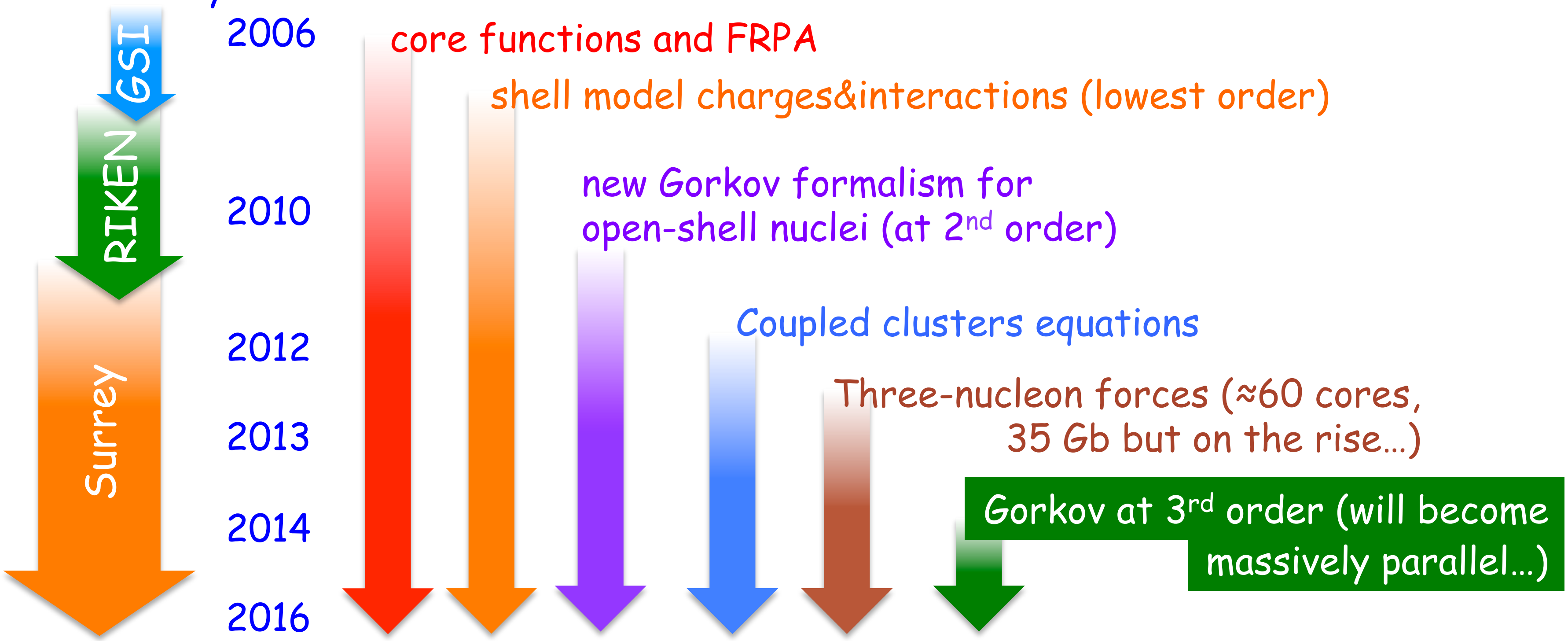
pics. credits: V. Somà

Ab-initio Nuclear Computation & BcDor code

BoccaDorata code:
(C. Barbieri 2006-16
V. Somà 2010-15
A. Cipollone 2011-14)

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

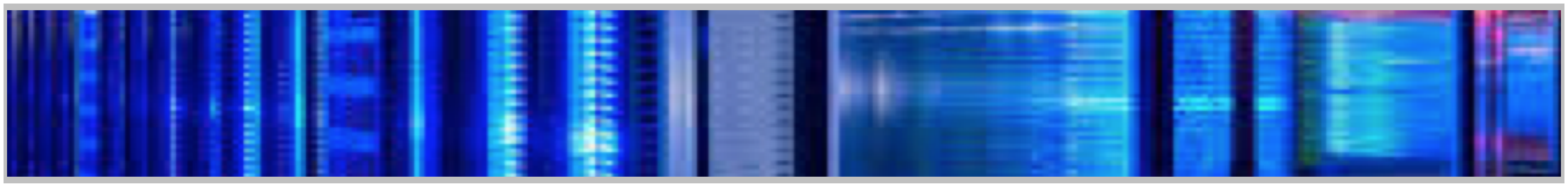
Code history:

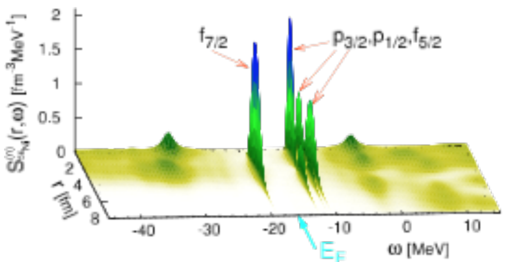


Ab-initio Nuclear Computation & BcDor code

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

Computational Many-Body Physics





Download

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.

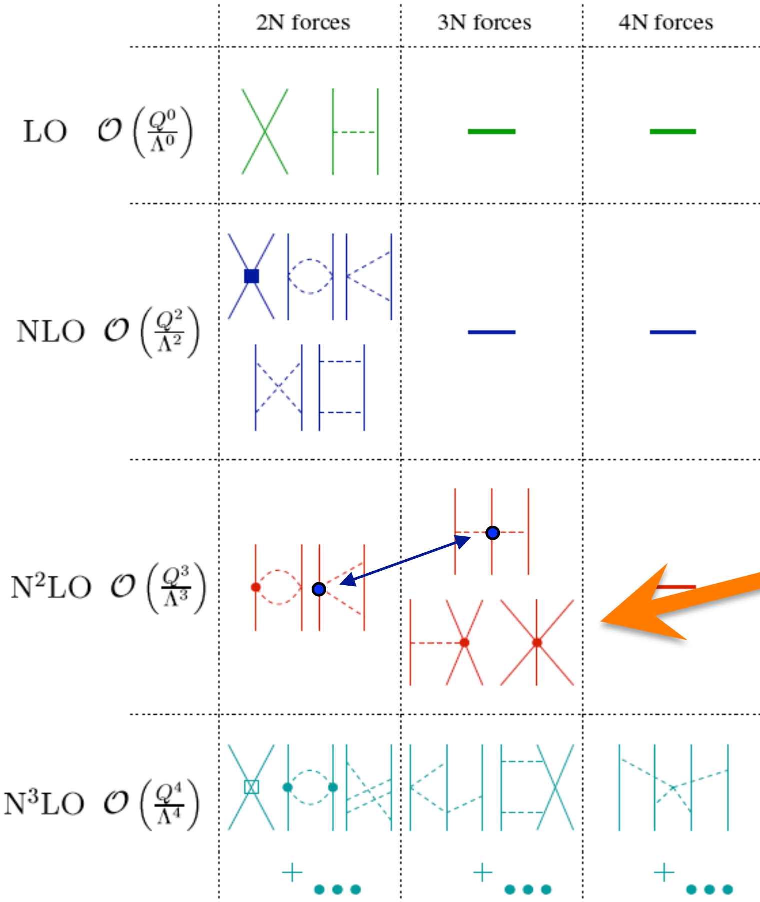
Relevant references (which can also help in using this code) are:

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

Chiral interactions for mid-mass isotopes

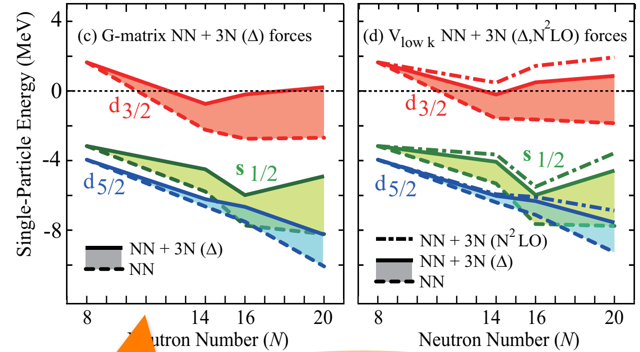
Modern realistic nuclear forces

Chiral EFT for nuclear forces:



(3NFs arise naturally at N2LO)

Single particle spectrum at E_{fermi}:

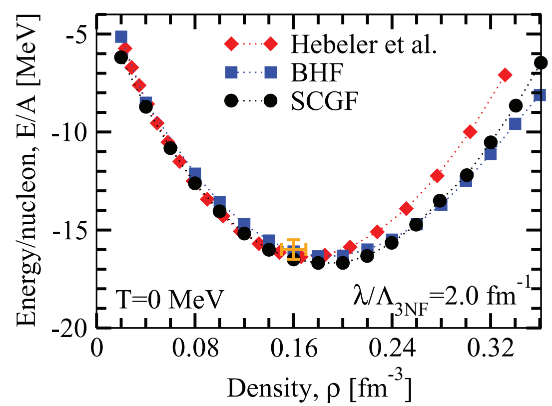


[T. Otsuka et al., Phys Rev. Lett **105**, 032501 (2010)]

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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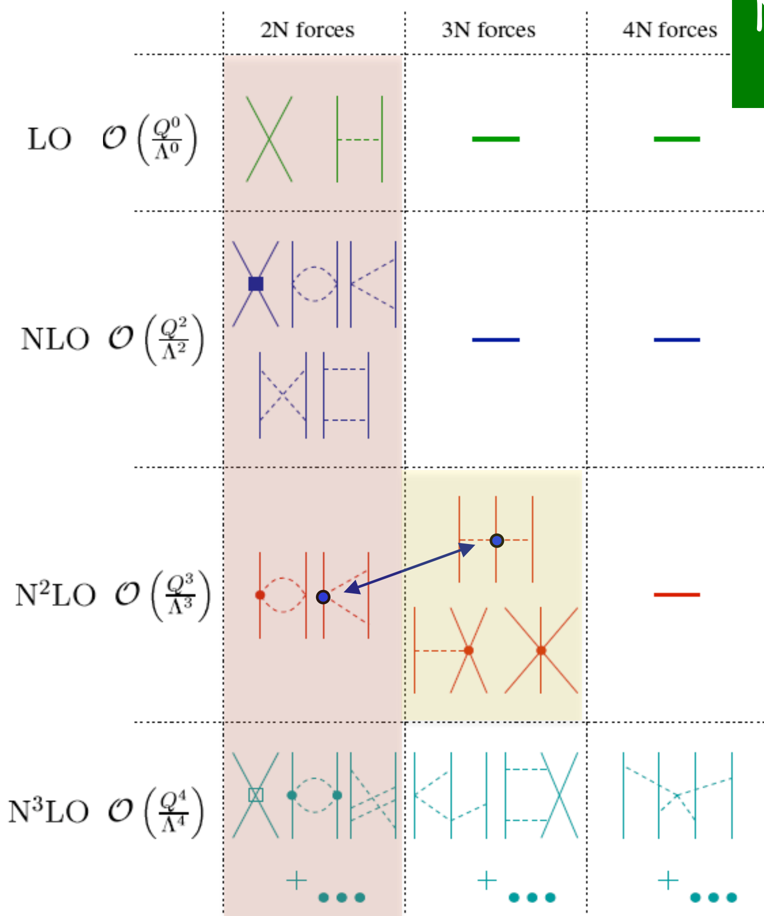
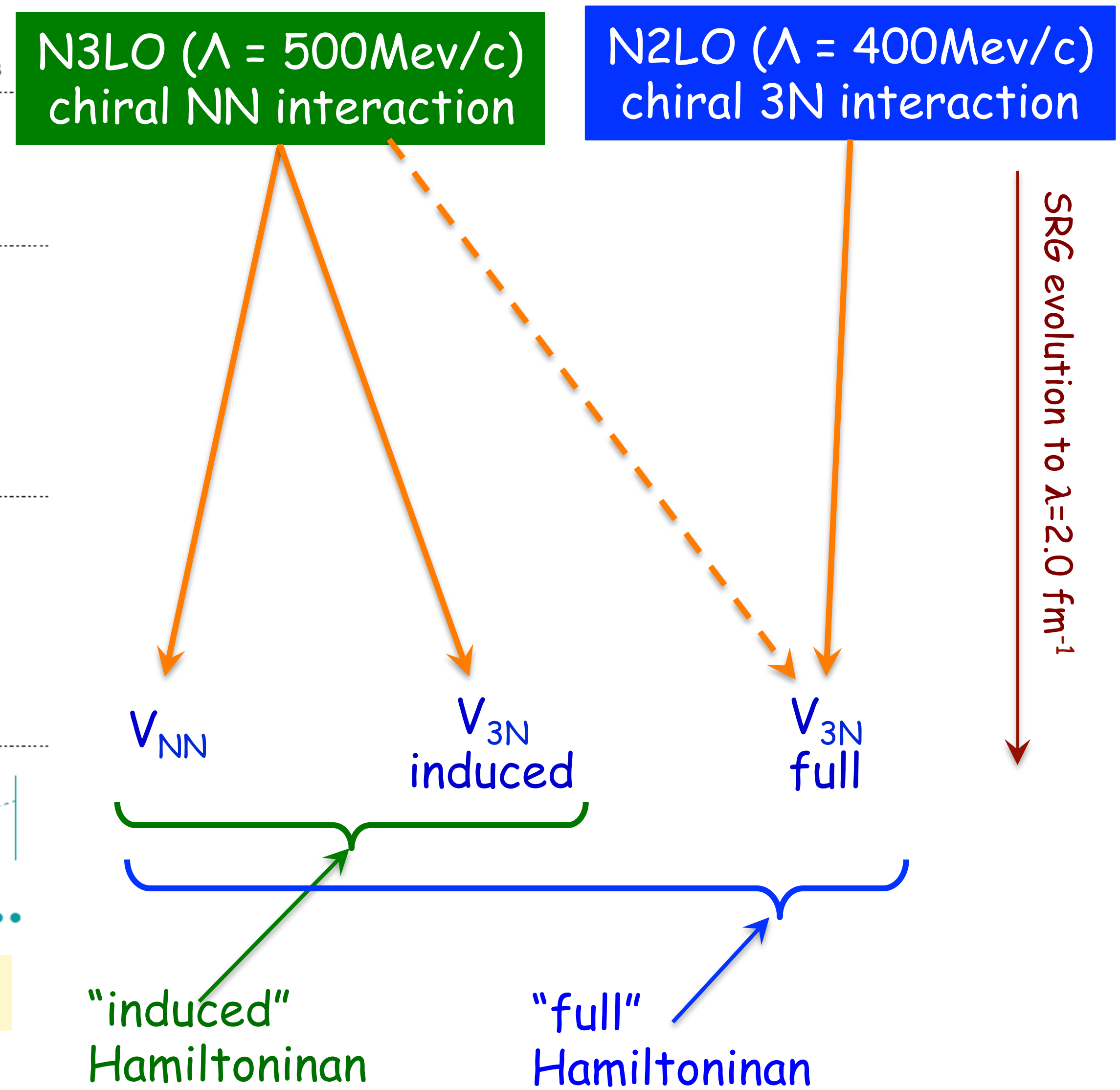
Chiral Nuclear forces - SRG evolved

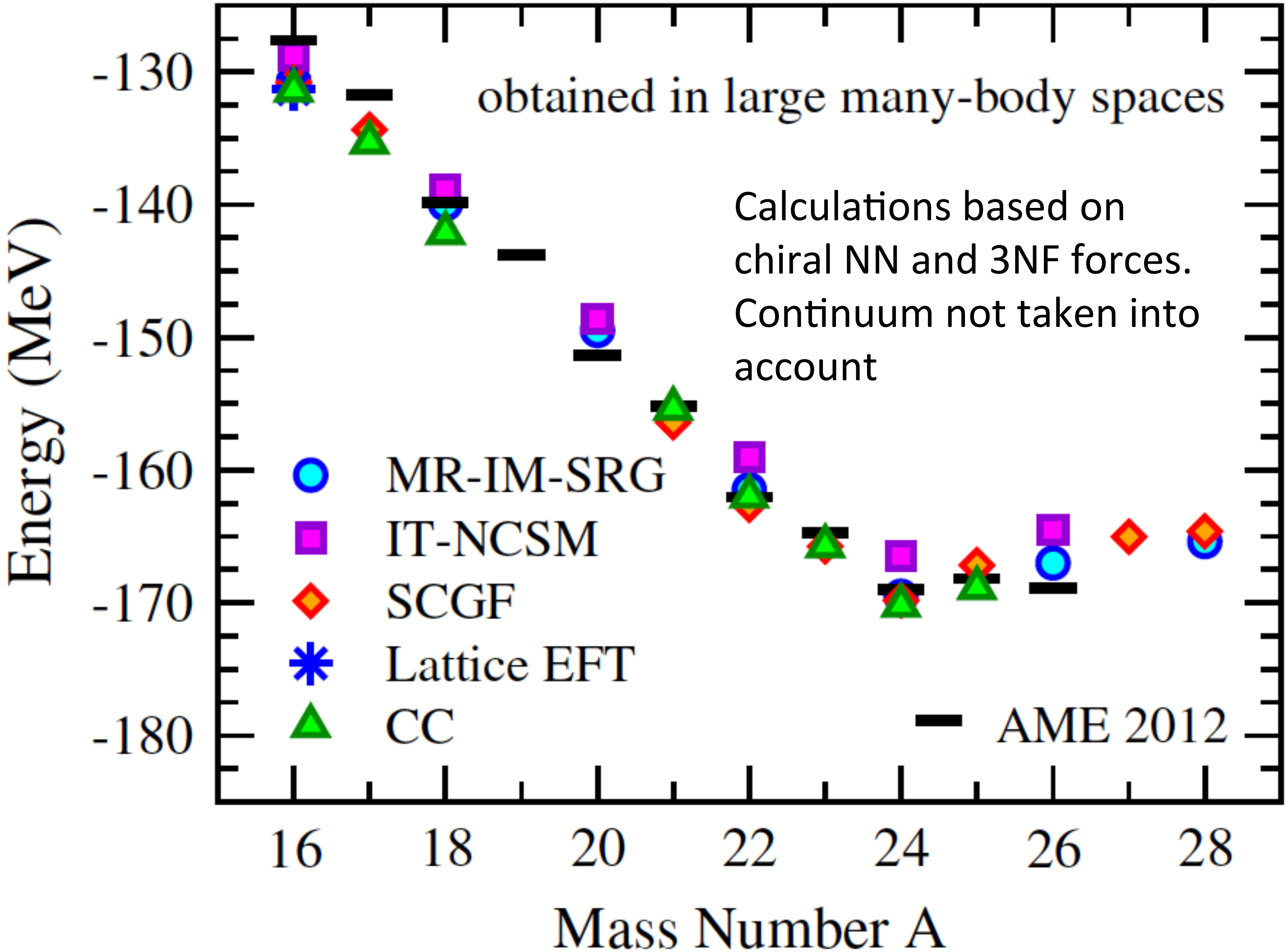




(3NFs arise naturally at N2LO)

