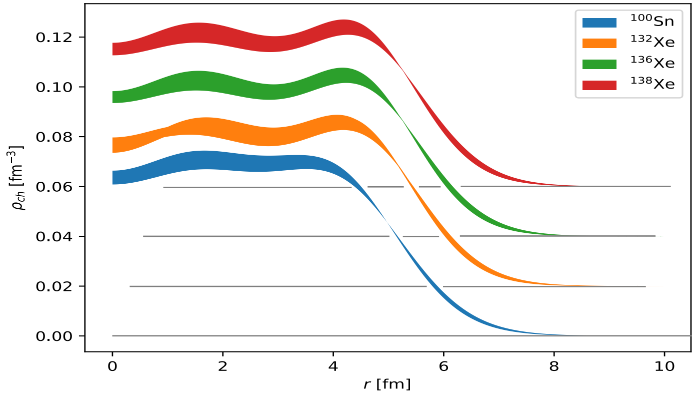
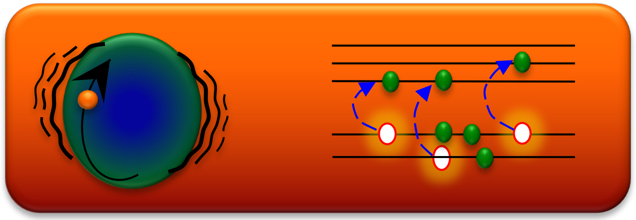
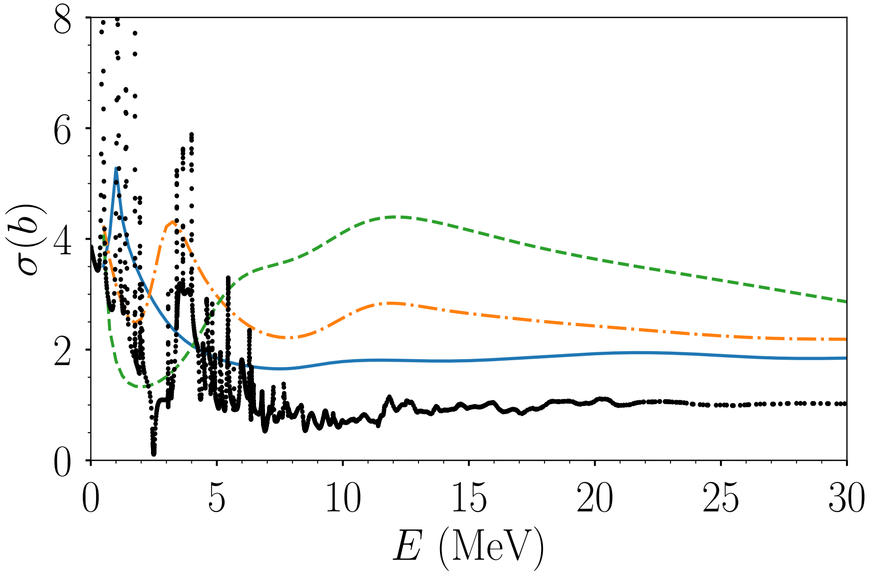
Ab Initio Computations of Ground States and Optical Potentials in Nuclei

Carlo Barbieri — Università degli studi di Milano

5 February 2021







Outline

The Self-Consistent Green's Function method (SCGF):

- ADC(n) and FRPA diagrammatic expansions (particle-vibration coupling)

Applications:

- Optical potentials from ab initio
  [A. Idini, CB, P. Navratil, Phys. Rev. Lett. **123**, 092501 (2019)]
- Reaching A≈132 mass
  [P. Arthuis, CB, M. Vorabbi, P. Finelli, Phys. Rev. Lett **125**, 182501 (2020)].
- (Hyper)nuclear forces from LQCD

-Mixed Local-Nonlocal cutoffs in chiral interactions (standard WPC) [Somà, Navratil, Raimondi, CB, Duguet, Phys Rev C **102**, 014301 (2020)]
(time permitting)

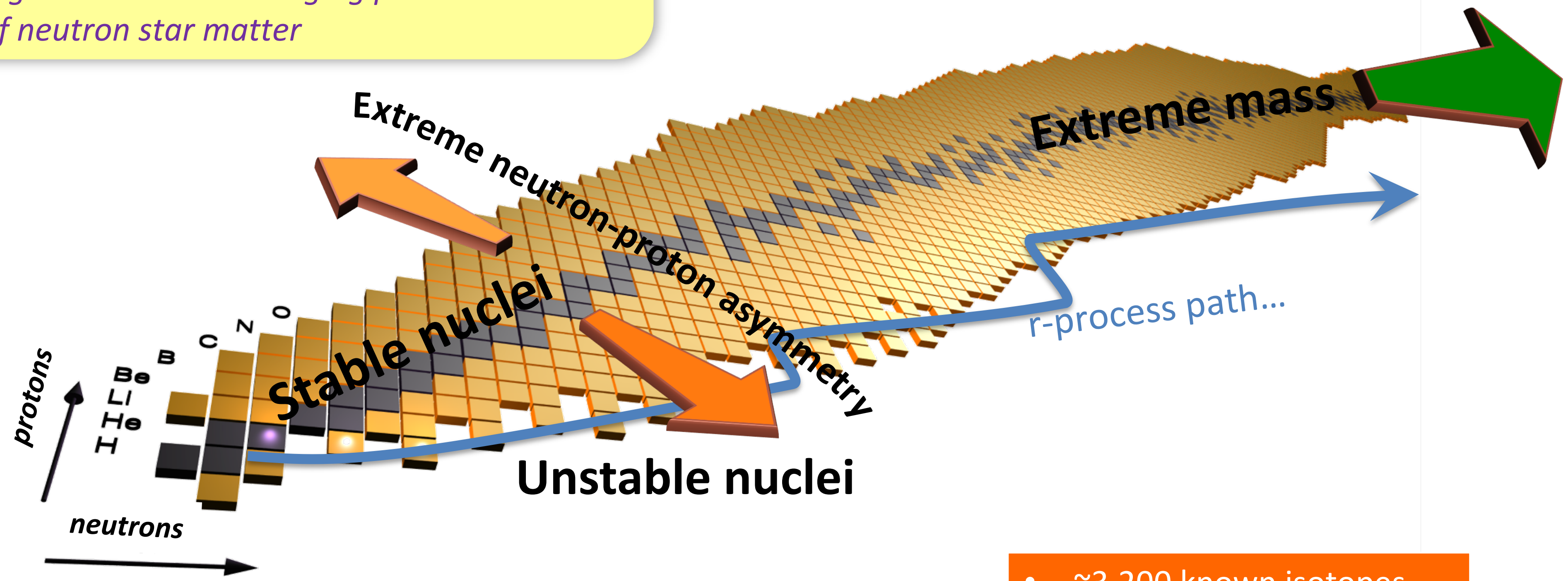
- Neutrino Nucleus scattering (@ GeV energies)
  (time permitting)

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)

Current Status of low-energy nuclear physics

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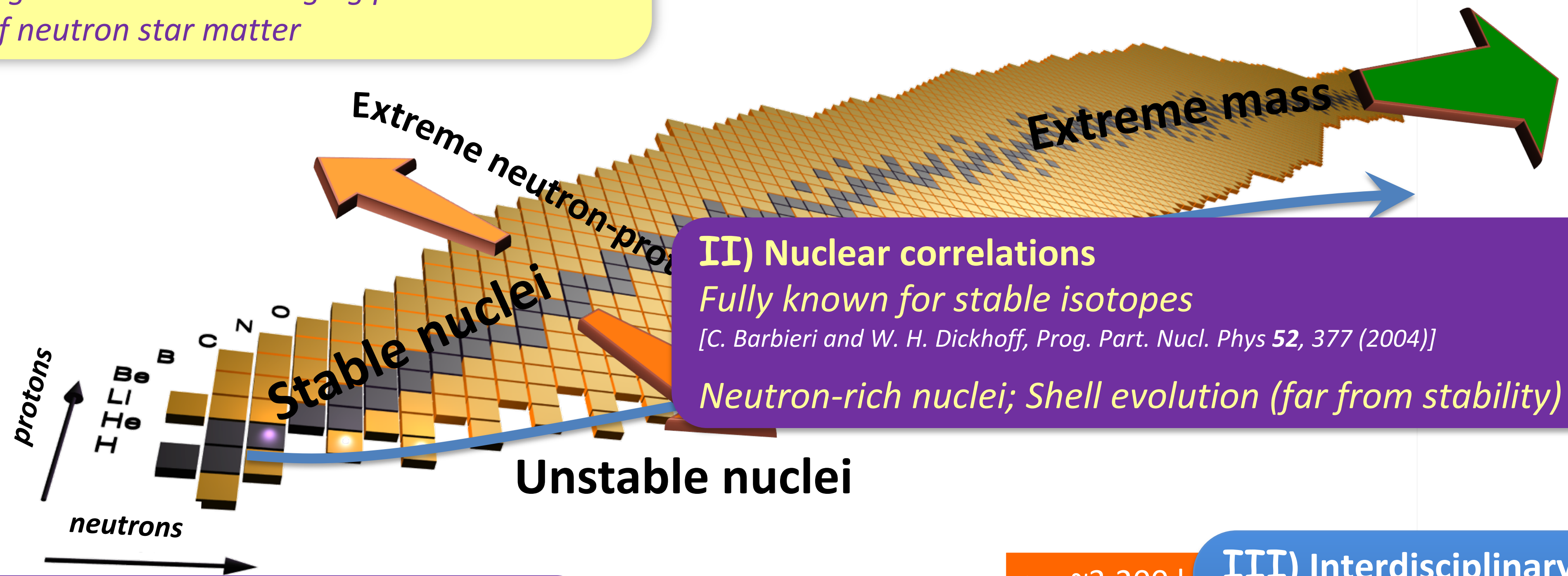
Binding and limits of stability
Coexistence of individual and collective behaviors
Self-organization and emerging phenomena
EOS of neutron star matter

Experimental programs
RIKEN, FAIR, FRIB, ISAC…



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

- ~3,200 k
- ~7,000 p
- Correlati
  in full fo

Nature **473**, 25

III) Interdisciplinary character
Astrophysics
Tests of the standard model
Other fermionic systems:
ultracold gasses; molecules;

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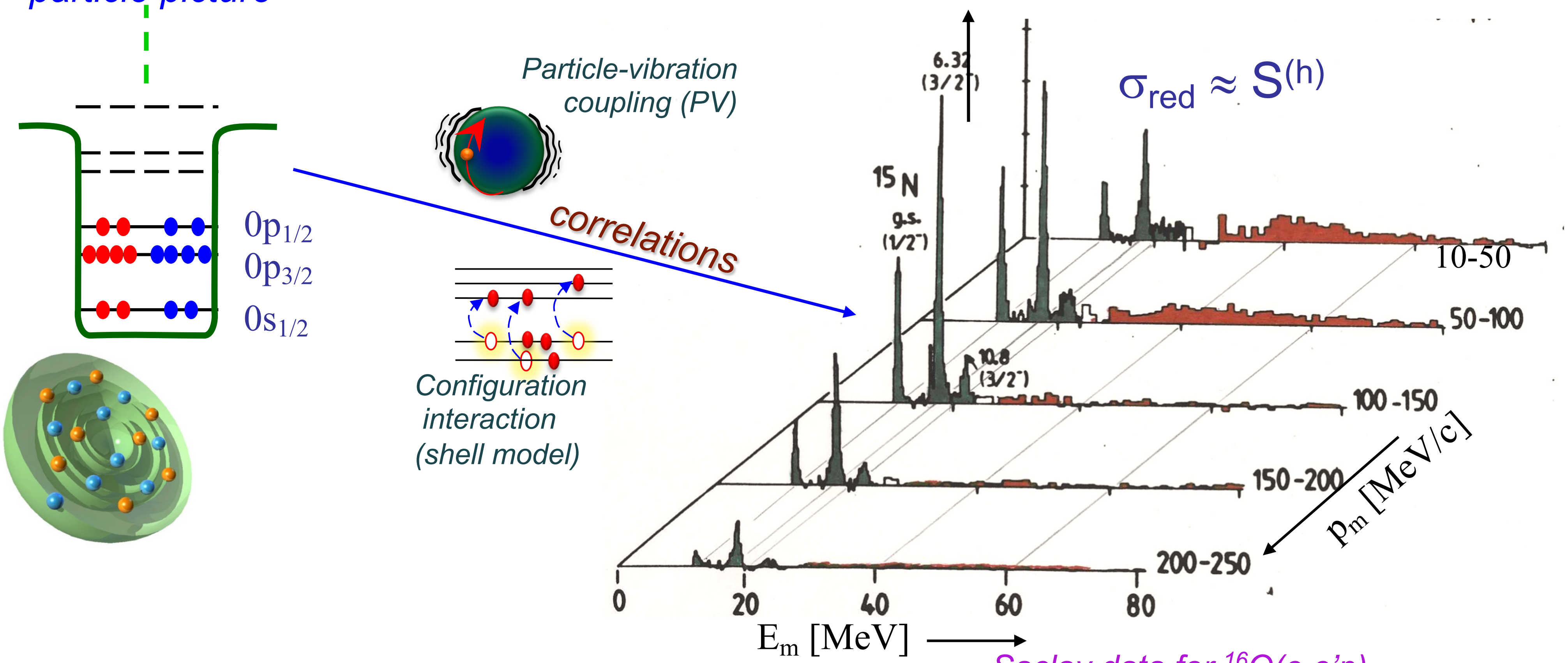
Concept of correlations

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

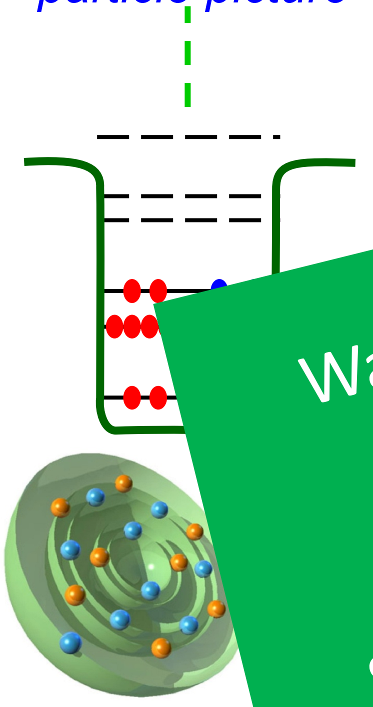


Saclay data for $^{16}O(e,e'p)$
[Mougey et al., Nucl. Phys. A335, 35 (1980)]

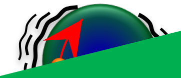
Understood for a few stable closed shells:
*[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys **52**, 377 (2004)]*

Concept of correlations

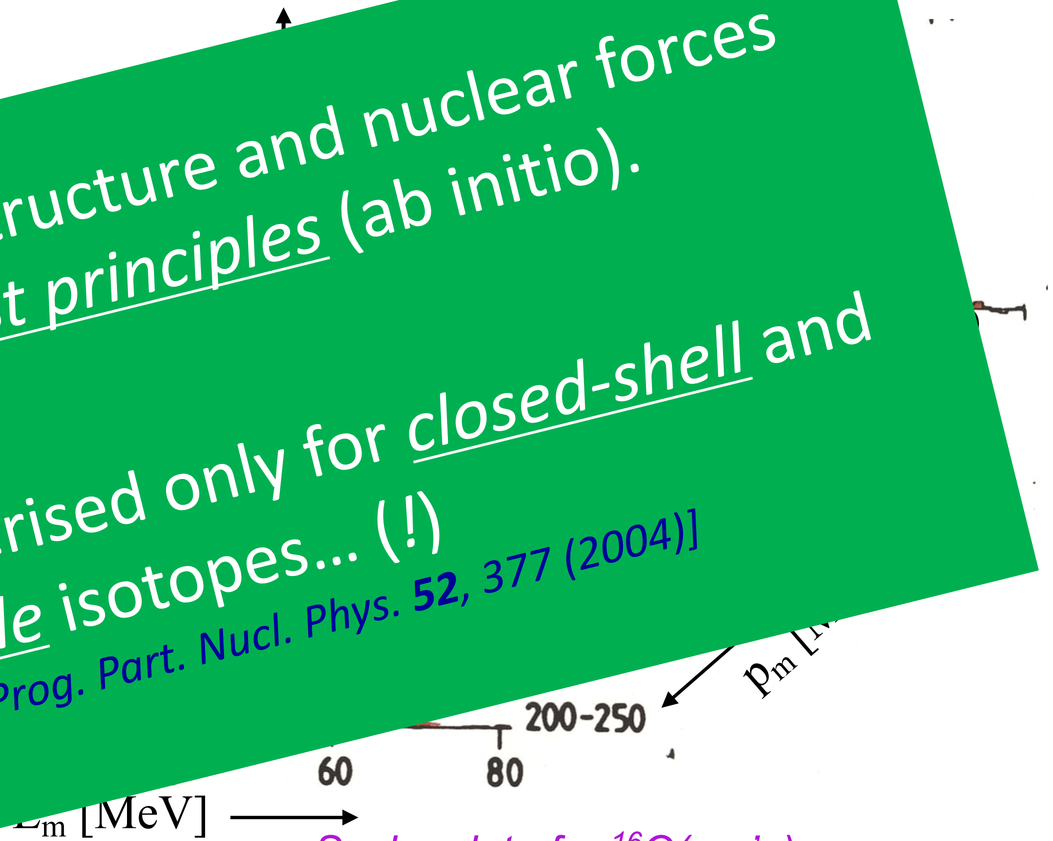
independent particle picture



Particle-vibration coupling (…



Spectral function: distribution of momentum (p_m) an… (E_m)



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

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

Understo… for a few stable closed shells:

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

Want to understand structure and nuclear forces *directly from first principles* (ab initio).

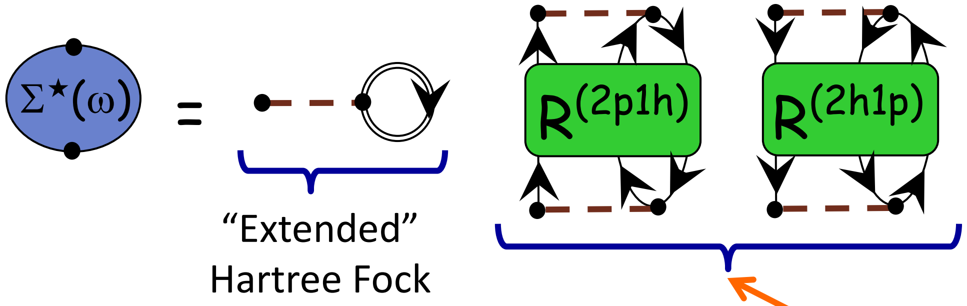
So far, fully characterised only for *closed-shell* and *stable* isotopes… (!)

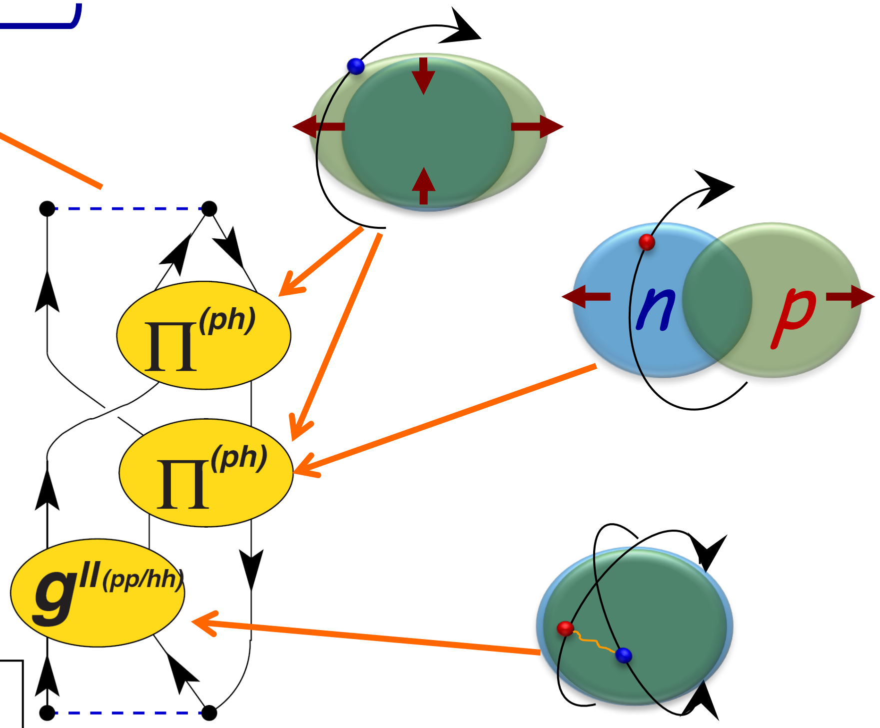
*[W. Dickhoff, CB, Prog. Part. Nucl. Phys. **52**, 377 (2004)]*