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

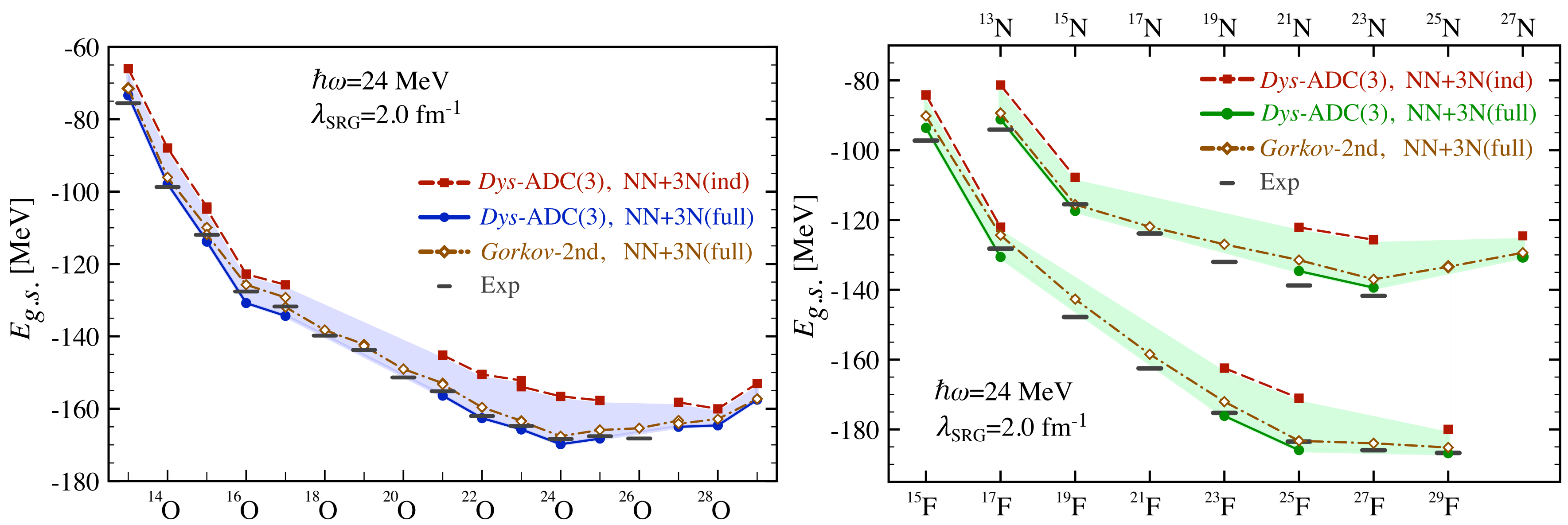
Benchmark of ab-initio methods in the oxygen isotopic chain



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 Phys. Rev. C **92**, 014306 (2015)



→ 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})

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

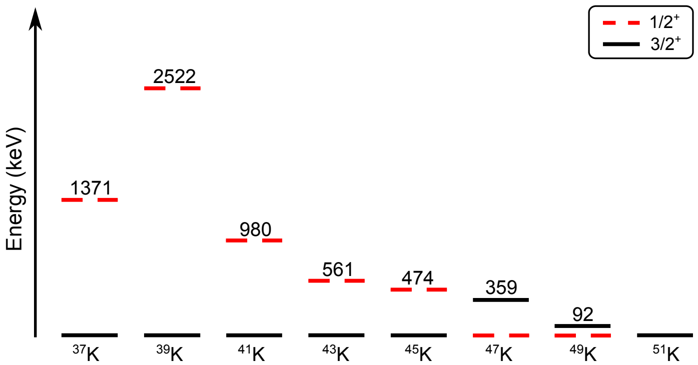


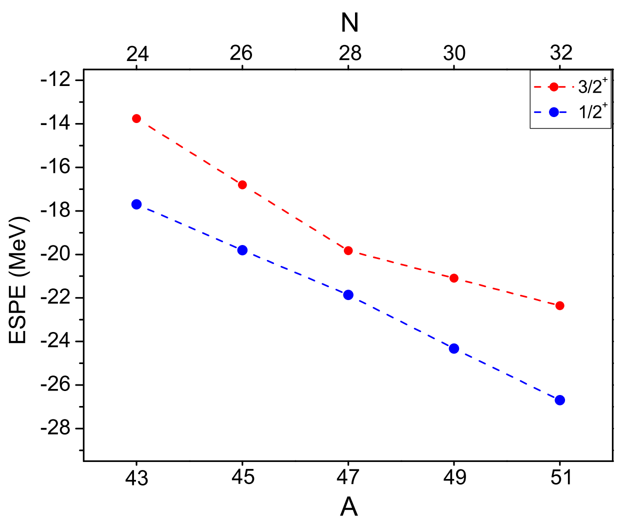
FIG. 1. (color online) Experimental energies for $1/2^+$ and $3/2^+$ states in odd-A K isotopes. Inversion of the nuclear spin is obtained in ^{47,49}K and reinversion back in ^{51}K. Results are

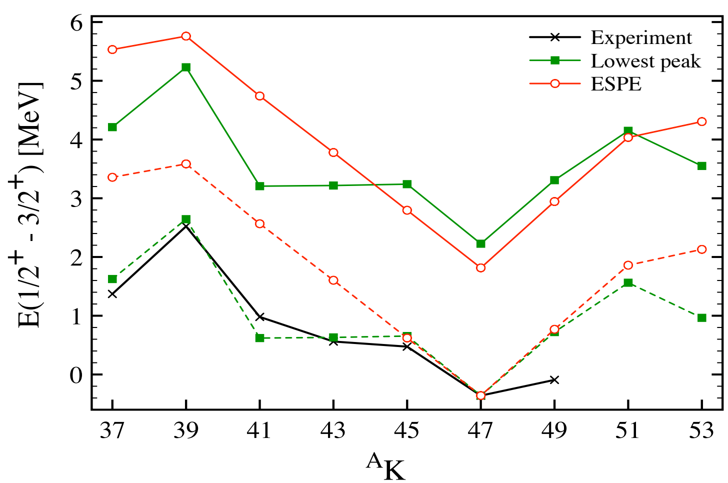
J. Papuga, et al., Phys. Rev. Lett. **110**, 172503 (2013);
J. Papuga, CB, et al., Phys. Rev. C **90**, 034321 (2014)

^{A}K isotopes

Laser spectroscopy @ ISOLDE

Change in separation described by chiral NN[EM(500)]+3NF[N2LO(400)]:





ESPE: "centroid" energies

(Gorkov calculations at 2nd order)

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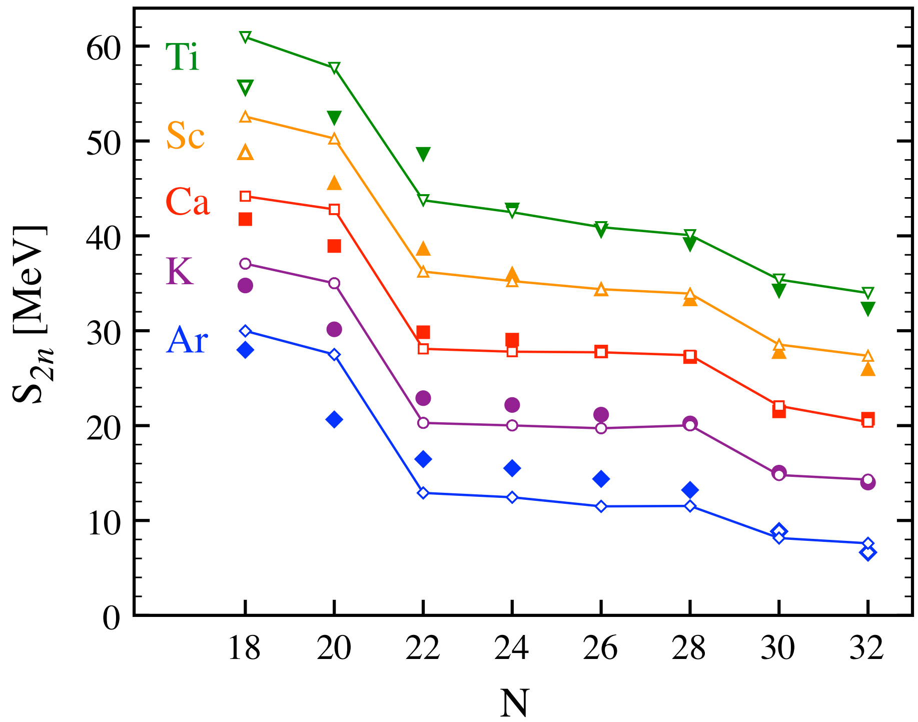
Neighbouring Ar, K, Ca, Sc, and Ti chains

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

Two-neutron separation energies predicted by chiral NN[EM(500)]+3NF[N2LO(400)]:



→ 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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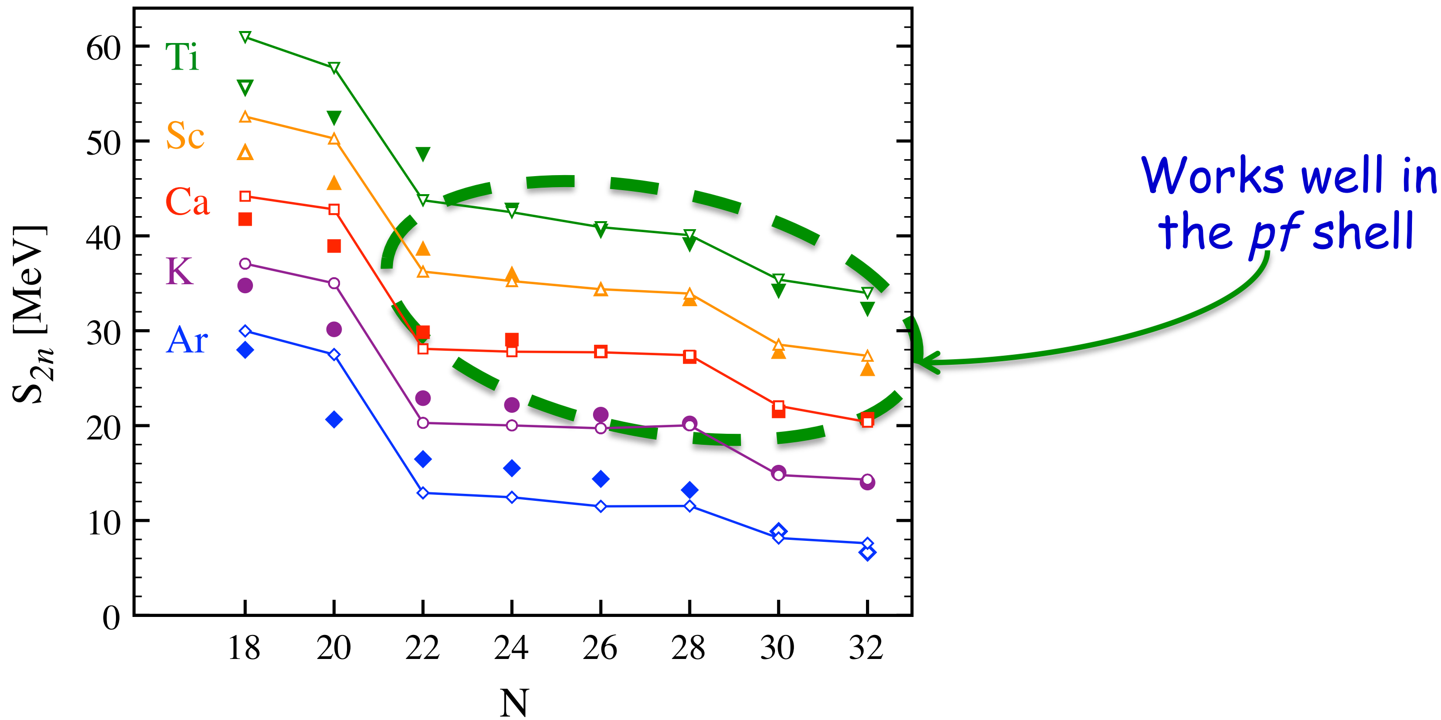

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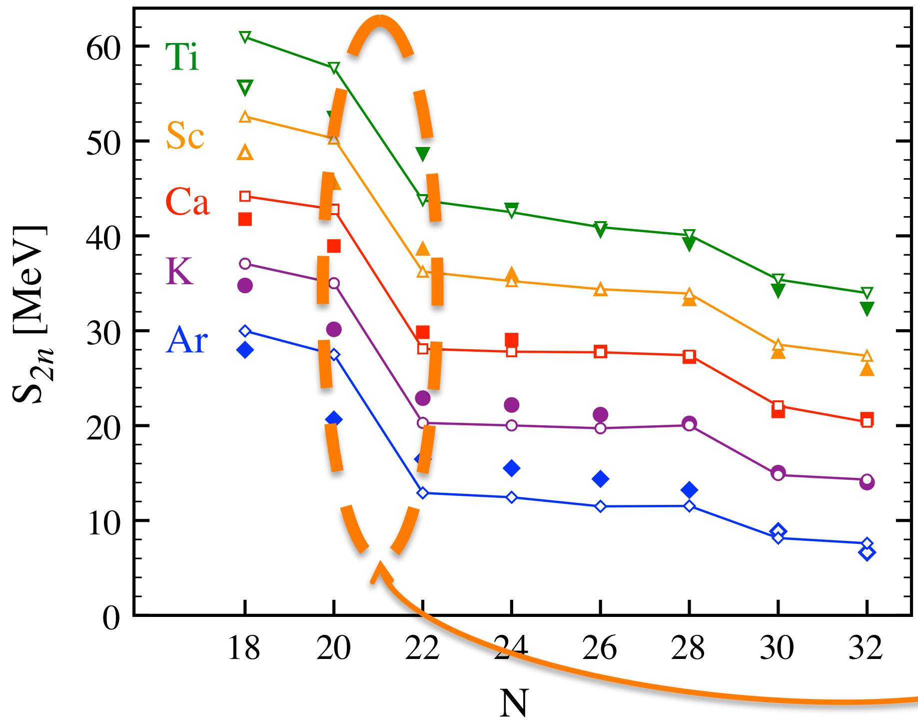


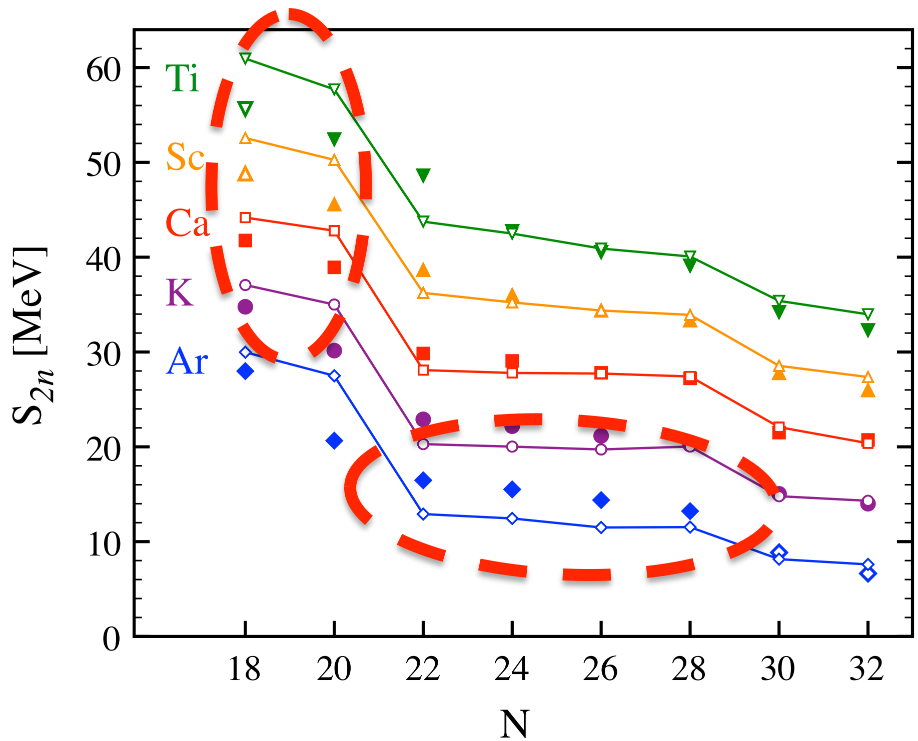
Over estimated
N=20 and Z=20 gaps

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

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[EM(500)]+3NF[N2LO(400)]:

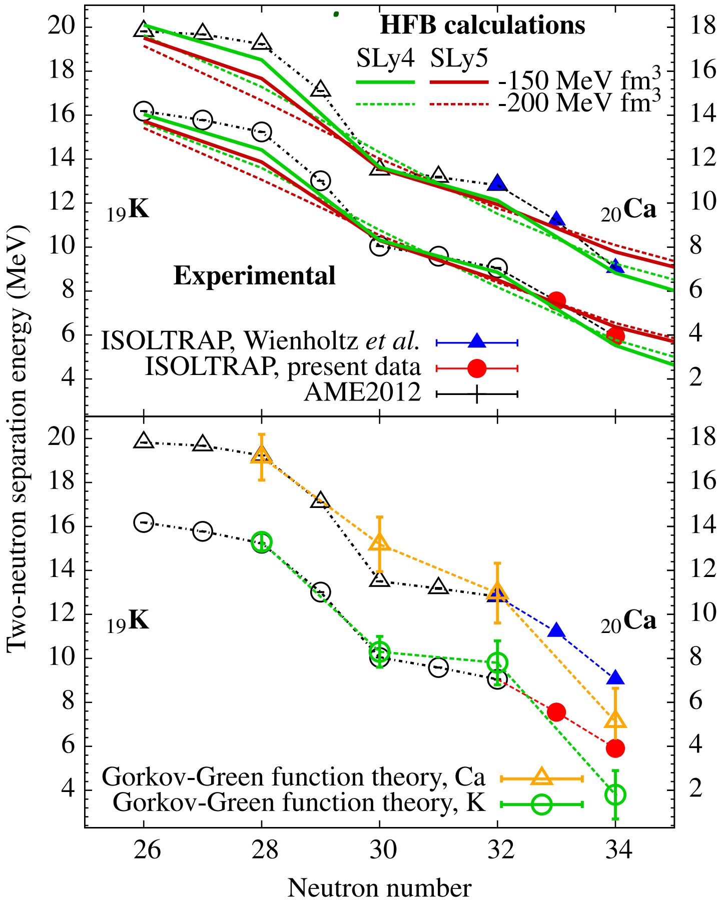


Lack of deformation due to quenched cross-shell quadrupole excitations

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

Two-neutron separation energies for neutron rich K isotopes

*M. Rosenbusch, CB, 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.

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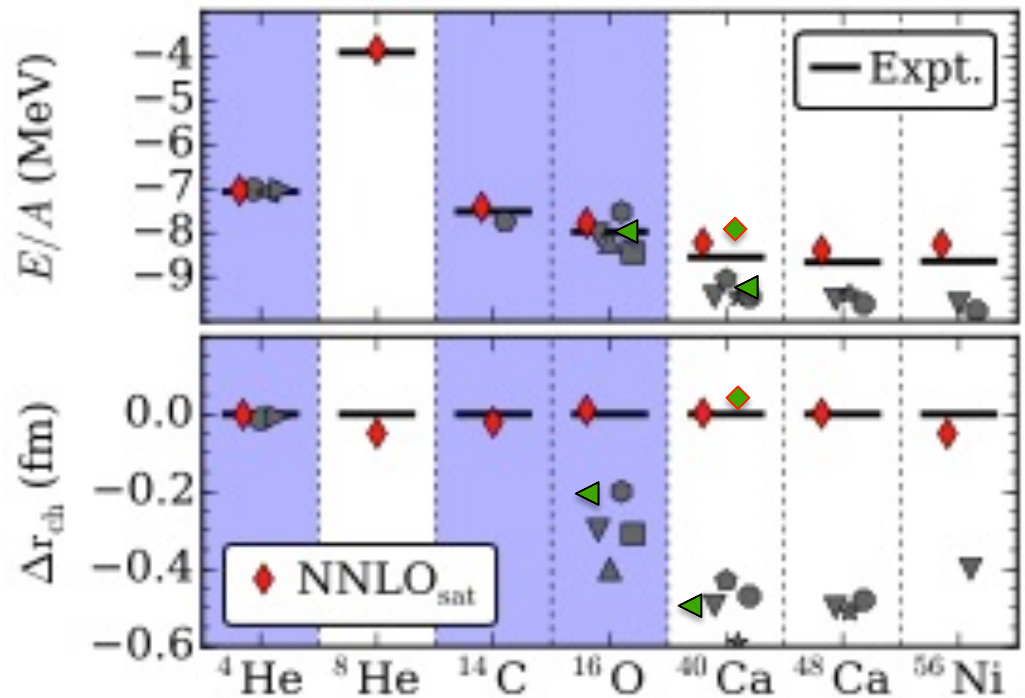
NNLO-sat : a global fit up to A≈24

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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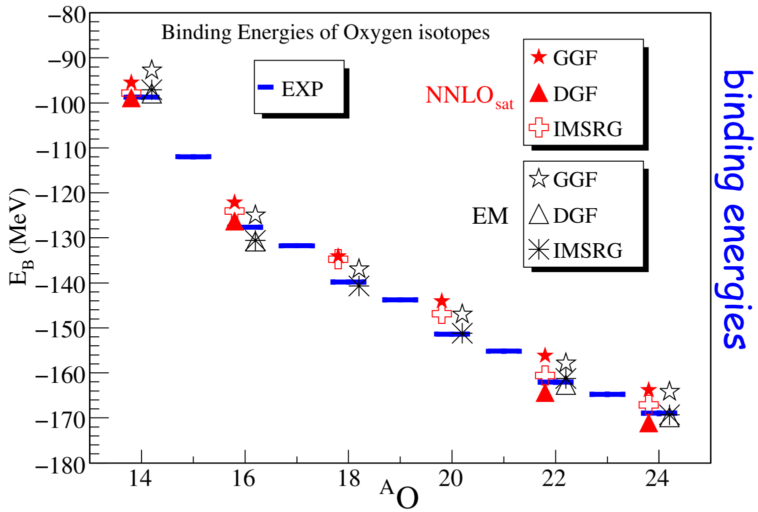
PRL **117,** 052501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JULY 2016

Radii and Binding Energies in Oxygen Isotopes: A Challenge for Nuclear Forces

V. Lapoux,[1,*] V. Somà,[1] C. Barbieri,[2] H. Hergert,[3] J. D. Holt,[4] and S. R. Stroberg[4]

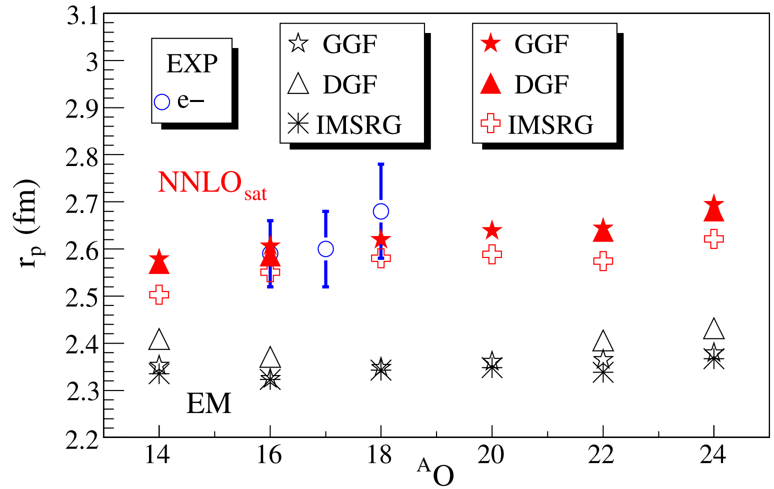
- New fits of chiral interactions (NNLOsat) highly improve comparison to data

- Deficiencies remain for neutron rich isotopes

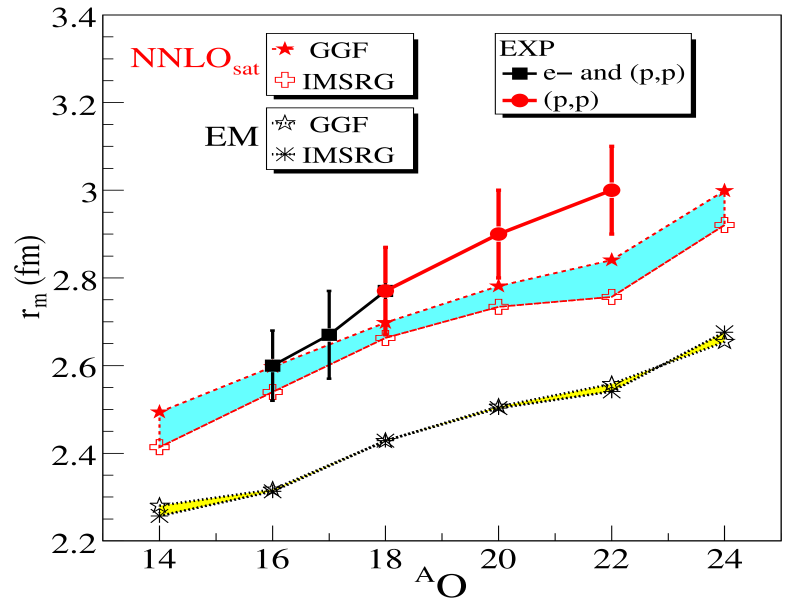


binding energies

FIG. 1. Oxygen binding energies. Results from SCGF and IMSRG calculations performed with EM [20–22] and NNLO$_{sat}$ [26] interactions are displayed along with available experimental data.



proton radii



matter radii

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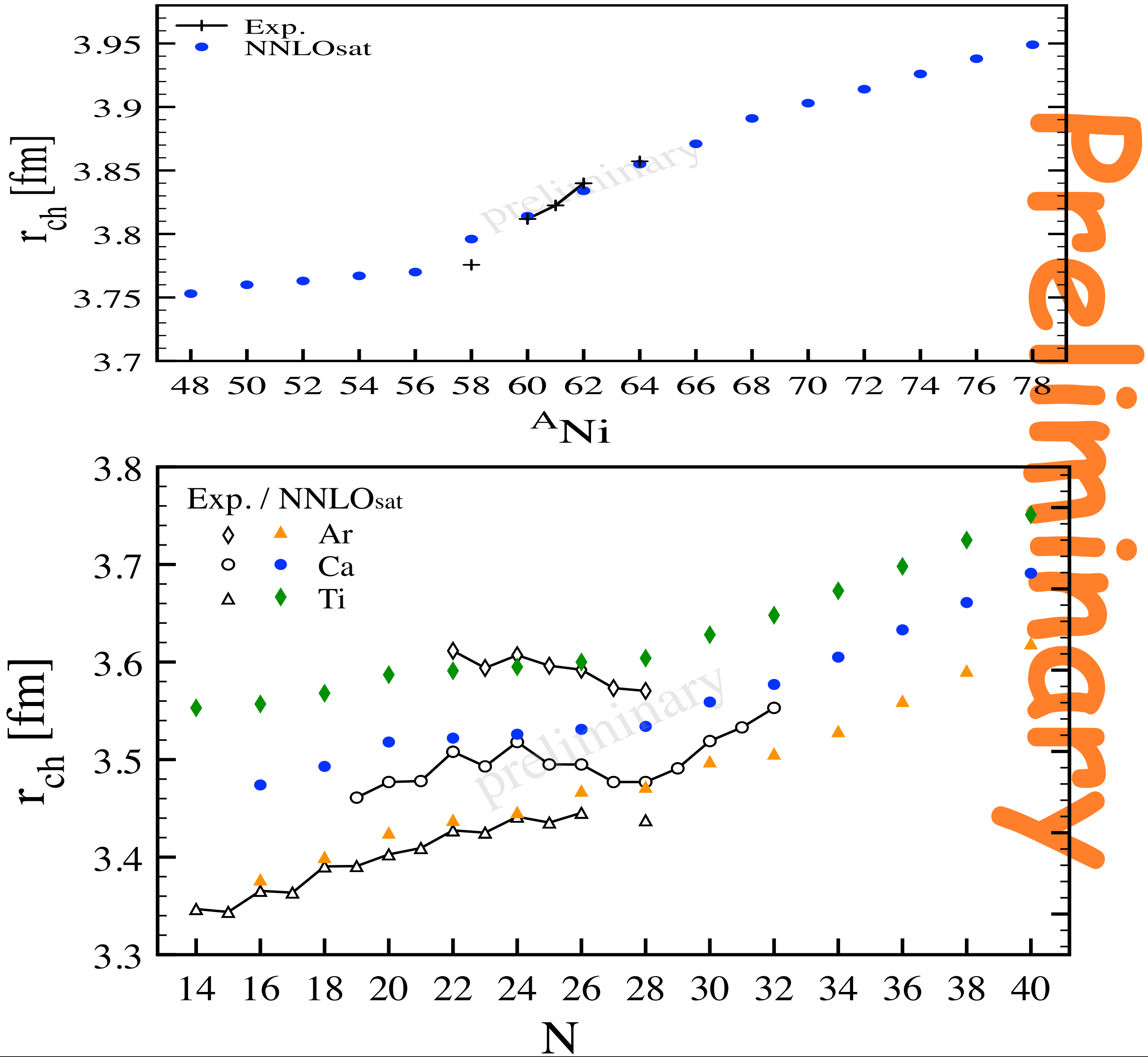
charge radii in the pf shell

Size of radii not prefect but remains overall correct throughout the ***pf*** shell with NNLO-sat.

This suggests that saturation is indeed under control.

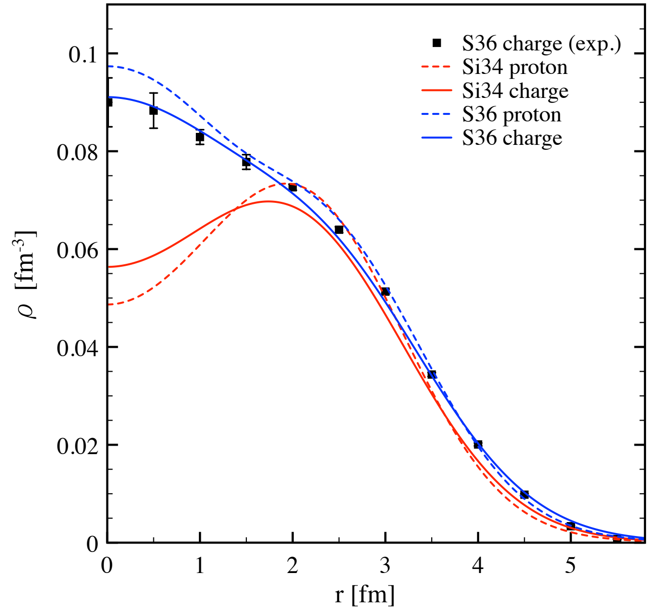
➔ Improvements of many-body truncations beyond 2nd order Gorkov will also be relevant.

(work in progress!)