The FRPA Method in Two Words

Particle vibration coupling is the main mechanism driving the redistribution and fragmentation of particle strength—expecially in the quasielastic regions around the Fermi surface…

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

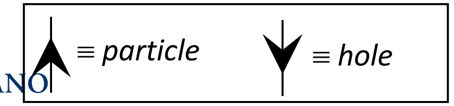




• A complete expansion requires *__all types__* of particle-vibration coupling

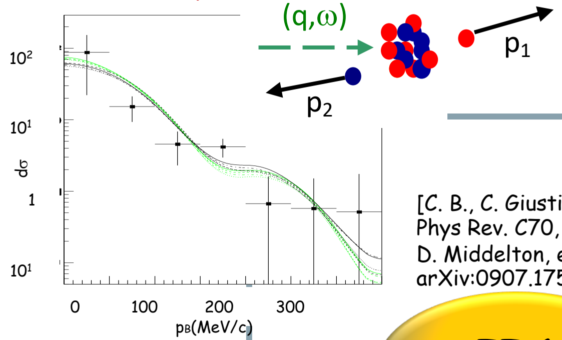
…these modes are all resummed exactly and to all orders in a *ab initio* many-body expansion.

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



Self-Consistent Green's Function Approach

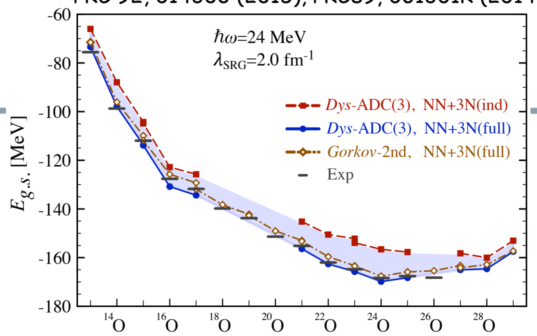
$^{16}O(e,e'pn)^{14}N$ @ MAINZ



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

Binding energies

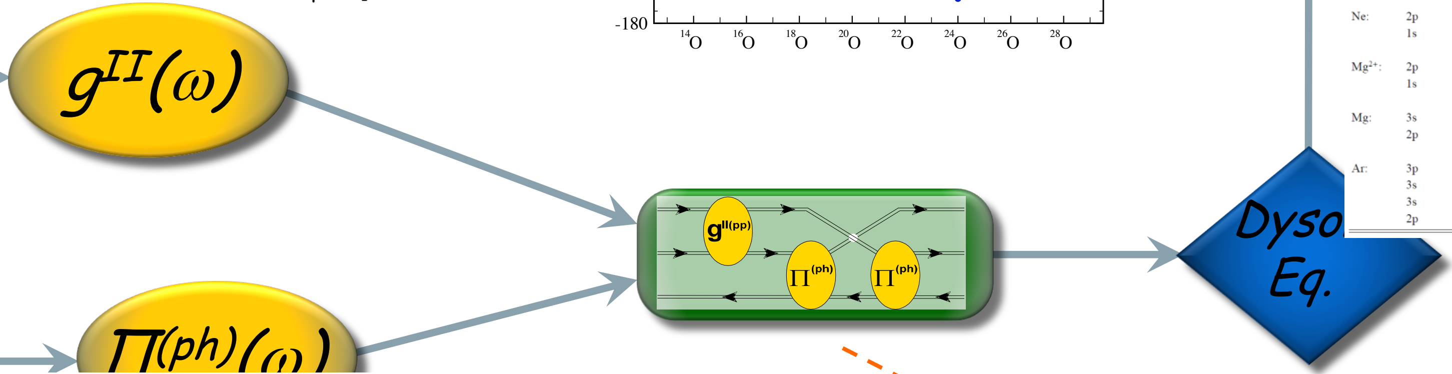
[PRL. 111, 062501 (2013),
PRC 92, 014306 (2015), PRC89, 061301R (2014)]



Ionization energies/ affinities, in atoms

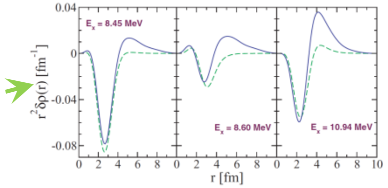
[CB, D. Van Neck,
AIP Conf.Proc.1120,104 ('09) & in prep]

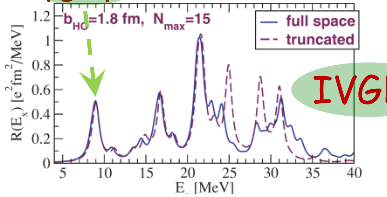
		Hartree-Fock	FRPAc	Experiment [16, 17]
He:	1s	0.918 (+14)	0.9008 (-2.9)	0.9037
Be^{2+}:	1s	5.6672 (+116)	5.6551 (-0.5)	5.6556
Be:	2s	0.3093 (-34)	0.3224 (-20.2)	0.3426
	1s	4.733 (+200)	4.5405 (+8)	4.533
Ne:	2p	0.852 (+57)	0.8037 (+11)	0.793
	1s	1.931 (+149)	1.7967 (+15)	1.782
Mg^{2+}:	2p	3.0068 (+56.9)	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
	3s		1.544	
	2p	9.571 (+411)	9.219 (+59)	9.160



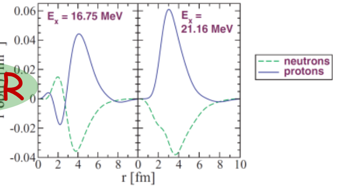
Isovector response for ^{32}Ar, ^{34}Ar

Proton Pygmy



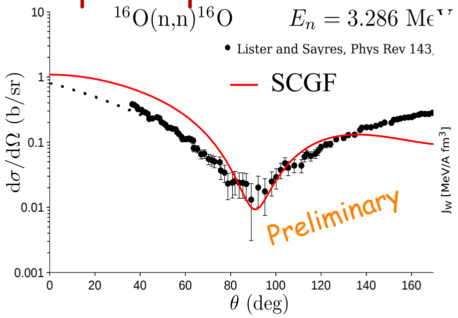


IVGDR

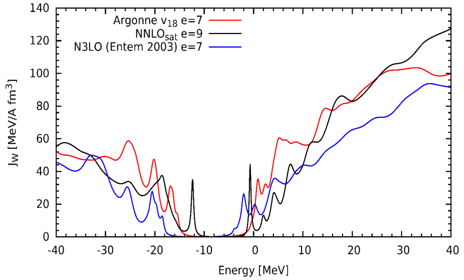


[C. B., K. Langanke, et al., Phys Rev. C77, 024304 (2008)]

Optical potential



arXiv:1612.01478 [nucl-th]



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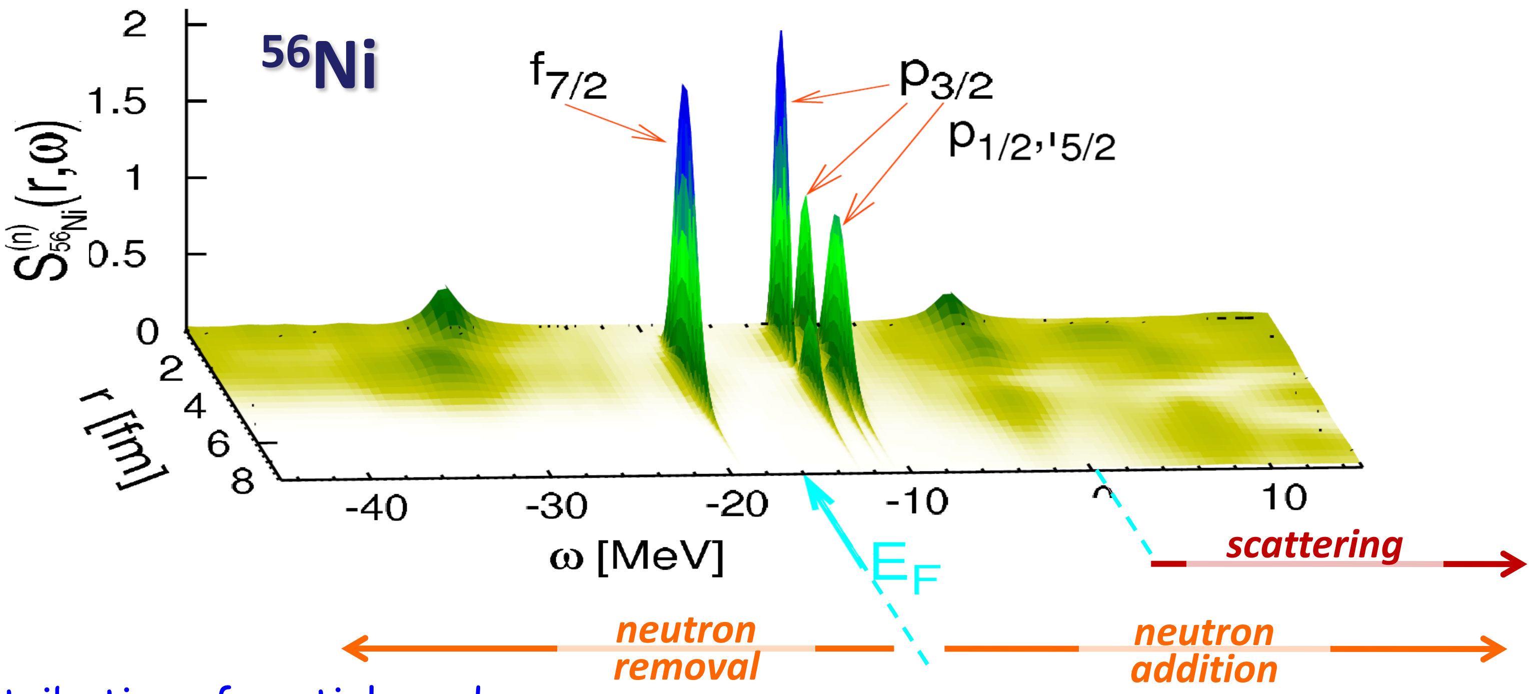
One-nucleon spectral function