Bubble nuclei... ^{34}Si prediction

[Simon Lecluse, V. Somà, T. Duguet, CB, P. Navrátil]

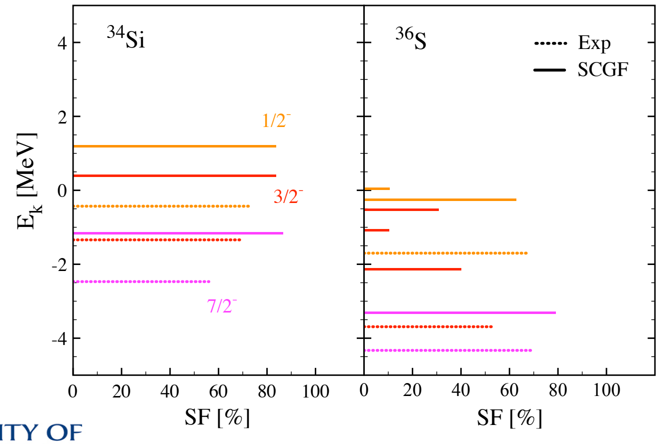


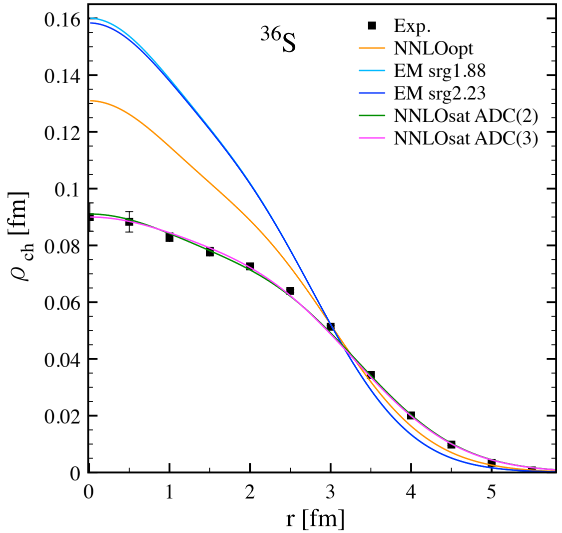
- ^{34}Si is unstable, charge distribution still unknown

- Suggested central depletion from mean-field simulations

- *Ab-initio* theory confirms predictions

Validated by charge distributions and neutron quasiparticle spectra:





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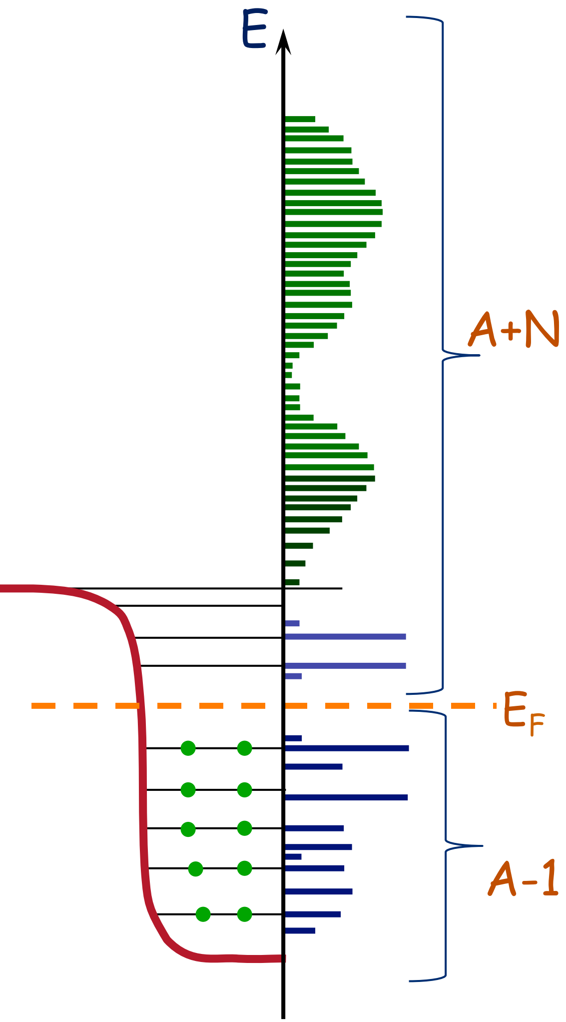
Ab-initio optical potentials



Nuclear self-energy $\Sigma^\star(\mathbf{r},\mathbf{r}';\varepsilon)$

- contains *both particle* and *hole* props.
- it is proven to be a Feshbach opt. pot
  → in general it is *non-local !*
- *must* satisfy the dispersion relation:

$$\Sigma^\star(\mathbf{r},\mathbf{r}';\varepsilon) = \Sigma^{HF}_{\alpha\beta} \; - \; \frac{1}{\pi}\int_{\varepsilon_T^>}^{\infty} dE' \, \frac{Im\,\Sigma^\star(\mathbf{r},\mathbf{r}';E')}{\varepsilon - E' + i\eta}$$

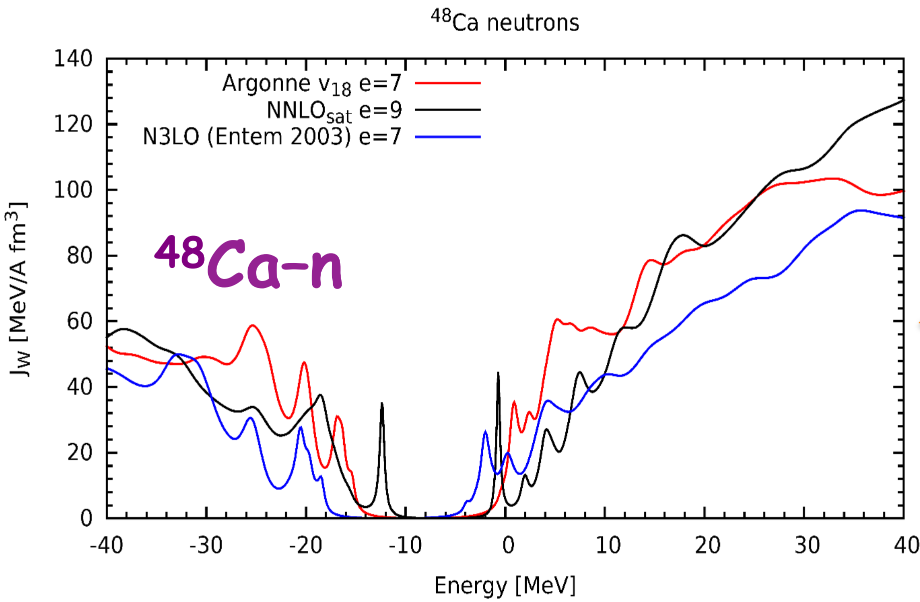
$$+\frac{1}{\pi}\int_{-\infty}^{\varepsilon_T^<} dE' \, \frac{Im\,\Sigma^\star(\mathbf{r},\mathbf{r}';E')}{\varepsilon - E' - i\eta}$$

$$\frac{1}{x \pm i\eta} = \mathcal{P}\frac{1}{x} \;\mp\; i\pi\delta(x)$$

$$\theta(\pm\tau) = \mp \lim_{\eta\to 0^+} \frac{1}{2\pi i}\int_{-\infty}^{+\infty} d\omega \frac{e^{-i\omega\tau}}{\omega \pm i\eta}$$

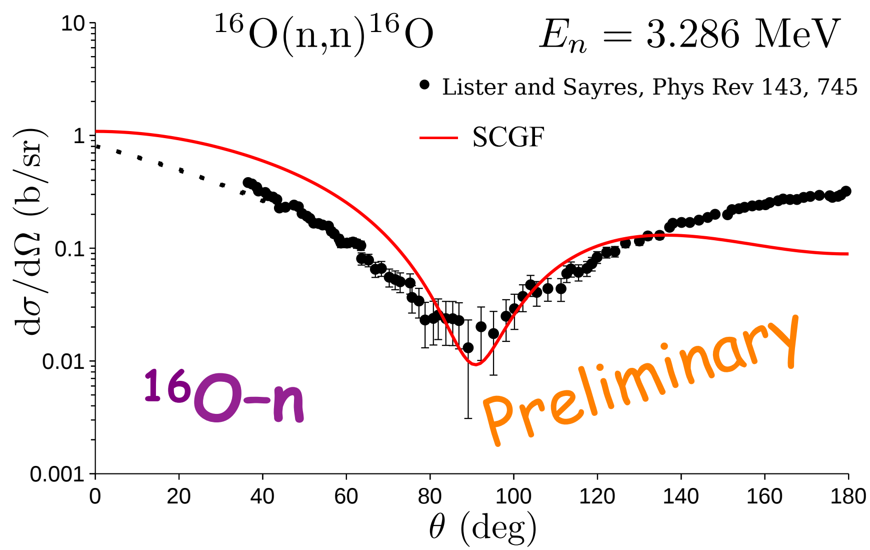
proper boundary conditions are driven by the causality principle

Ab-initio optical potentials



Overall absorption from OP (integral of imaginary part)

Low energy scattering



[Andrea Idini, CB, in prep]

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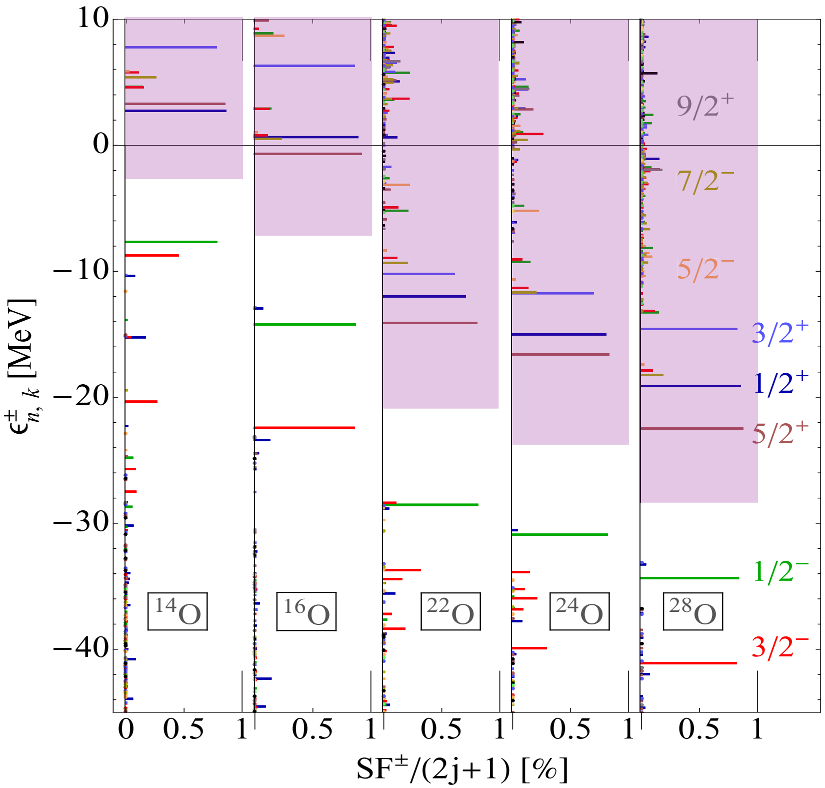
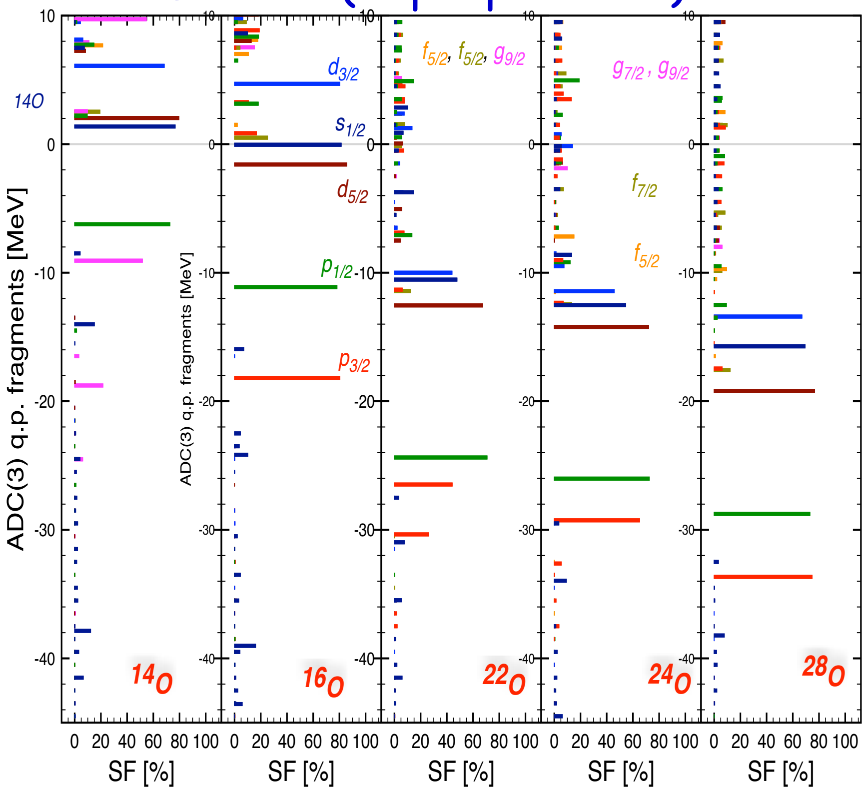
Proton spectral strength in Oxygen

A. Cipollone, CB, P. Navrátil, Phys. Rev. Lett. **111**, 062501 (2013)
and Phys. Rev. C **92**, 014306 (2015)
and ***in preparation***

EM-N3LO(500)/3NF-NNLO(400)



NNLO-sat (in preparation)



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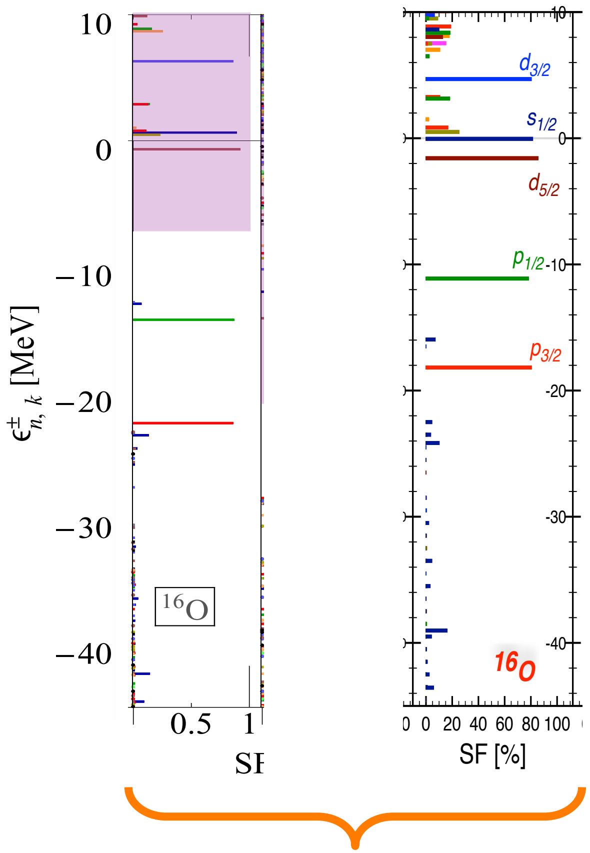
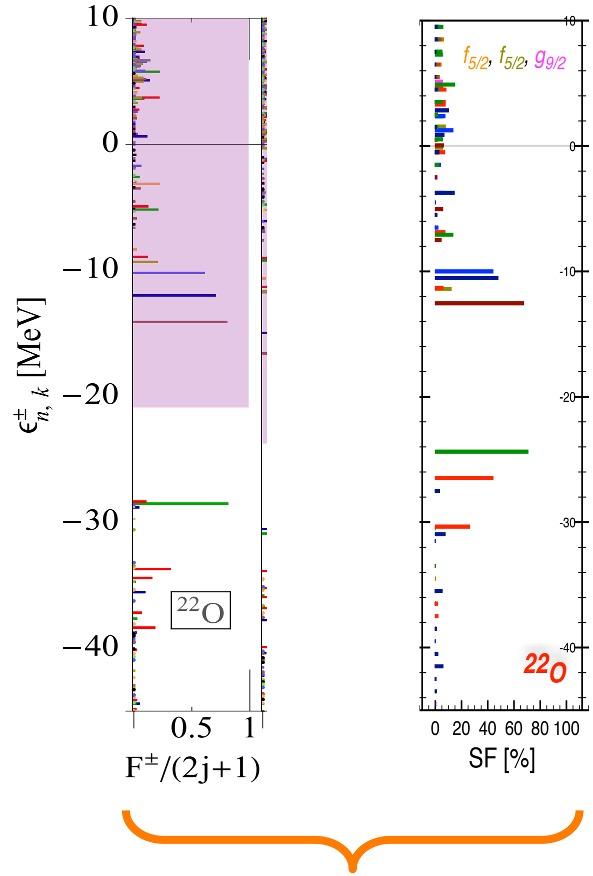
Spectroscopic factors

Proton spectral strength in Oxygen

A. Cipollone, CB, P. Navrátil, Phys. Rev. Lett. **111**, 062501 (2013)
and Phys. Rev. C **92**, 014306 (2015)
and ***in preparation***

More in detail:

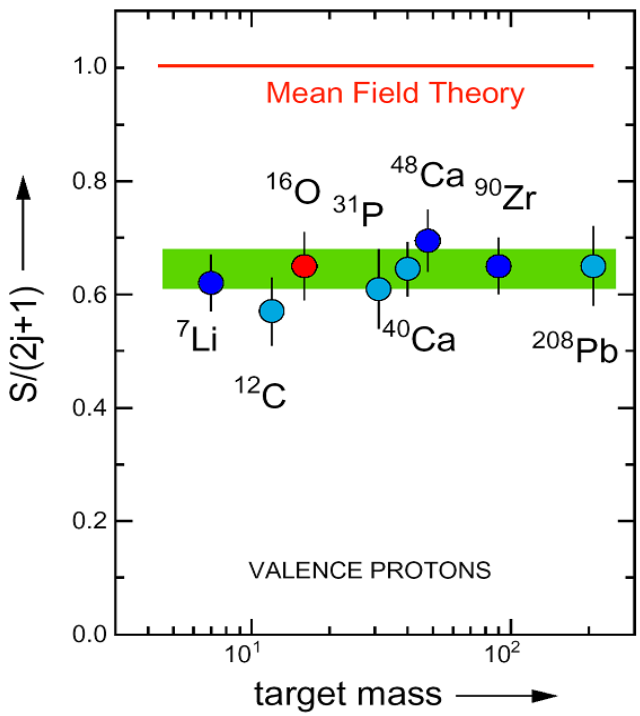




Quenching of SF in stable nuclei

Nucl. Phys. A553 (1993) 297c

NIKHEF:



A common misconception about SRC:

"The quenching is constant over all stable nuclei, so it must be a short-range effect"

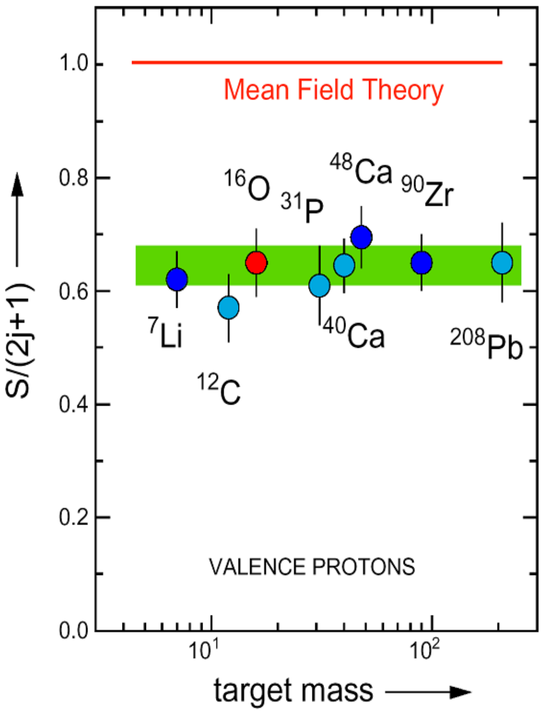
Actually, NO!

All calculations show that SRC have just a small effect at the Fermi surface. And the correlation to the experimental p-h gap is much more important.

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

Quenching of SF in stable nuclei

NIKHEF:
Nucl. Phys. A553 (1993) 297c



	$S_{p1/2}$	$S_{p3/2}$
• Short-range correlations oriented methods:		
– VMC [Argonne, '94]	0.90	
– GF(SRC) [St.Louis-Tübingen '95]	0.91	0.89
– FHNC/SOC [Pisa '00]	0.90	
• Including particle-phonon couplings:		
– GF(FRPA) [St.Louis '01]	0.77	0.72
[CB et al., Phys. Rev. C**65**, (02)]		
• Experiment:	0.63	0.67 ±0.07 (estimated uncertainty)

SRC are present and verified experimentally

BUT the are NOT the dominant mechanism for quenching SF!!!

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)]

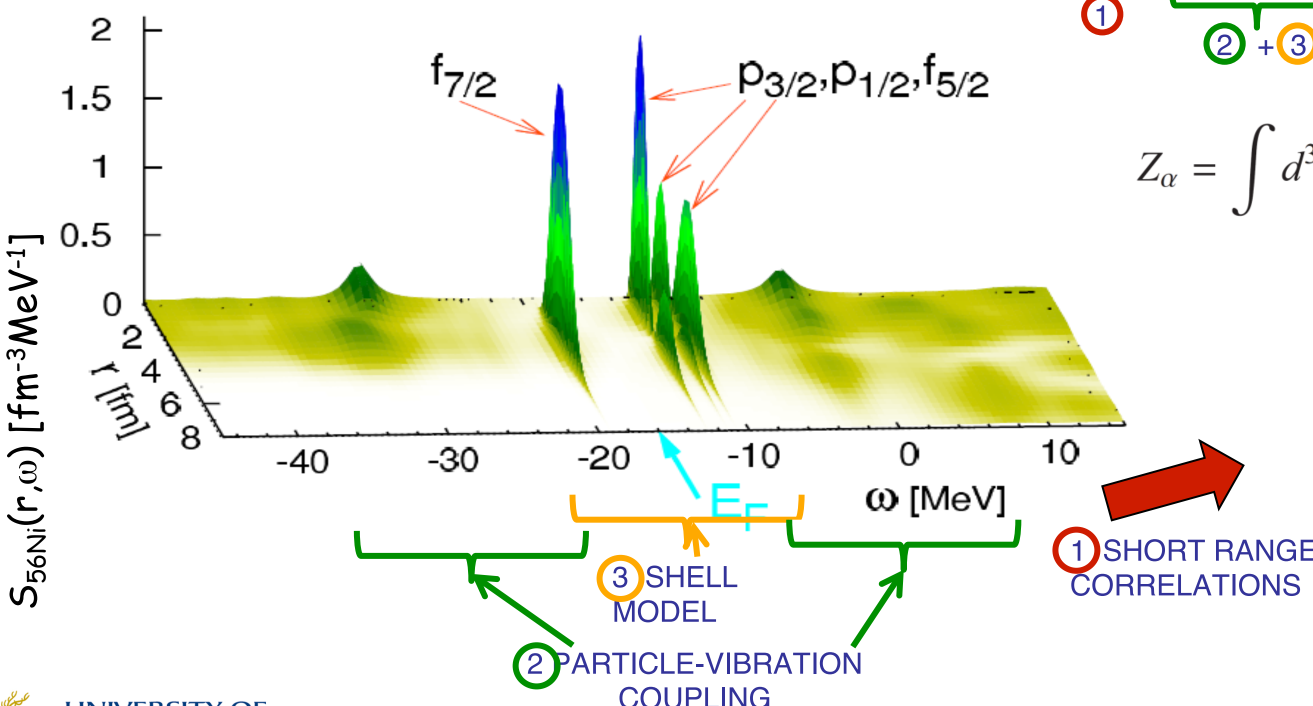
...with analogous conclusions for ^{48}Ca

	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

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



Dependence of Spect. Fact. from p-h gap

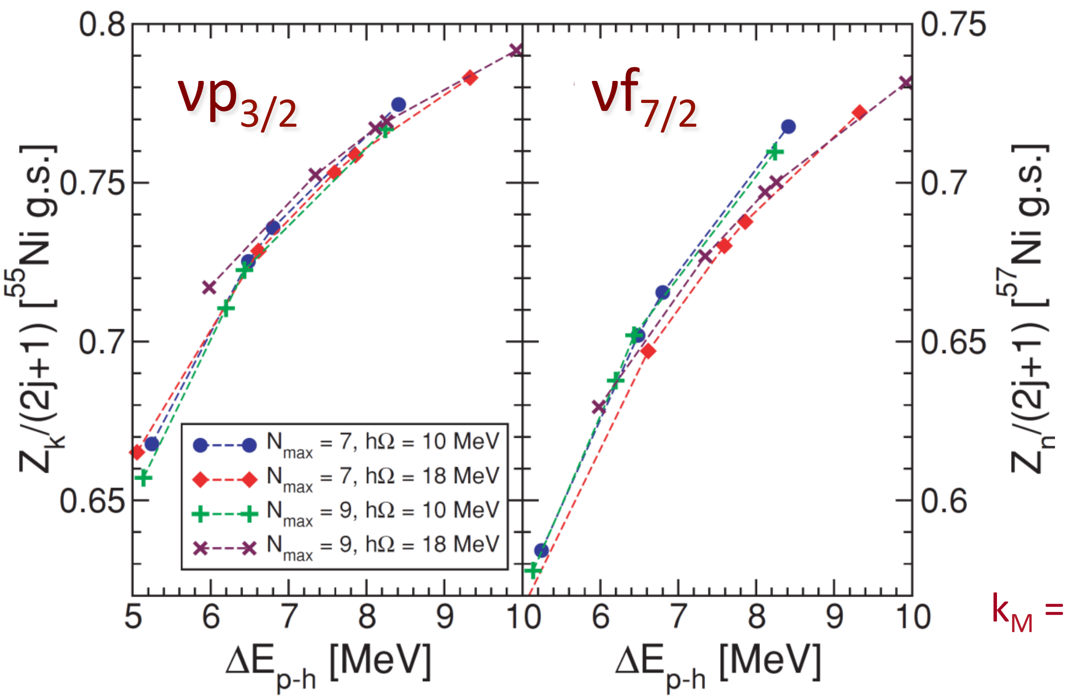
N3LO needs a monopole correction to fix the p-h gap:

$$\begin{cases} \Delta V^{T}_{fr} \rightarrow \Delta V^{T}_{fr} - (-1)^{T} \kappa_{M}, \\ \Delta V^{T}_{ff} \rightarrow \Delta V^{T}_{ff} - 1.5(1-T)\kappa_{M}, \end{cases}$$

$r \equiv p_{3/2}, p_{1/2}, f_{5/2}$

$f \equiv f_{7/2}$

Experimental Eph is found for k_M =0,57



k_M = 0.4-0.7 MeV

small k_M ← → large k_M

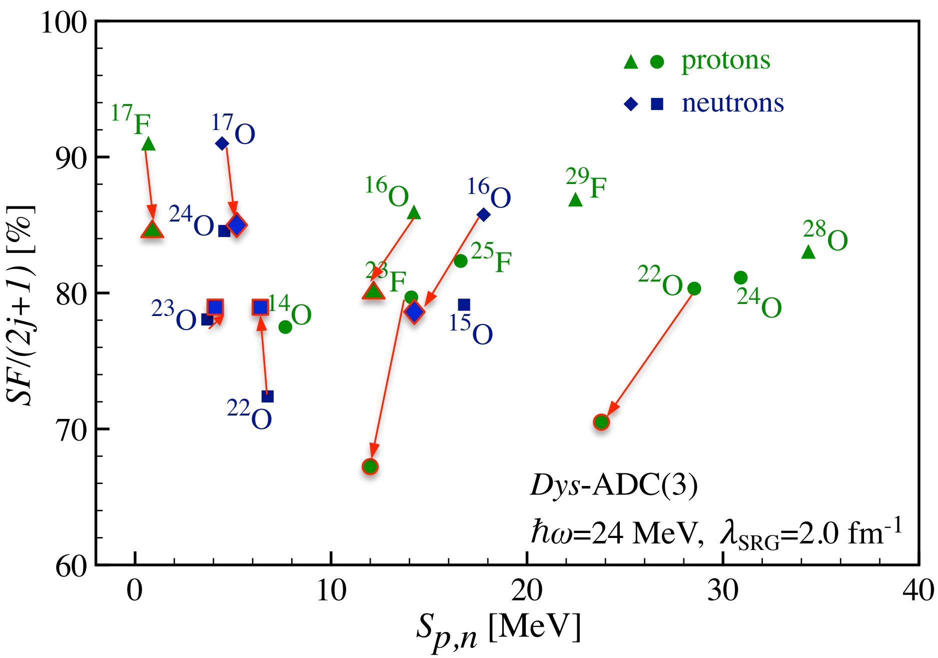
N3LO interaction + monopole corr.

[CB, M.Hjorth-Jensen, Pys.Rev.C79, 064313 (2009)]

Z/N asymmetry dependence of SFs - Theory

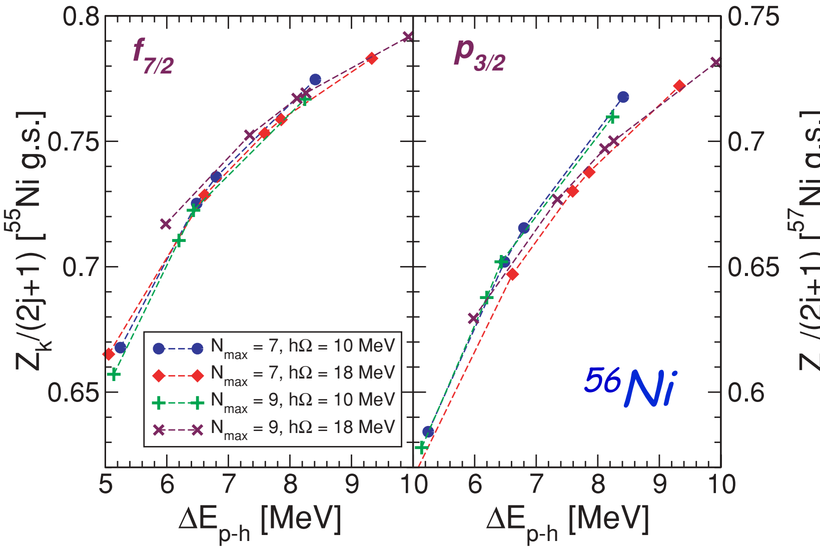
Ab-initio calculations explain (a very weak) the Z/N dependence but the effect is much lower than suggested by direct knockout

Rather the quenching is high correlated to the gap at the Femi surface.



A. Cipollone, CB, P Navrátil
Phys. Rev. C**92**, 014306 (2015)

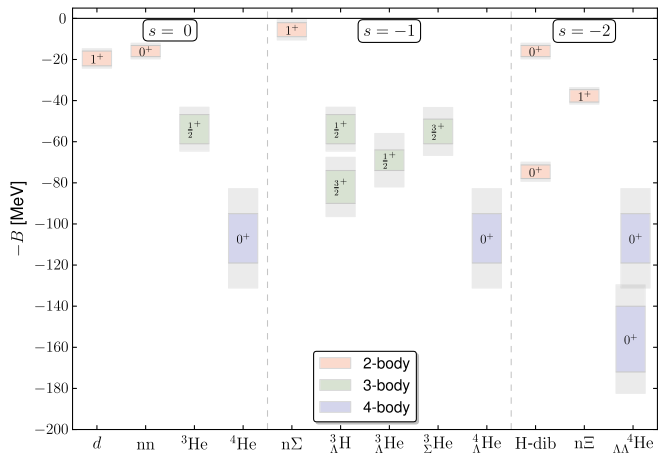
Spectroscopic factor are strongly correlated to p-h gaps:



CB, M. Hjorth-Jensen,
Phys. Rev. C **79**, 064313 (2009)

Study of nuclear interactions from Lattice QCD

Other paths in LQCD, see:



NPLQCD, PRD**87**, 034506 (2013)

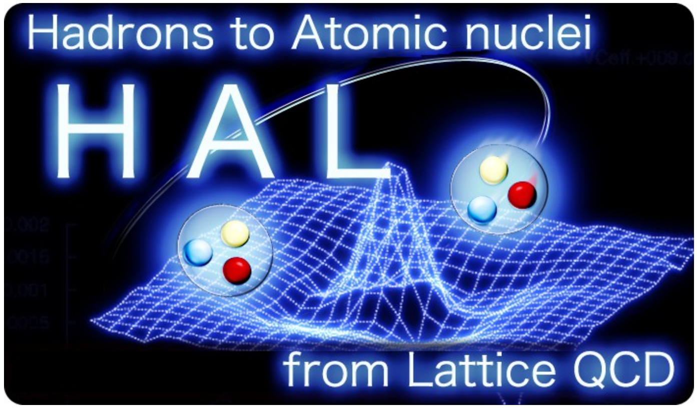
nuclei, the deuteron and the dineutron in 2 + 1 flavor QCD with $m_\pi = 0.51$ GeV and $m_N = 1.32$ GeV. The bound states are distinguished from the attractive scattering states by investigating the spatial volume dependence of the energy shift ΔE_L. In the infinite spatial volume limit we obtain

$$-\Delta E_\infty = \begin{cases} 43(12)(8) & \text{MeV for } ^4\text{He}, \\ 20.3(4.0)(2.0) & \text{MeV for } ^3\text{He}, \\ 11.5(1.1)(0.6) & \text{MeV for } ^3\text{S}_1, \\ 7.4(1.3)(0.6) & \text{MeV for } ^1\text{S}_0. \end{cases} \quad (17)$$

PACS-CS PRD **86**, 074514 (2012)

Study of nuclear interactions from Lattice QCD

In collaboration with:



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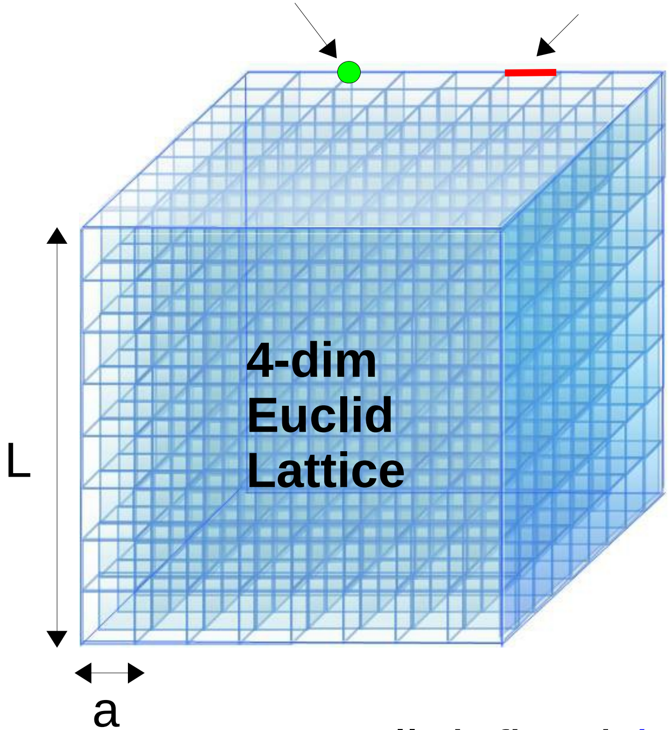
Lattice QCD

$$L = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + \bar{q}\gamma^\mu \left(i\partial_\mu - g t^a A^a_\mu \right) q - m \bar{q} q$$

quarks q
on the sites

gluons $U = e^{iaA_\mu}$
on the links



Vacuum expectation value

$$\langle O(\bar{q}, q, U) \rangle$$

path integral

$$= \int dU\, d\bar{q}\, dq\, e^{-S(\bar{q},q,U)}\, O(\bar{q}, q, U)$$

$$= \int dU \det D(U) e^{-S_U(U)}\, O(D^{-1}(U))$$

quark propagator

$$= \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} O(D^{-1}(U_i))$$

{ U_i } : ensemble of gauge conf. U
generated w/ probability $\det D(U)\, e^{-S_U(U)}$

- Well defined (regularized)
- Manifest gauge invariance
- Fully non-perturbative
- Highly predictive

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Slide, courtesy of T. Inoue (YITP talk, Oct. 8th 2015)

The HAL-QCD Method

Define a general potential U(***r***,***r'***) which is and non-local but energy independent up to inelastic threshold, such that:

$$\frac{-\nabla^2}{2\mu}\varphi_{\vec{k}}(\vec{r}) \;+ \int d\vec{r}\,'U(\vec{r},\vec{r}\,')\varphi_{\vec{k}}(\vec{r}\,') \;=\; E_{\vec{k}}\varphi_{\vec{k}}(\vec{r})$$

for the Nambu-Bethe-Salpeter (NBS) wave function,

$$\varphi_{\vec{k}}(\vec{r}) = \sum \langle 0|B_i(\vec{x}+\vec{r},t)B_j(\vec{x},t)|B=2,\vec{k}\rangle$$