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



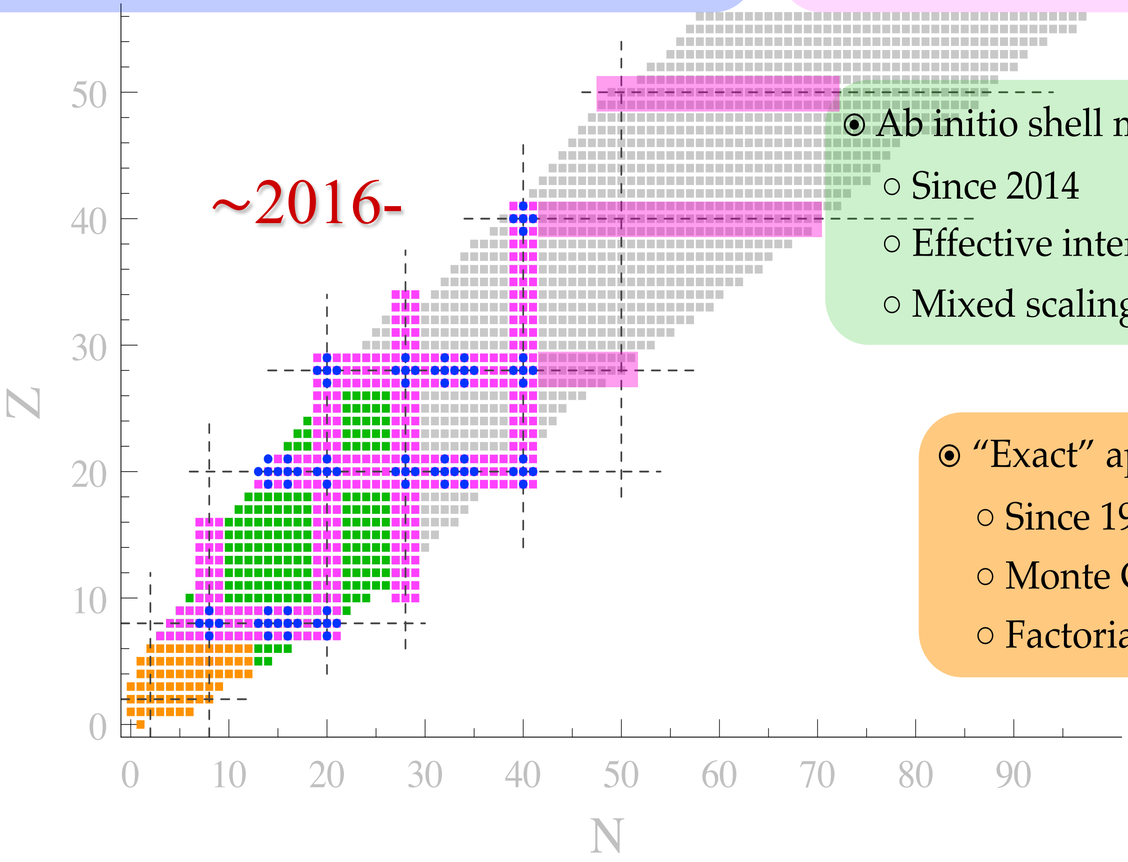
Distribution of particle and hole neutron states in ^{56}Ni

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

Reach of ab initio methods across the nuclear chart

- Approximate approaches for closed-shell nuclei
  - Since 2000's
  - SCGF, CC, IMSRG
  - Polynomial scaling

- Approximate approaches for open-shells
  - Since 2010's
  - GGF, BCC, MR-IMSRG
  - Polynomial scaling



- Ab initio shell model
  - Since 2014
  - Effective interaction via CC/IMSRG
  - Mixed scaling

- "Exact" approaches
  - Since 1980's
  - Monte Carlo, CI, …
  - Factorial scaling

Key developments in *SCGF*:

Dyson ADC(2), ADC(3)
Schirmer 1982

Dyson ADC(4), ADC(5)
Schirmer 1983 (formalism)

Particle-vibration coupling, FRPA(3)
CB 2000, 2007

Gorkov ADC(2): open shells!
Somà 2011, 2013

3-nucleon forces basic formalism
Carbone, Cipollone 2013

3NFs in Dyson ADC(3)
Raimondi 2018

Gorkov ADC(3) and higher orders (automatic)
Raimoindi, Arthuis 2019

Deformation
???

Symmetry restoration
???

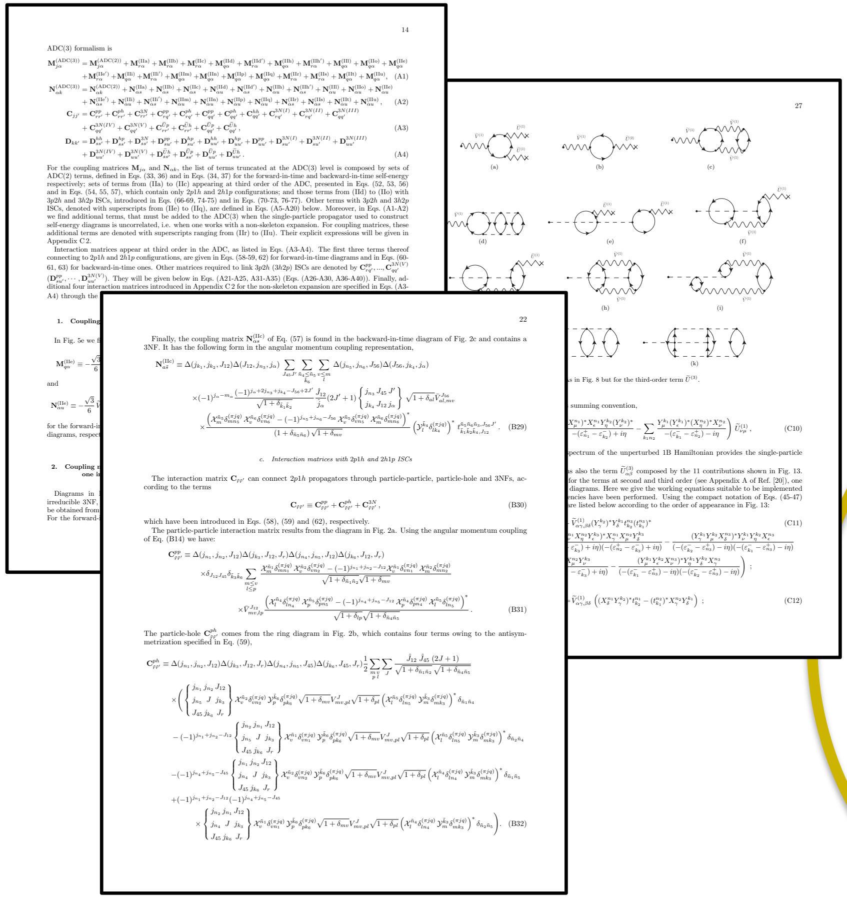
Slide, courtesy of V. Somà

sions for 1st & 2nd o

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

Inclusion of NNN forces

➔ 3p2h/3h2p terms relevant to next-generation high-precision methods.



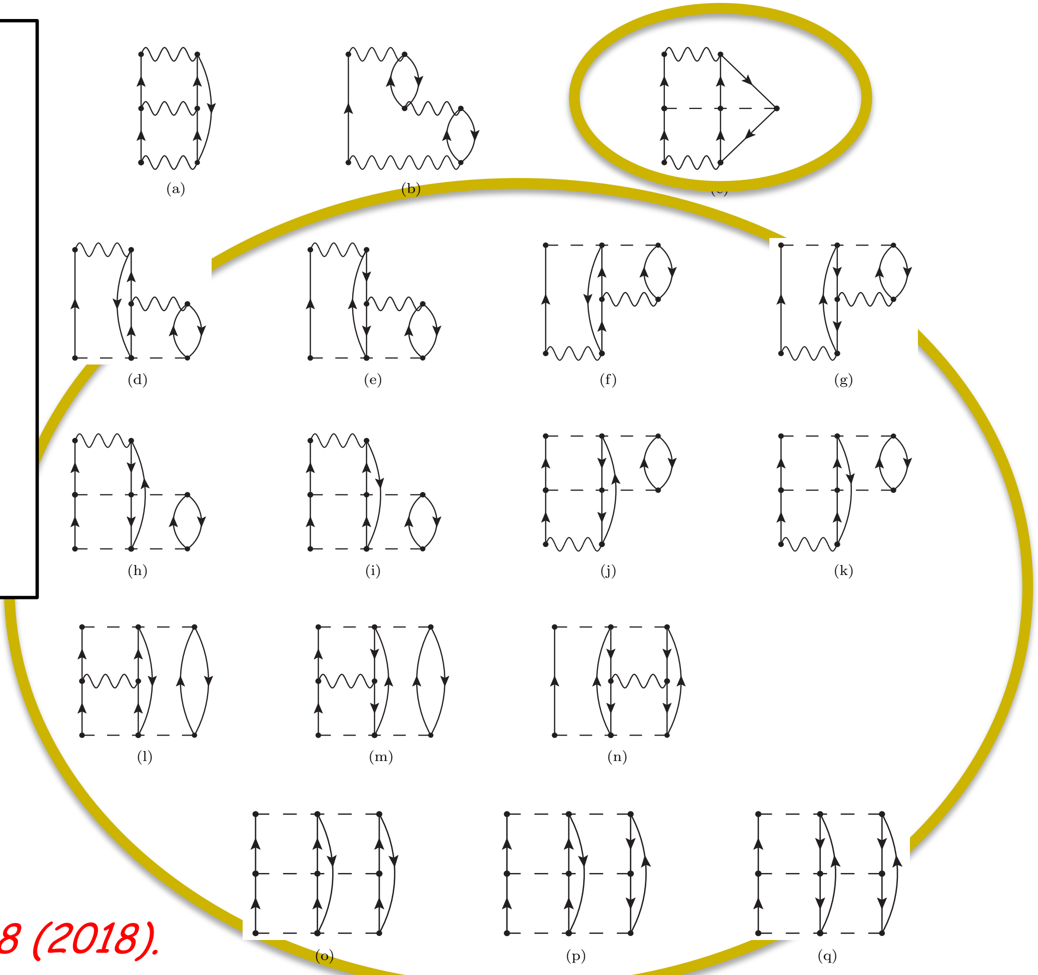
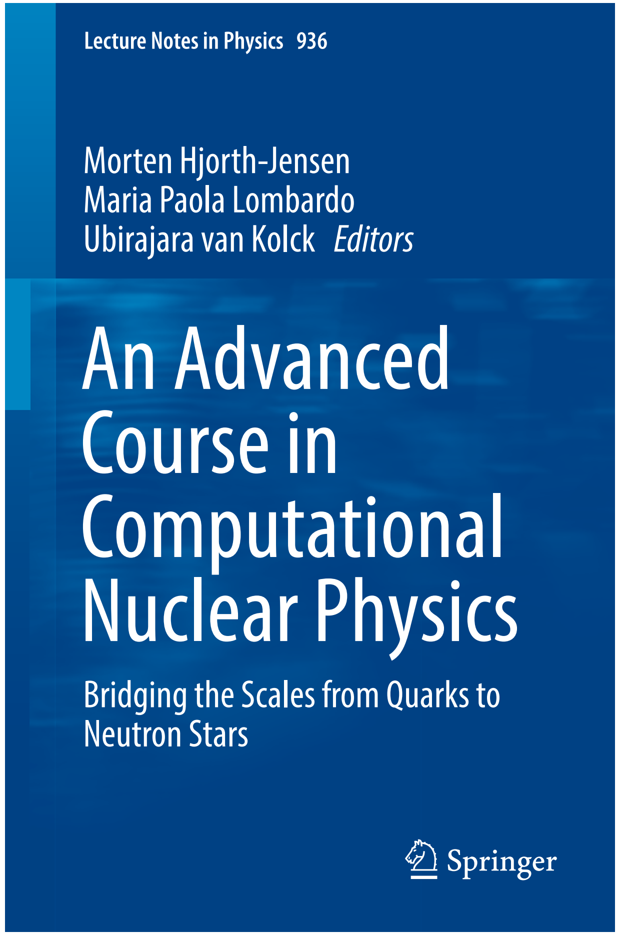