Operationally, measure the 4-pt function on the QCD Lattice

$$\psi(\vec{r},t) = \sum_{\vec{x}}\langle 0|B_i(\vec{x}+\vec{r},t)B_j(\vec{x},t)\,J(t_0)|0\rangle = \sum_{\vec{k}} A_{\vec{k}}\varphi_{\vec{k}}(\vec{r})e^{-W_{\vec{k}}(t-t_0)} + \ldots$$

and extract U(***r***,***r'***) from:

$$\left\{2M_B - \frac{\nabla^2}{2\mu}\right\}\psi(\vec{r},t) \;+ \int d\vec{r}\,'U(\vec{r},\vec{r}\,')\psi(\vec{r}\,',t) \;=-\frac{\partial}{\partial t}\psi(\vec{r},t)$$

A *local potential* V(**r**) is then obtained through a derivative expansion of U(***r***,***r'***), which *must give the same observables* of the LQCD simulation:

$$U(\vec{r},\vec{r}\,') = \delta(\vec{r}-\vec{r}\,')V(\vec{r},\nabla) = \delta(\vec{r}-\vec{r}\,')\left\{V(\vec{r}) + \mathcal{O}(\nabla) + \mathcal{O}(\nabla^2) + \ldots\right\}$$

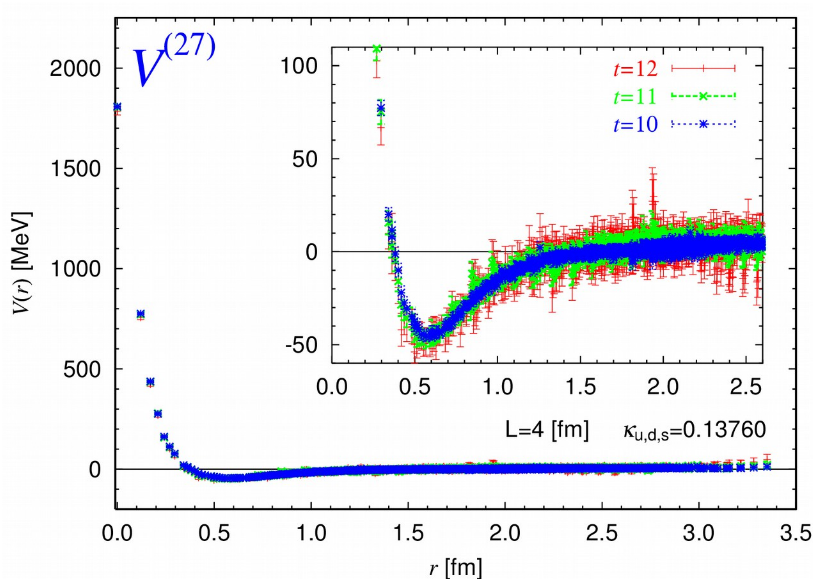
Tensor/Yukawa force in S-D

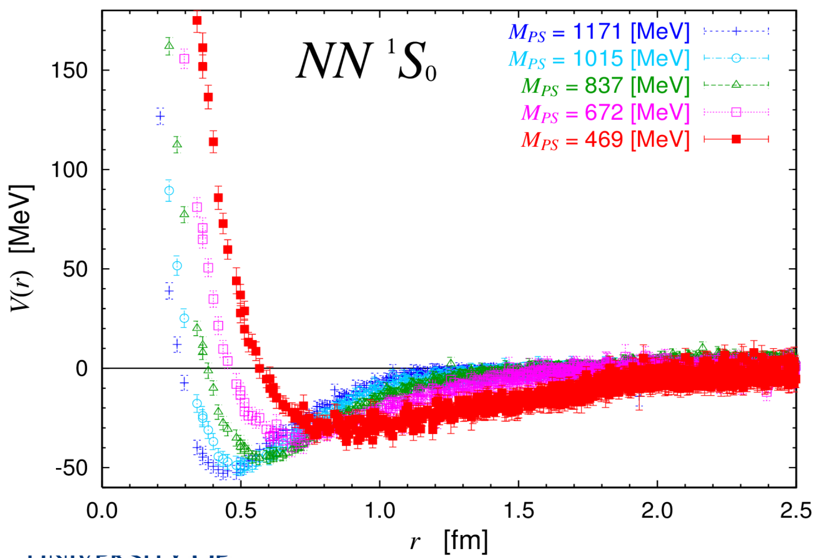
Spin-orbit force, P waves

$$\Rightarrow\; V(\vec{r}) = \frac{1}{2\mu}\frac{\nabla^2\psi(\vec{r},t)}{\psi(\vec{r},t)} - \frac{\frac{\partial}{\partial t}\psi(\vec{r},t)}{\psi(\vec{r},t)} - 2M_B$$

Prog. Theor. Phys. 123 89 (2010); Phys. Lett. B712 , 437 (2012); Prog. Theor. Exp. Phys. 01A105 (2012)

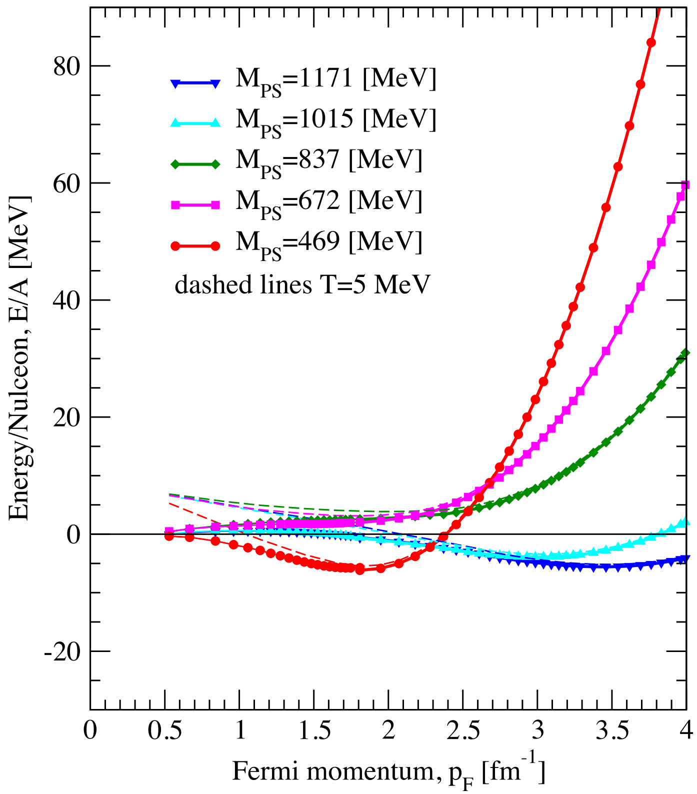
Two-Nucleon HAL potentials





Quark mass dependence of *V(r)* for NN partial wave ($^1S_0$, $^3S_1$, $^3S_1$-$^3D_1$)

➔ Potentials become stronger m_π as decreases.



T. Inoue *et al.*,
Phys. Rev. Lett. **111** 112503 (2013).

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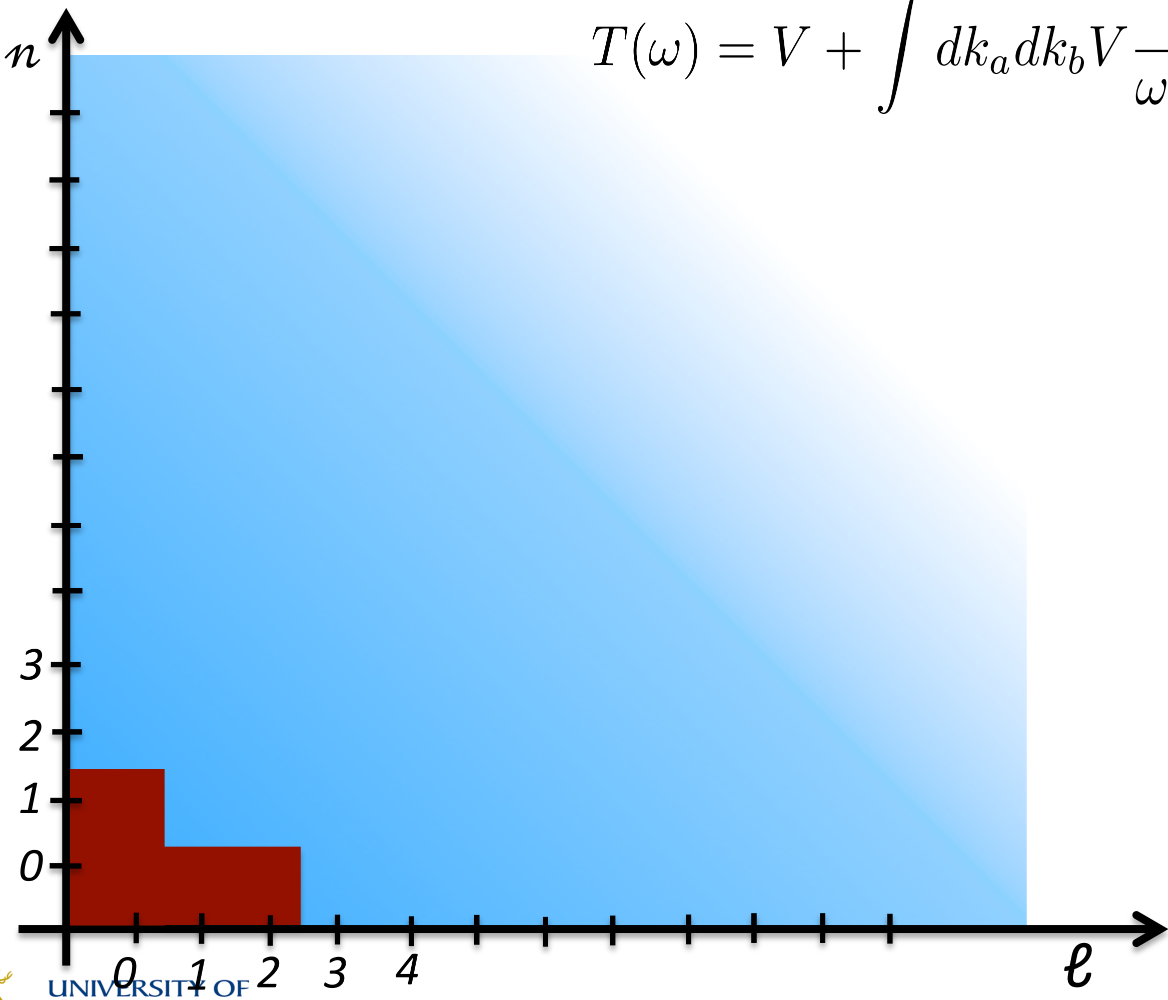
Prog. Theor. Exp. Phys. 01A105 (2012)

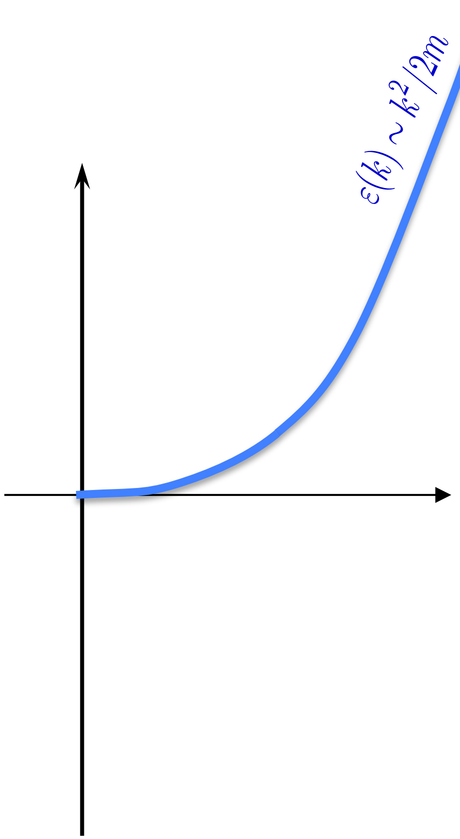
(Finite-T results by A. Carbone, priv. comm.)

Analysis of Brueckner HF

Scattering of two nucleon in free space:

$$T(\omega) = V + \int dk_a dk_b V \frac{1}{\omega - k_a^2/2m - k_b^2/2m + i\eta} T(\omega)$$

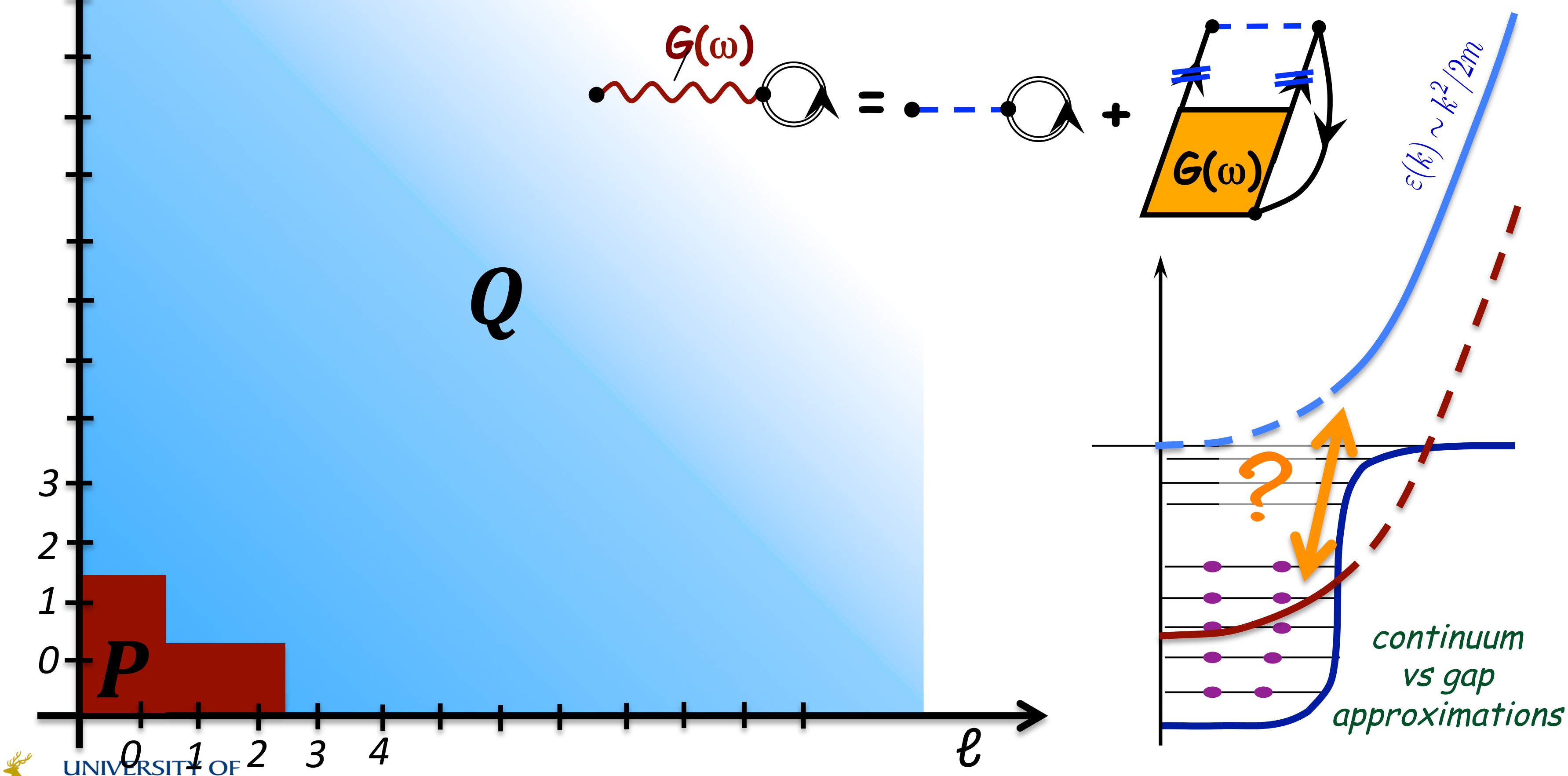




Analysis of Brueckner HF

Scattering of two nucleons outside the Fermi sea (➔BHF):

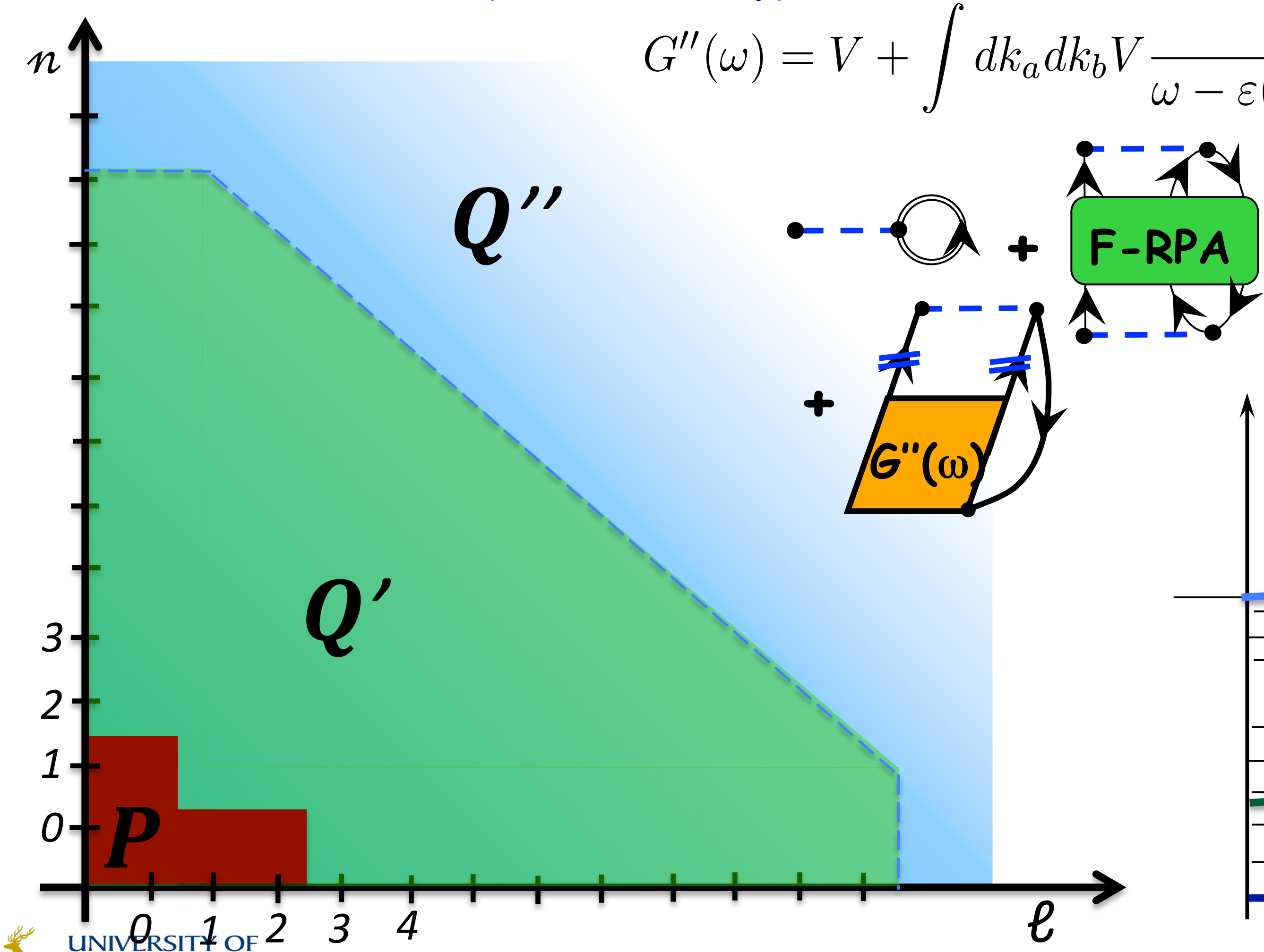
$$G(\omega) = V + \int dk_a dk_b V \frac{\hat{Q}}{\omega - \varepsilon(k_a) - \varepsilon(k_b) + i\eta} G(\omega)$$

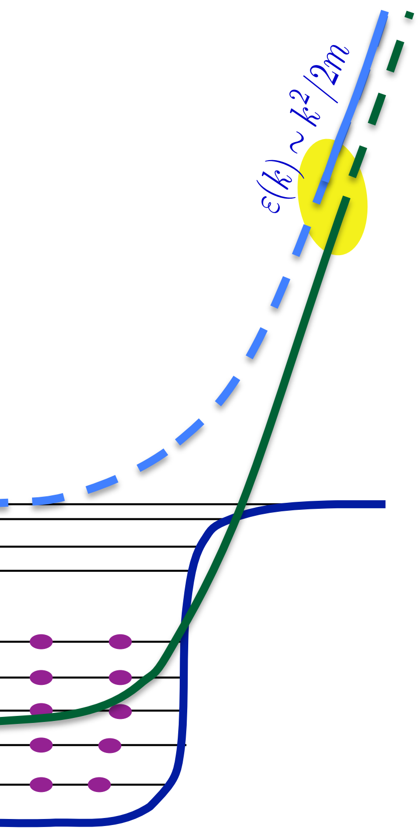


Mixed SCGF-Brueckner approach

Solve full many-body dynamics in model space (P+Q') and the Goldstone's ladders outside it (i.e. in Q'' only):

$$G''(\omega) = V + \int dk_a dk_b V \frac{\hat{Q}''}{\omega - \varepsilon(k_a) - \varepsilon(k_b) + i\eta} G''(\omega)$$

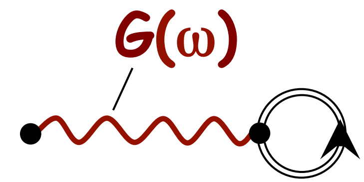


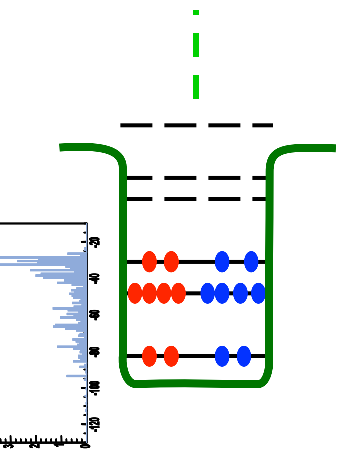


Treating short-range corr. with a G-matrix

- The short-range core can be treated by summing ladders outside the model space:

$$\Sigma^{\mathrm{MF}}_{\alpha\beta}(\omega) = i \sum_{\gamma\delta} \int \frac{d\omega'}{2\pi} G_{\alpha\gamma,\delta\beta}(\omega+\omega') g_{\delta\gamma}(\omega') \quad =$$





$$\Sigma^{\star}(\mathbf{r},\mathbf{r}';\omega) = \Sigma^{MF}(\mathbf{r},\mathbf{r}';\omega) + \tilde{\Sigma}(\mathbf{r},\mathbf{r}';\omega) \,.$$

$$Z_\alpha = \int d\mathbf{r}\, |\psi_\alpha^{A\pm1}(\mathbf{r})|^2 = \left.\frac{1}{1 - \frac{\partial \Sigma^{\star}_{\hat{\alpha}\hat{\alpha}}(\omega)}{\partial\omega}}\right|_{\omega=\pm(E_\alpha^{A\pm1} - E_0^A)}$$

Two contributions to the derivative:

- $\Sigma^{\mathrm{MF}}_{\alpha\beta}(\omega)$ is due to scattering to (high-k) states in the Q space
- $\Sigma(\mathbf{r},\mathbf{r}';\omega)$ accounts for low-energy (long range) correlations

(Galitskii-Migdal-Boffi-) Koltun sumrule

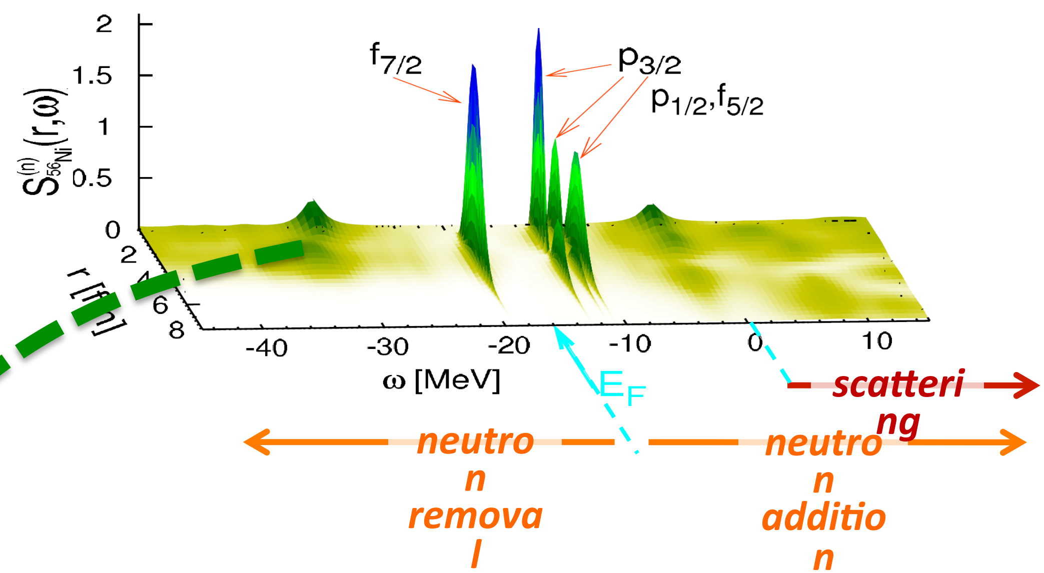
- Koltun sum rule (with NNN interactions):

$$\sum_\alpha \frac{1}{\pi}\int_{-\infty}^{\epsilon_F^-} d\omega\,\omega\,\mathrm{Im}\,G_{\alpha\alpha}(\omega) \;=\; \langle\Psi_0^N|\hat{T}|\Psi_0^N\rangle + 2\langle\Psi_0^N|\hat{V}|\Psi_0^N\rangle + 3\langle\Psi_0^N|\hat{W}|\Psi_0^N\rangle$$

two-body

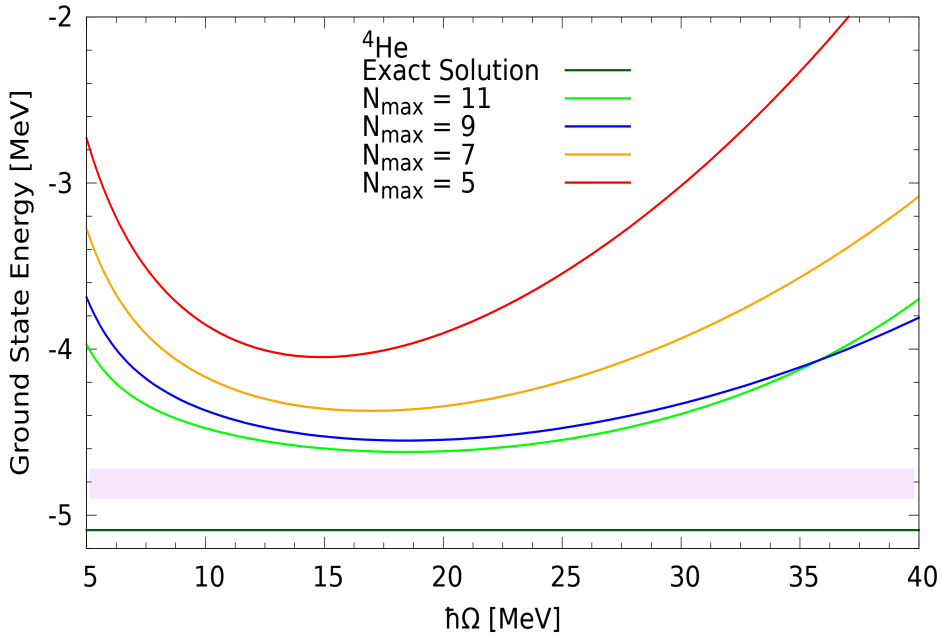
three-body

$$E_0^N = \frac{1}{2\pi}\int_{-\infty}^{\epsilon_F^-} \mathrm{d}\omega \sum_{\alpha\beta}(T_{\alpha\beta}+\omega\delta_{\alpha\beta})\mathrm{Im}\,G_{\beta\alpha}(\omega) - \frac{1}{2}\langle\Psi_0^N|\widehat{W}|\Psi_0^N\rangle$$



High-k and missing energy tail from SRC… (currently neglected in calculating Koltun SR)

Benchmark on ^{4}He

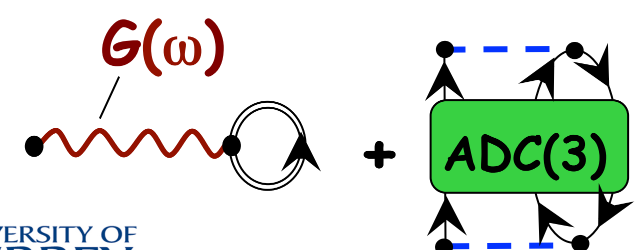


Can benchmark the Gmtx+ADC(3) method on light ^{4}He, where exact solutions are possible:

	G(ω) + ADC(3)	Exact
HALQCD @ $m_\pi \approx 470$MeV	4.8(1) MeV	5.09 MeV[1]

[1]H. Nemura *et al.*, Int. J. Mod. Phys. E **23**, 1461006 (2014)

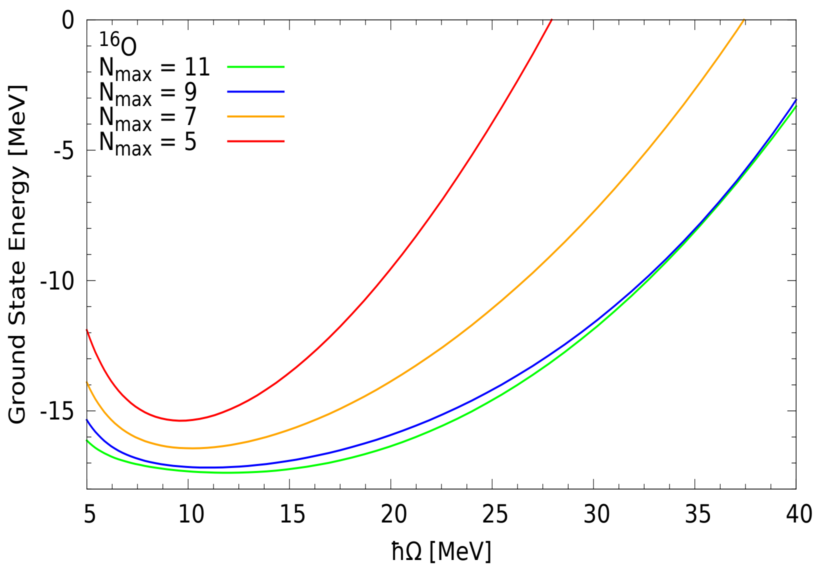
➔ *Can expect accuracy on binding energies at about 10%*



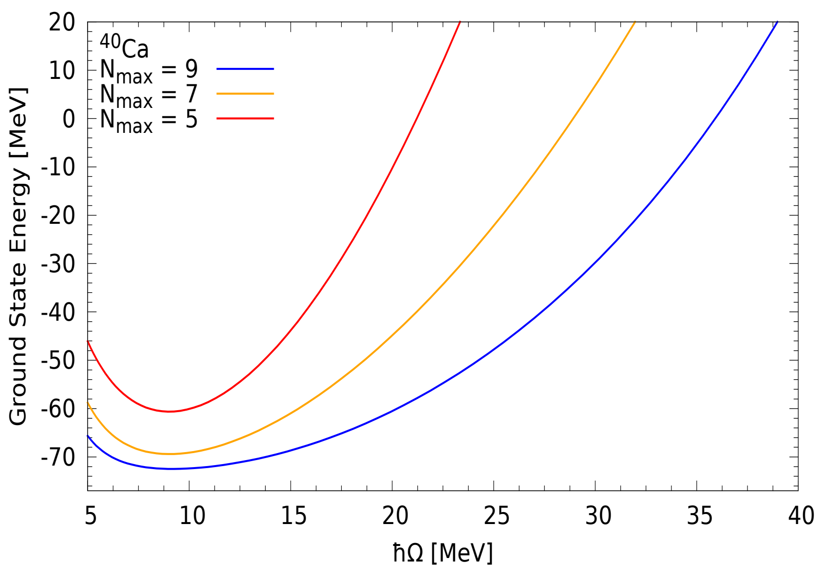
$$G''(\omega) = V + \int dk_a dk_b V \frac{\hat{Q}''}{\omega - \varepsilon(k_a) - \varepsilon(k_b) + i\eta} G''(\omega)$$

Binding of ^{16}O and ^{40}Ca:

^{16}O m_{PS}= 469 MeV



^{40}Ca m_{PS}= 469 MeV



Binding energies are ~17 MeV ^{16}O and 70-75MeV for ^{40}Ca. Possibly being underestimated by 10%

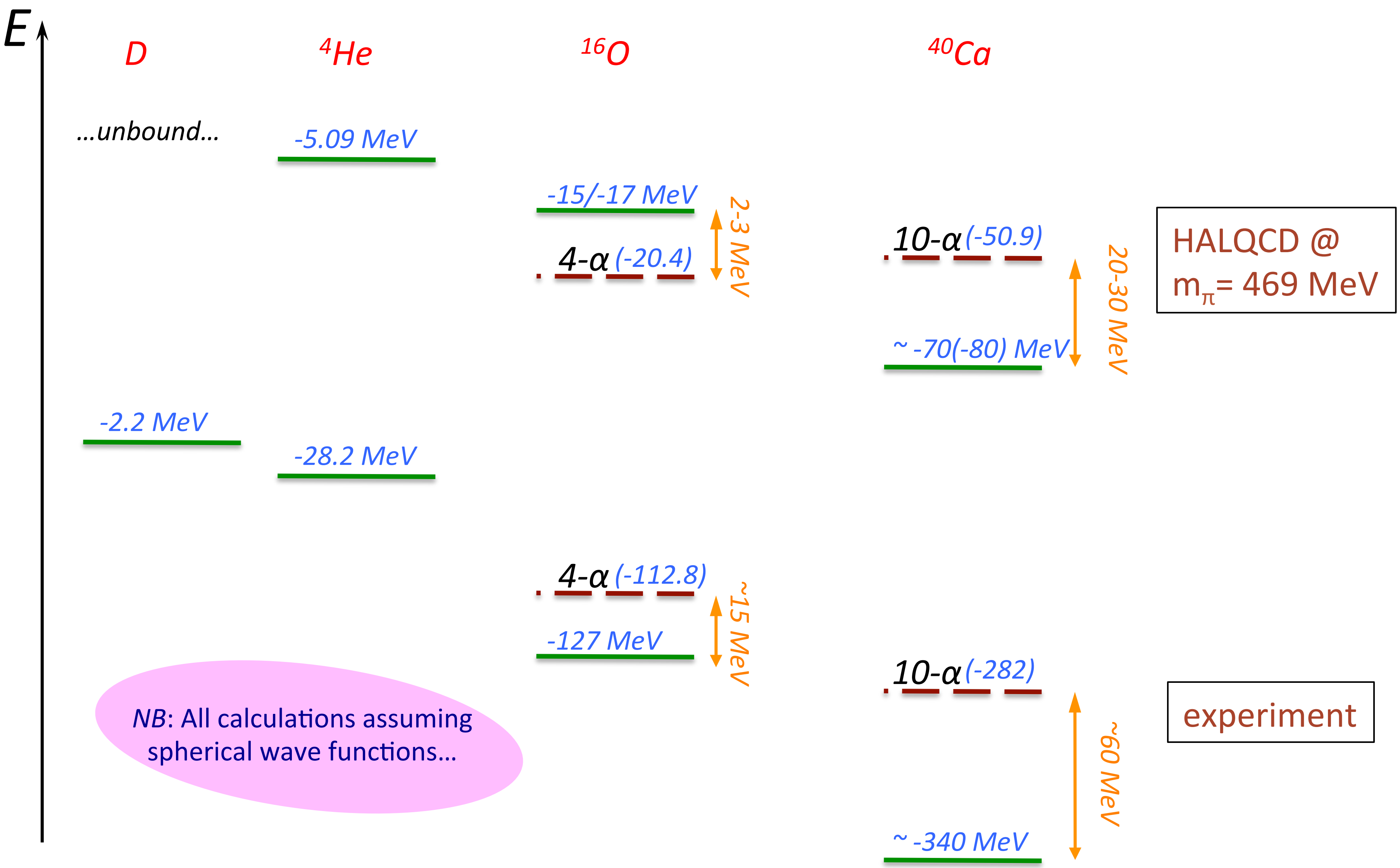
➔ ^{16}O at $m_\pi \approx$ 470 MeV is unstable toward 4-α breakup!