FIG. 5. 1PI, *skeleton* and *interaction irreducible* self-energy diagrams appearing at 3^{rd}-order in perturbative expansion (7), making use of the effective hamiltonian of Eq. (9).

Formalism already laid out:
F. Raimondi, CB, Phys. Rev. C97, 054308 (2018).

Ab-initio Nuclear Computation & BcDor code

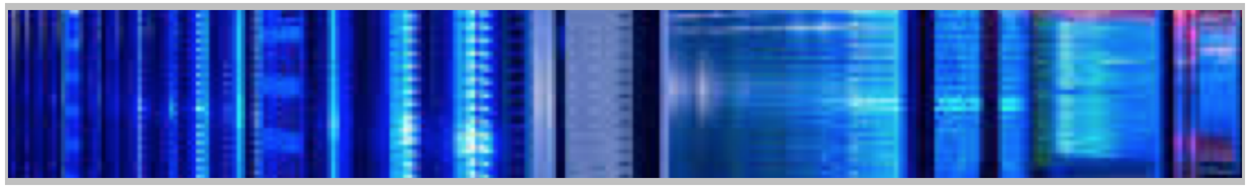
Self-consistent Green's function formalism
and methods for Nuclear Physics

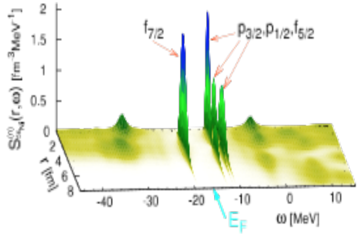


CB and A. Carbone,
chapter 11 of
Lecture Notes in Physics 936 (2017)

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)

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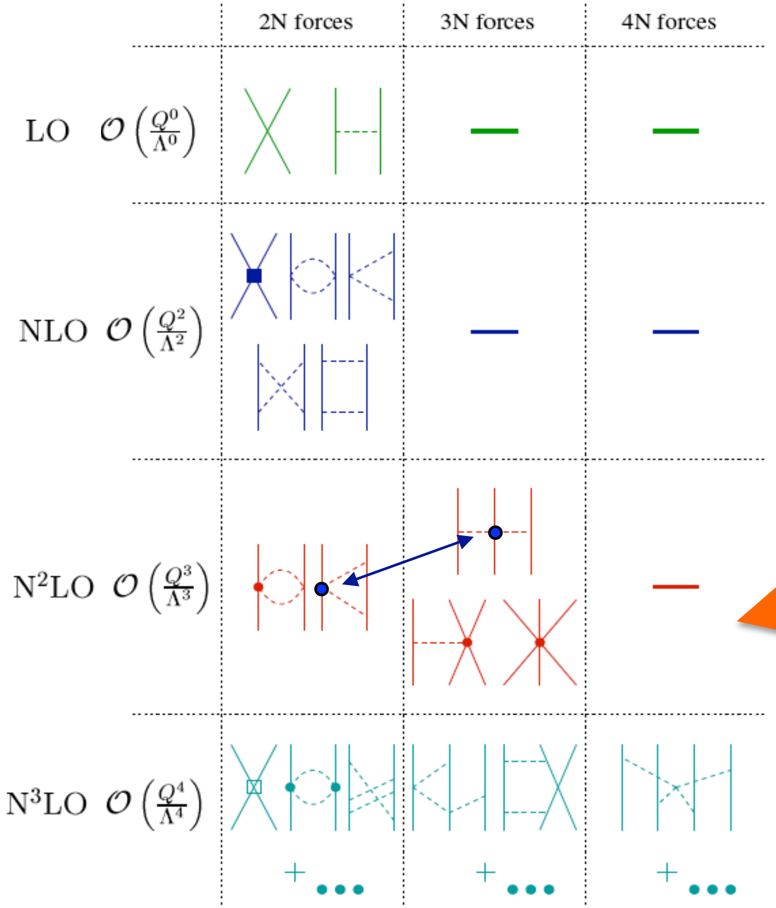
Chiral EFT interactions
and
3-nucleon forces

in mid-mass isotopes

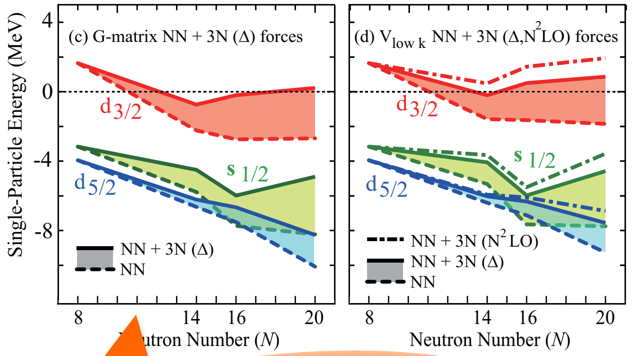
Realistic nuclear forces form Chiral EFT

Chiral EFT for nuclear forces:



(3NFs arise naturally at N2LO)

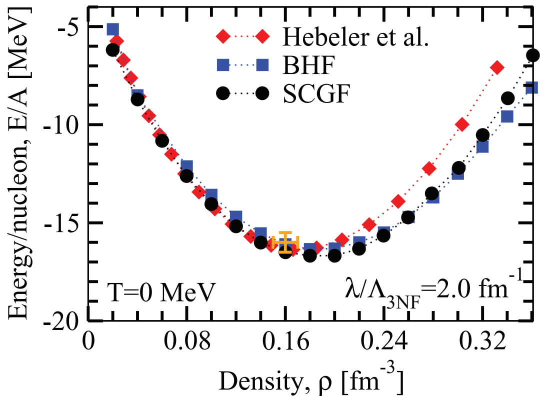
Single particle spectrum at E_{fermi}:



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

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

Saturation of nuclear matter:

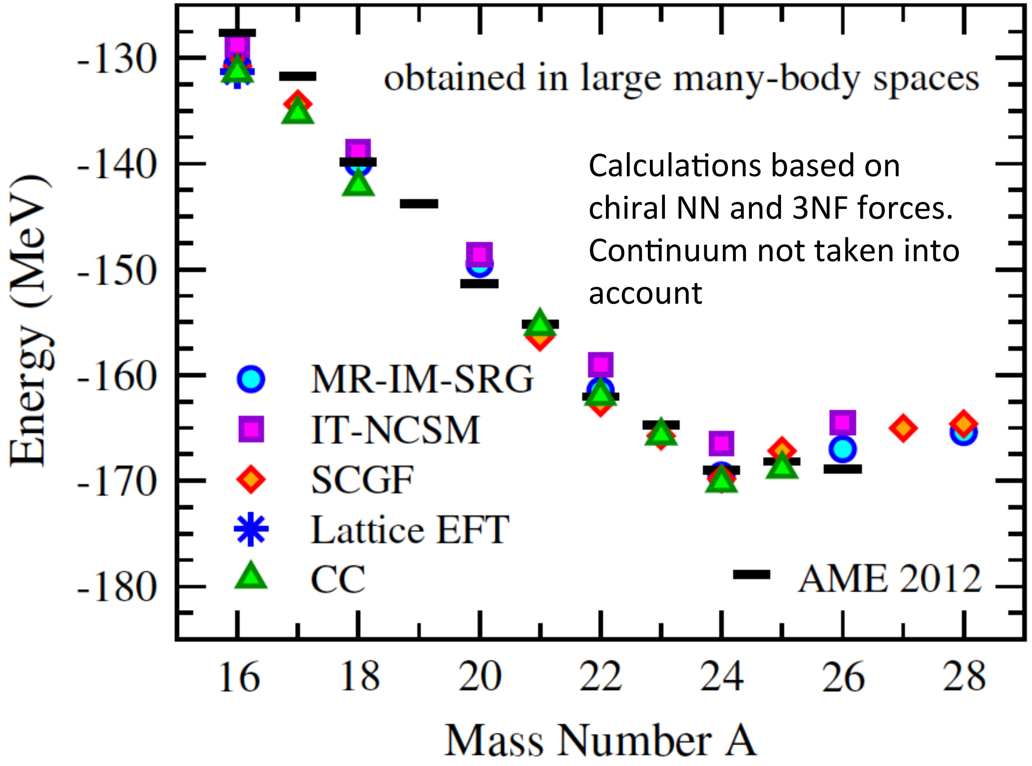


[A. Carbone et al., Phy.s Rev. C **88**, 044302 (2013)]

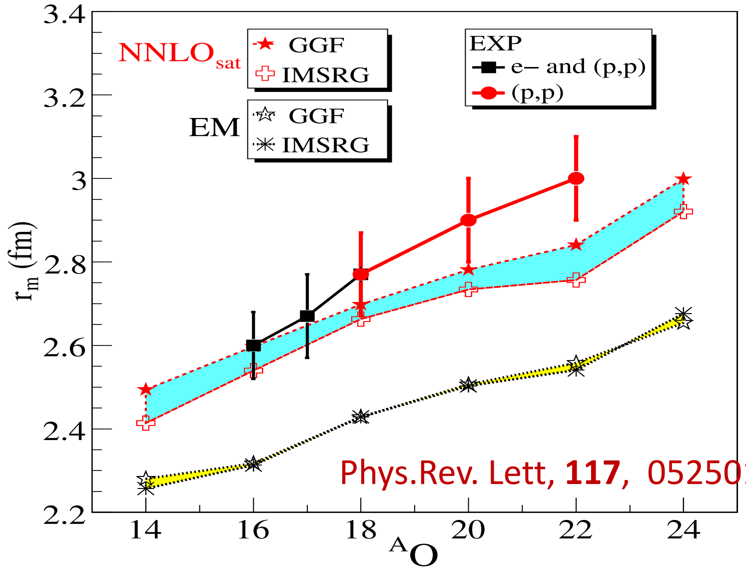
Benchmark of ab-initio methods for oxygen isotopic chain

First success of chital-EFT interactions on oxygen isotopes….

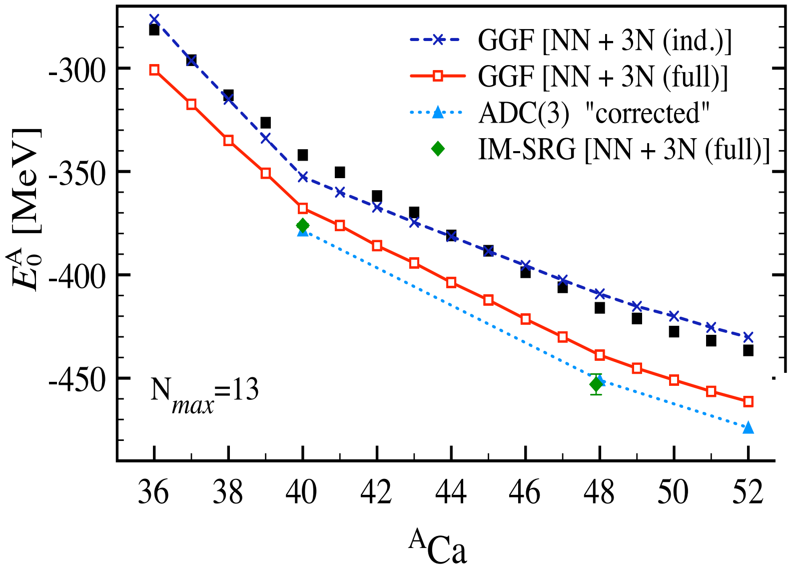
…but still poor for radii and larger isotopes:



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



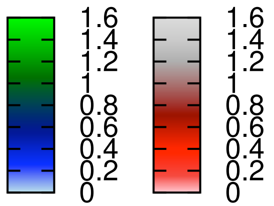
Phys.Rev. Lett, **117**, 052501 ('16)



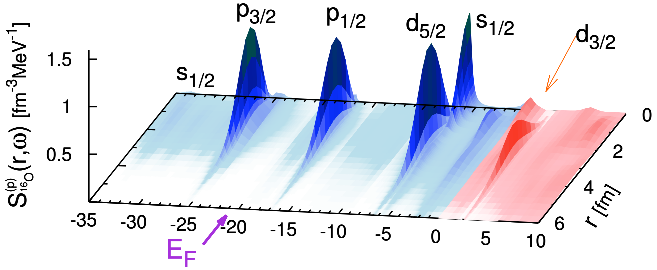
Phys. Rev. C**89**, 061301R (2014)

Neutron spectral function of Oxygens

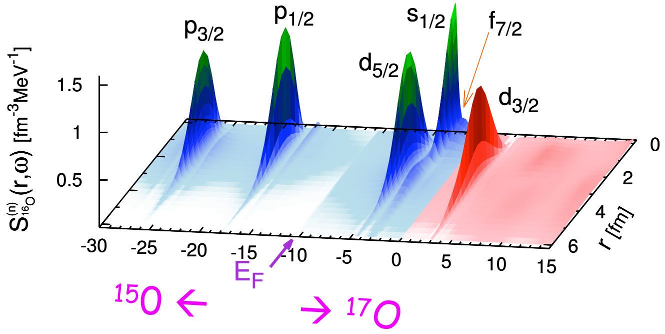
A. Cipollone, CB, P. Navrátil, *Phys. Rev. C* ***92**, 014306 (2015)*



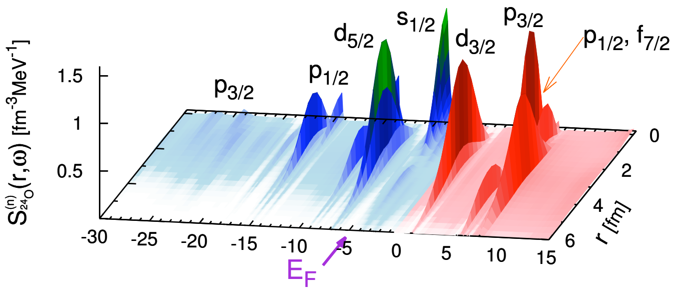
^{14}O:



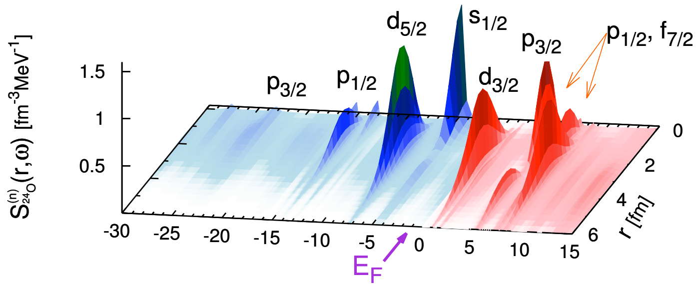
^{16}O:



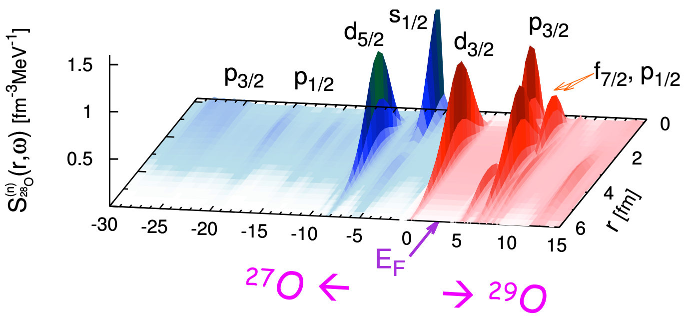
^{22}O:



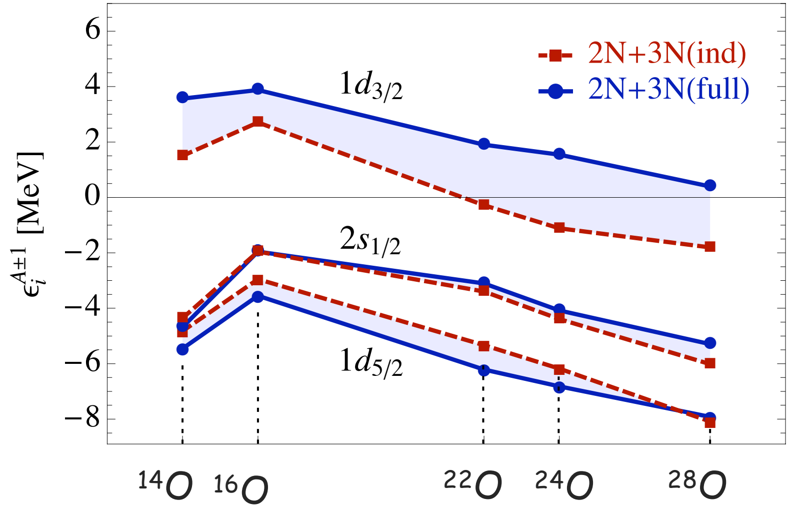
^{24}O:



^{28}O:

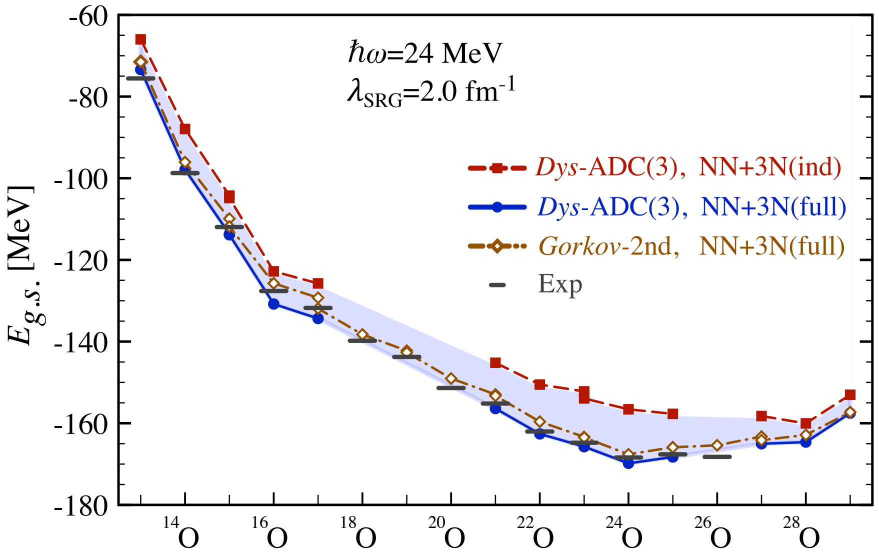


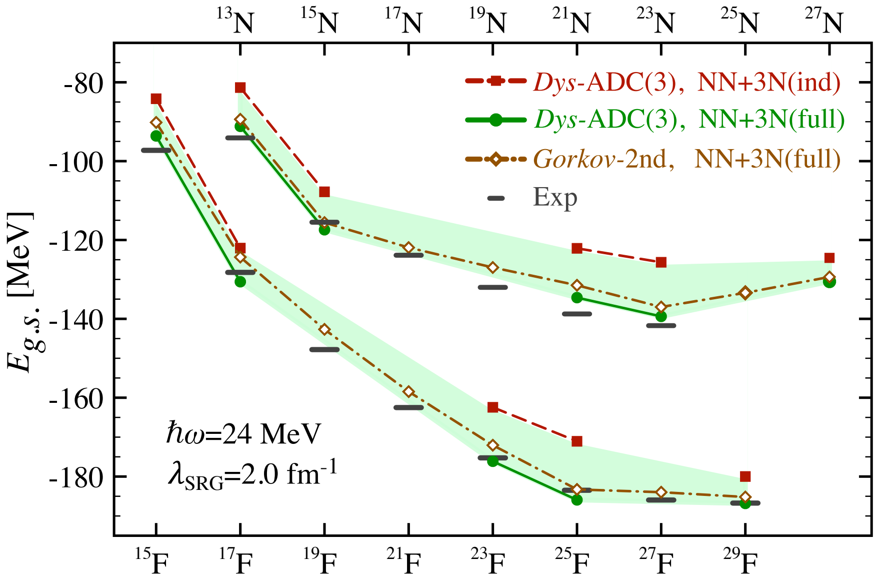
Neutron quasiparticle energies



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).]

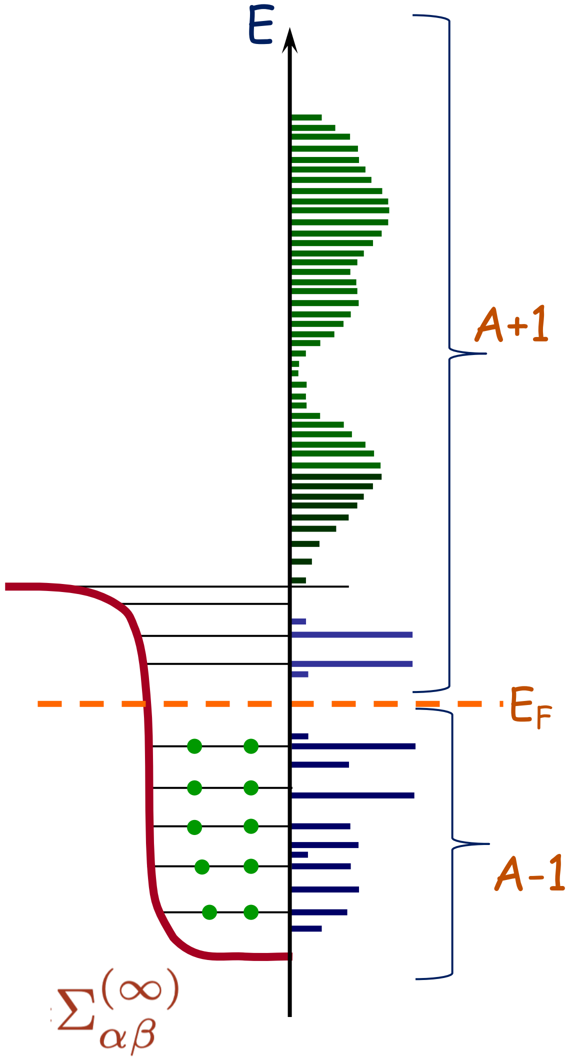
N3LO (Λ = 500Mev/c) chiral NN interaction evolved to 2N + 3N forces (2.0fm^{-1})
N2LO (Λ = 400Mev/c) chiral 3N interaction evolved (2.0fm^{-1})

Ab initio optical potentials from propagator theory

Relation to Fesbach theory:
Mahaux & Sartor, Adv. Nucl. Phys. 20 (1991)
Escher & Jennings Phys. Rev. C**66**, 034313 (2002)

Previous SCGF work:
CB, B. Jennings, Phys. Rev. C**72**, 014613 (2005)
S. Waldecker, CB, W. Dickhoff, Phys. Rev. C**84**, 034616 (2011)
A. Idini, CB, P. Navrátil, Phys. Rv. Lett. **123**, 092501 (2019)

Microscopic optical potential

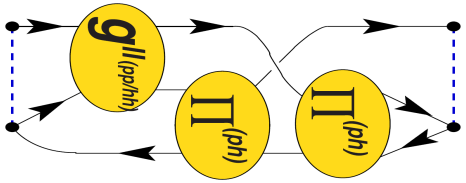


Nuclear self-energy $\Sigma^\star(\mathbf{r},\mathbf{r}';\varepsilon)$:

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

$$\Sigma^\star_{\alpha\beta}(\omega) = \Sigma^{(\infty)}_{\alpha\beta} + \underbrace{\sum_{i,j} \mathbf{M}^\dagger_{\alpha,i}\left[\frac{1}{E-(\mathbf{K}^>+\mathbf{C})+i\Gamma}\right]_{i,j}\mathbf{M}_{j,\beta} + \sum_{r,s}\mathbf{N}_{\alpha,r}\left[\frac{1}{E-(\mathbf{K}^<+\mathbf{D})-i\Gamma}\right]_{r,s}\mathbf{N}^\dagger_{s,\beta}}_{\text{Particle-vibration couplings}}$$

mean-field



Solve scattering and overlap functions directly in momentum space:

$$\Sigma^{\star\, l,j}(k,k';E) = \sum_{n,\,n'} R_{n\,l}(k)\,\Sigma^{\star\, l,j}_{n,\,n'}\,R_{n\,l}(k')$$

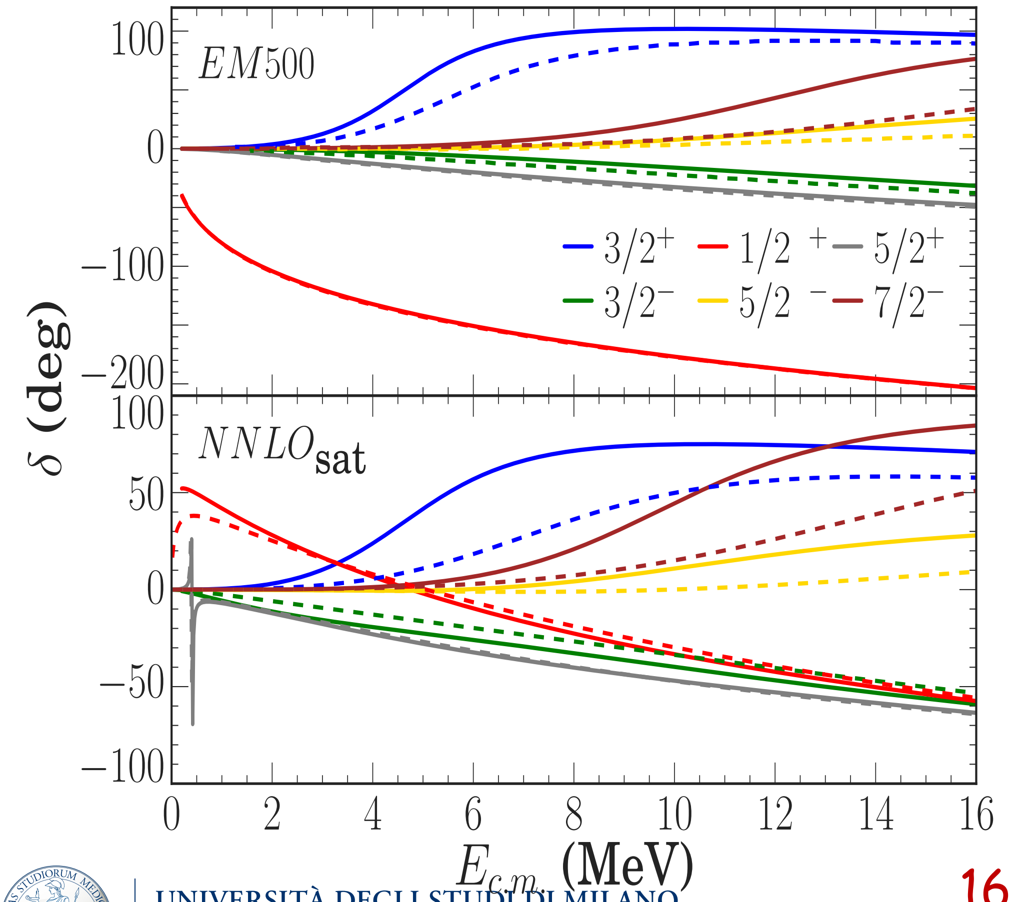
$$\frac{k^2}{2\mu}\psi_{l,j}(k) + \int \mathrm{d}k'\,k'^2\,\Sigma^{\star l,j}(k,k';E_{c.m.})\psi_{l,j}(k') = E_{c.m.}\psi_{l,j}(k)$$

Low energy scattering – from SCGF

[A. Idini, CB, Navratil,
Phys. Rev. Lett. **123**, 092501 (2019)]

Benchmark with NCSM-based scattering.

Scattering from mean-field only:



- - - - - - NCSM/RGM [without core excitations]

EM500: NN-SRG λ_{SRG}= 2.66 fm^{-1}, Nmax=18 (IT)
[PRC**82**, 034609 (2010)]

NNLOsat: Nmax=8 (IT-NCSM)

——— SCGF [$\Sigma^{(\infty)}$ only], always Nmax=13

$^{16}O(n,n')^{16}O$

Low energy scattering – from SCGF

[A. Idini, CB, Navratil,
Phys. Rev. Lett. **123**, 092501 (2019)]

Benchmark with NCSM-based scattering.