	Oxygen-16	Calcium-40
$G(\omega)$ + ADC(3)	-17.4(3) MeV	-75.4(7) Mev
Separate ^4He clusters	-20.36 MeV	-50.9 MeV

TABLE II. Comparison of ^{16}O and ^{40}Ca ground state energies using M_{PS}=469 MeV/c^2.

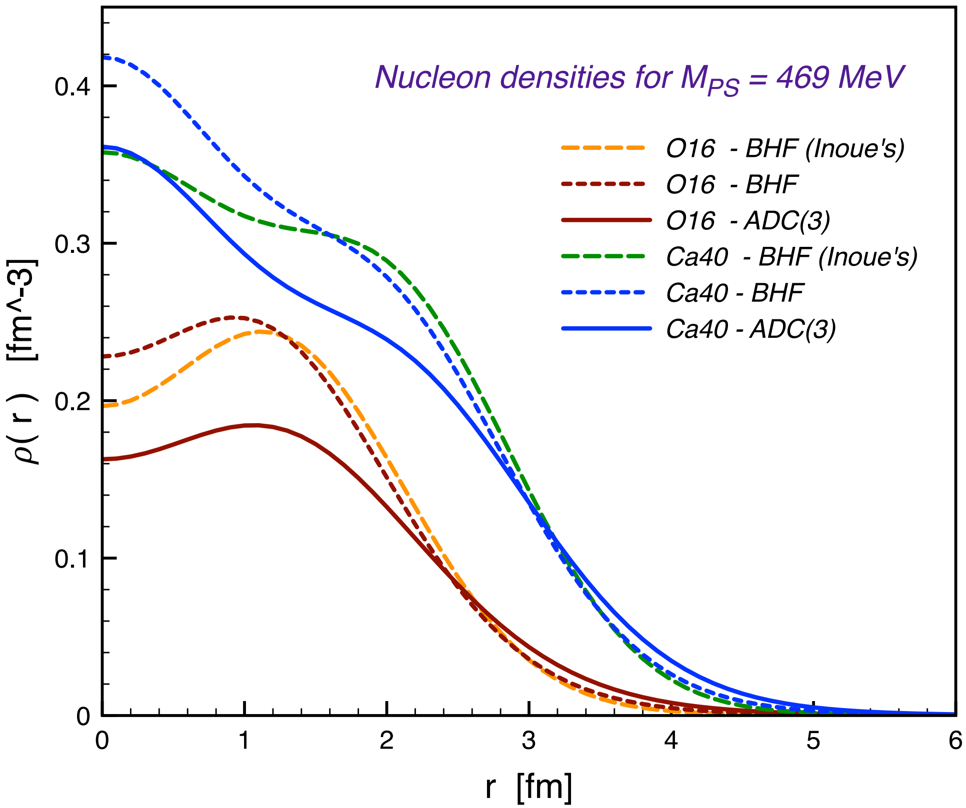
[C.S.McIlroy, CB, HAL coll., in prep]

Results for binding



C. McIlroy, CB, et al., *in preparation*

Matter distribution of ^{16}O and ^{40}Ca:

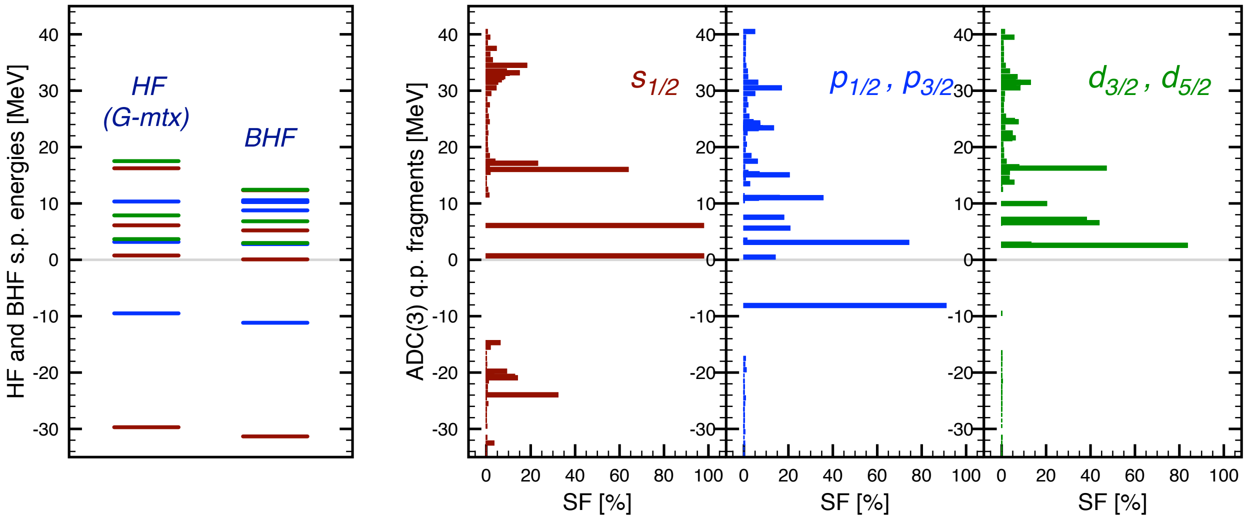


Calculated matter radii at $m_\pi \approx$ 470 MeV:

		^{16}O	^{40}Ca
$r_{pt-matter}$:	BHF [18]	2.35 fm	2.78 fm
	GHF	2.39 fm	2.78 fm
	G(ω) + ADC(3)	2.64 fm	2.97 fm
r_{charge}:	G(ω) + ADC(3)	2.79 fm	3.10 fm
	Experiment [44, 45]	2.73 fm	3.48 fm

[C.S.McIlroy, CB, HAL coll., in prep]

Spectral strength in ^{16}O and ^{40}Ca:



Particle-hole gaps

^{16}O

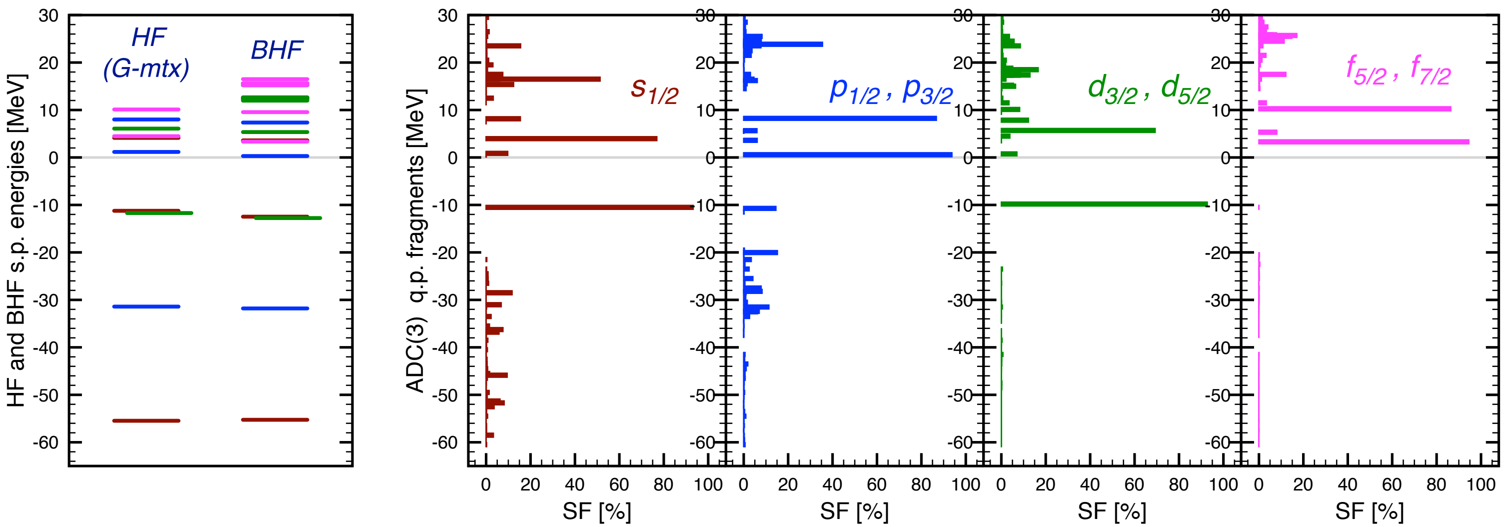
m_π= 469 MeV: ~8 MeV

Expt (phys m_π): 11.5 MeV

^{40}Ca

m_π= 469 MeV: ~10 MeV

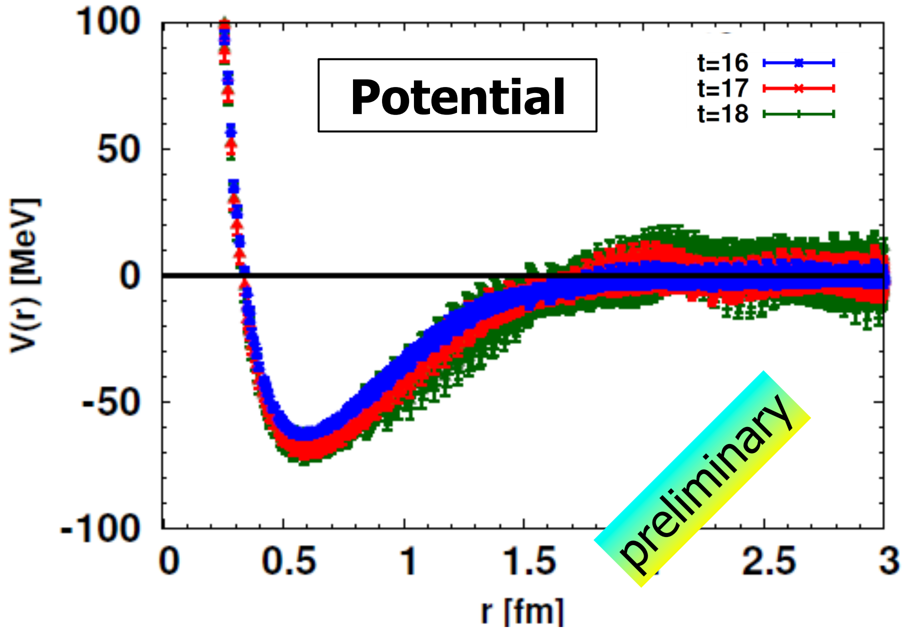
Expt (phys m_π): 7.5 MeV



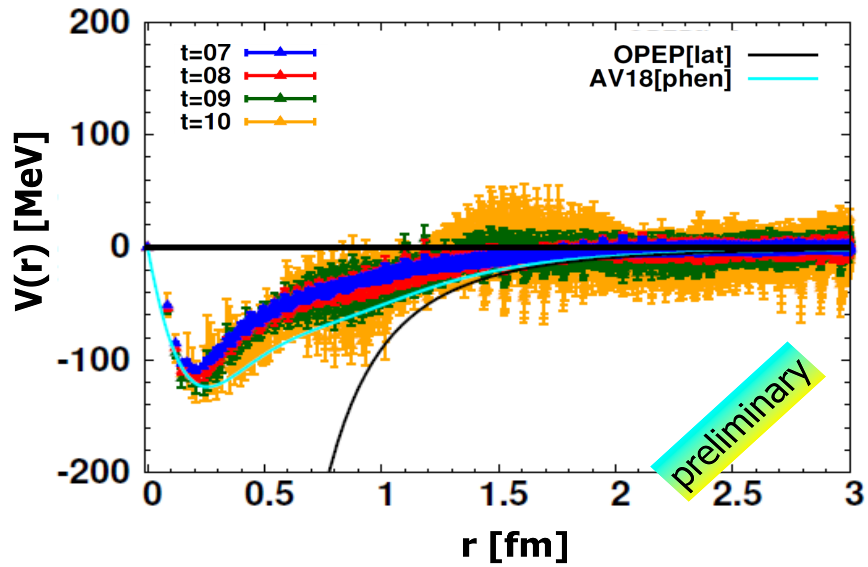
Future application for Ys in nuclei now possible

- Physical mass now under reach ($m_\pi \approx 145$ MeV) for hyperons
- Need to improve on statistic for the NN sector

$\Omega\Omega$ potential



$NN(^3S_1)$ tensor potential



HALQCD coll. -- Talk of ***S. Aoki*** at Kavli institute, Oct. 2016

Summary

Thank you for your attention!!!

Mid-masses and chiral interactions:

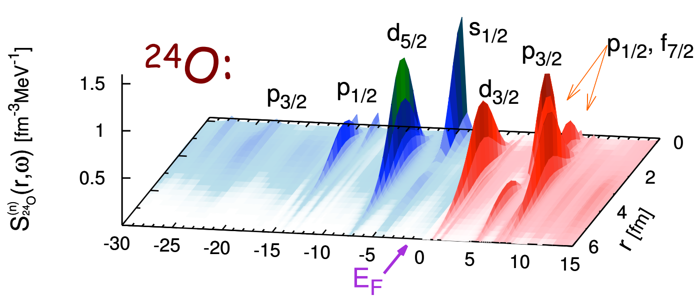
→ *Leading order 3NF are crucial to predict many important features that are observed experimentally (drip lines, saturation, orbit evolution, etc…)*

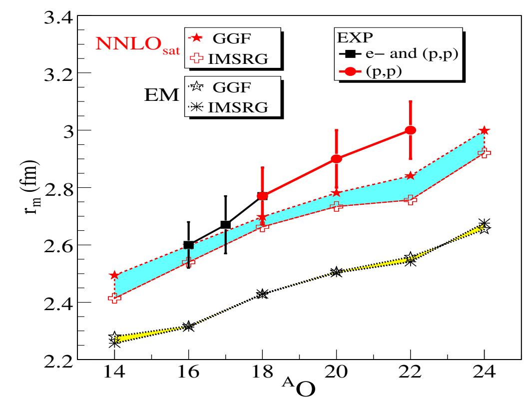
→ *Experimental binding is predicted accurately up to the lower sd shell (A≈30) but deteriorates for medium mass isotopes (Ca and above) with roughly 1 MeV/A over binding.*

→ *New fits of chiral interaction are promising for low-energy observables*

→ *Comparison of spectroscopic strength with experiment is much improved…*

→ *Nuclear forces from Lattice-QCD approaching physical pion mass*





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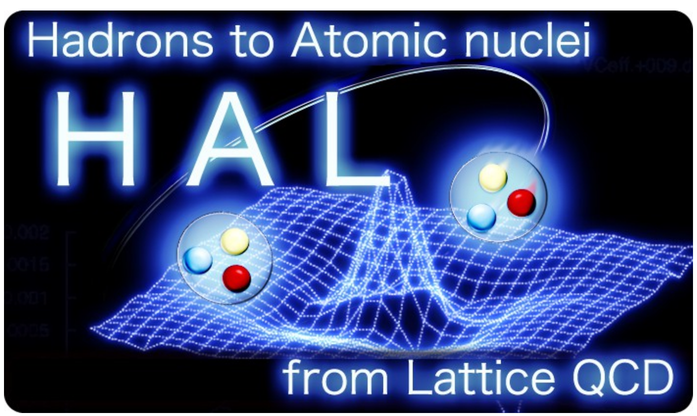

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