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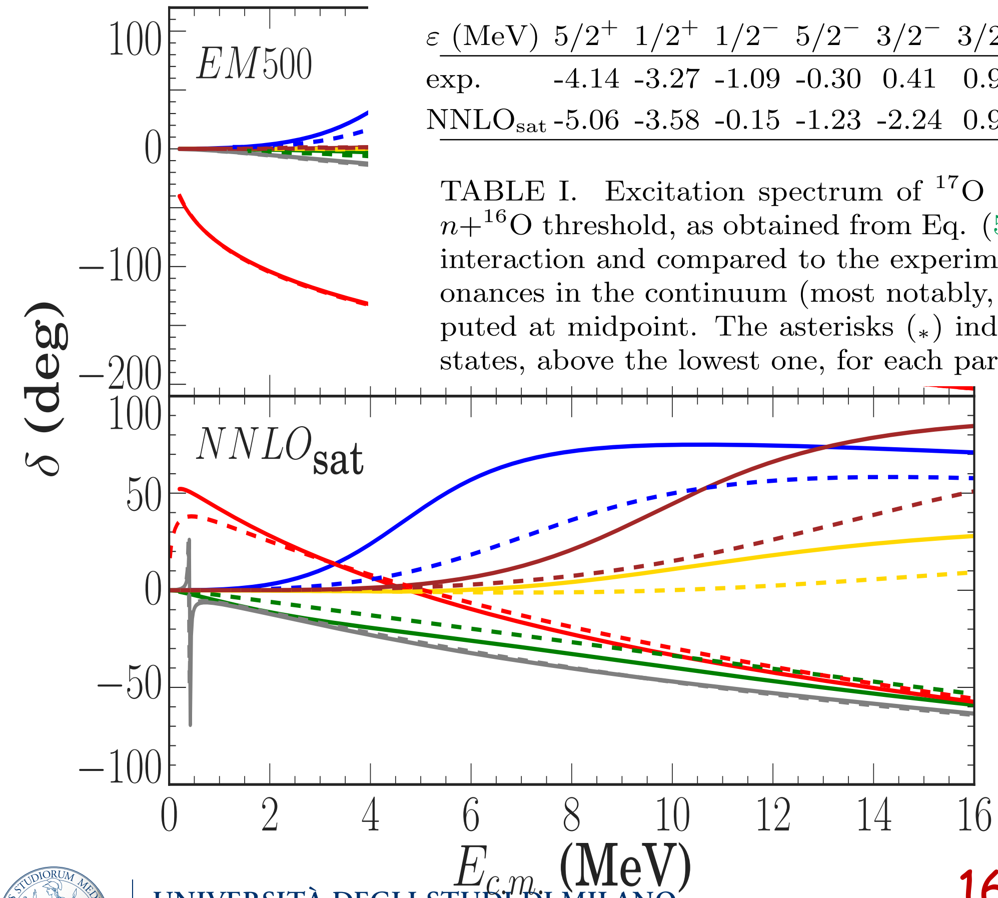
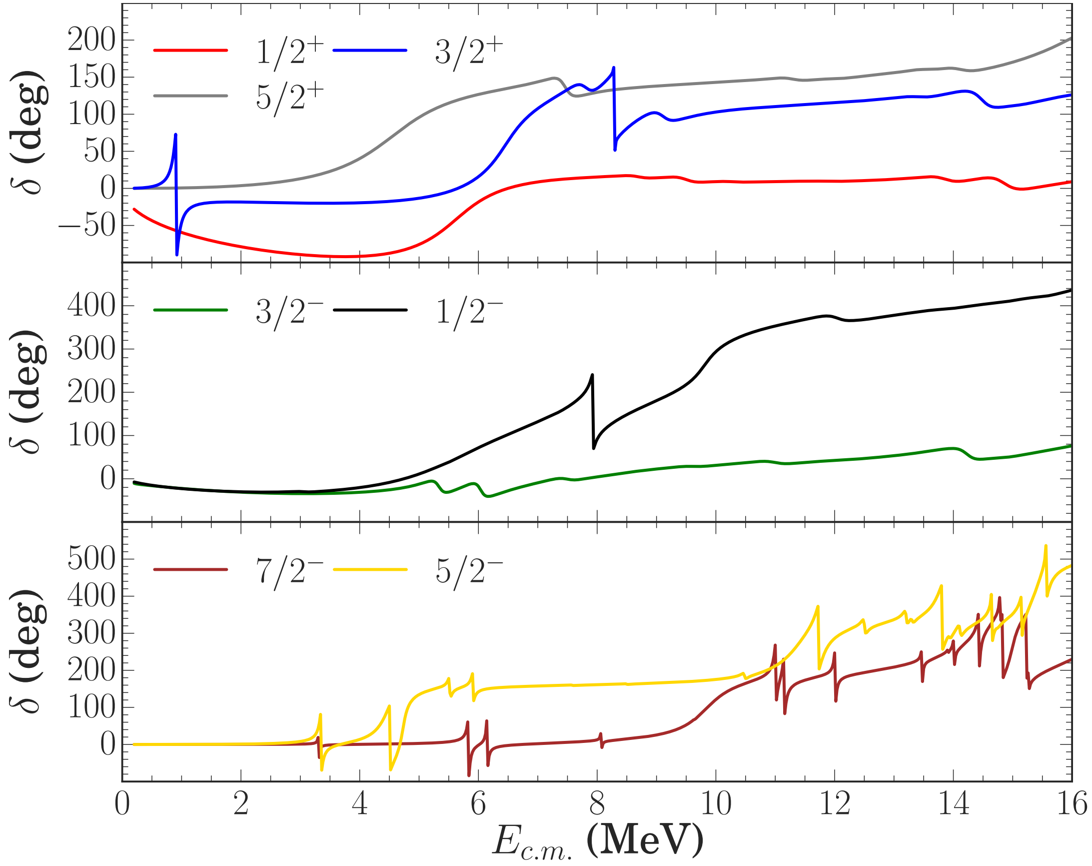


ε (MeV)	$5/2^+$	$1/2^+$	$1/2^-$	$5/2^-$	$3/2^-$	$3/2^+$	$5/2^+_*$	$5/2^-_*$	$7/2^-_*$
exp.	-4.14	-3.27	-1.09	-0.30	0.41	0.94	3.23	3.02	3.54
NNLO$_{\rm sat}$	-5.06	-3.58	-0.15	-1.23	-2.24	0.91	4.57	3.36	3.37

TABLE I. Excitation spectrum of ^{17}O with respect to the n+^{16}O threshold, as obtained from Eq. (5) and the NNLO$_{\rm sat}$ interaction and compared to the experiment [45]. Broad resonances in the continuum (most notably, the $5/2^+$) are computed at midpoint. The asterisks ($_*$) indicate higher excited states, above the lowest one, for each partial wave.

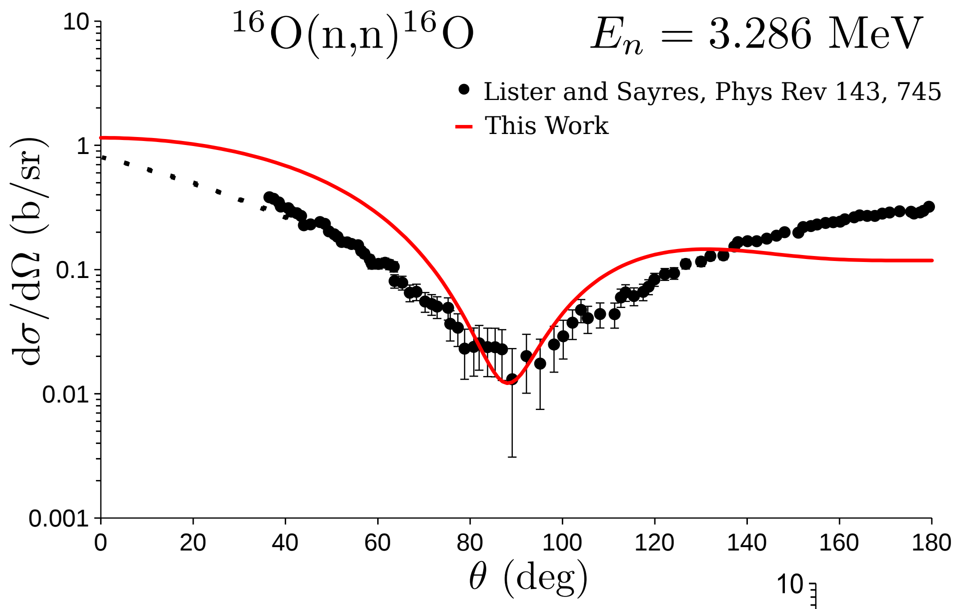
Full self-energy from SCGF:

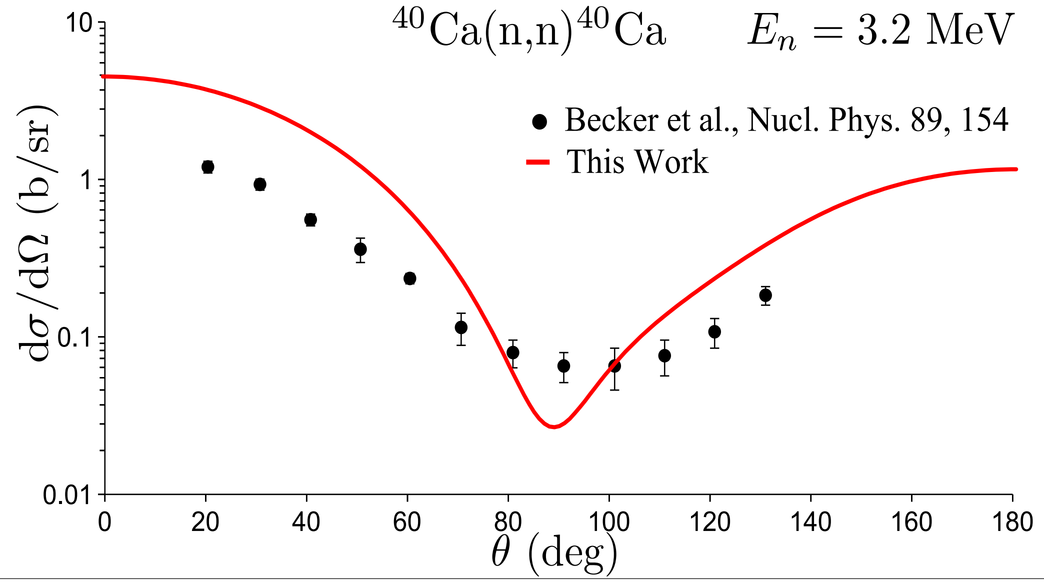


$^{16}O(n,n')^{16}O$

Low energy scattering - from SCGF

[A. Idini, CB, Navrátil, PRL**123**, 092501 (2019)]

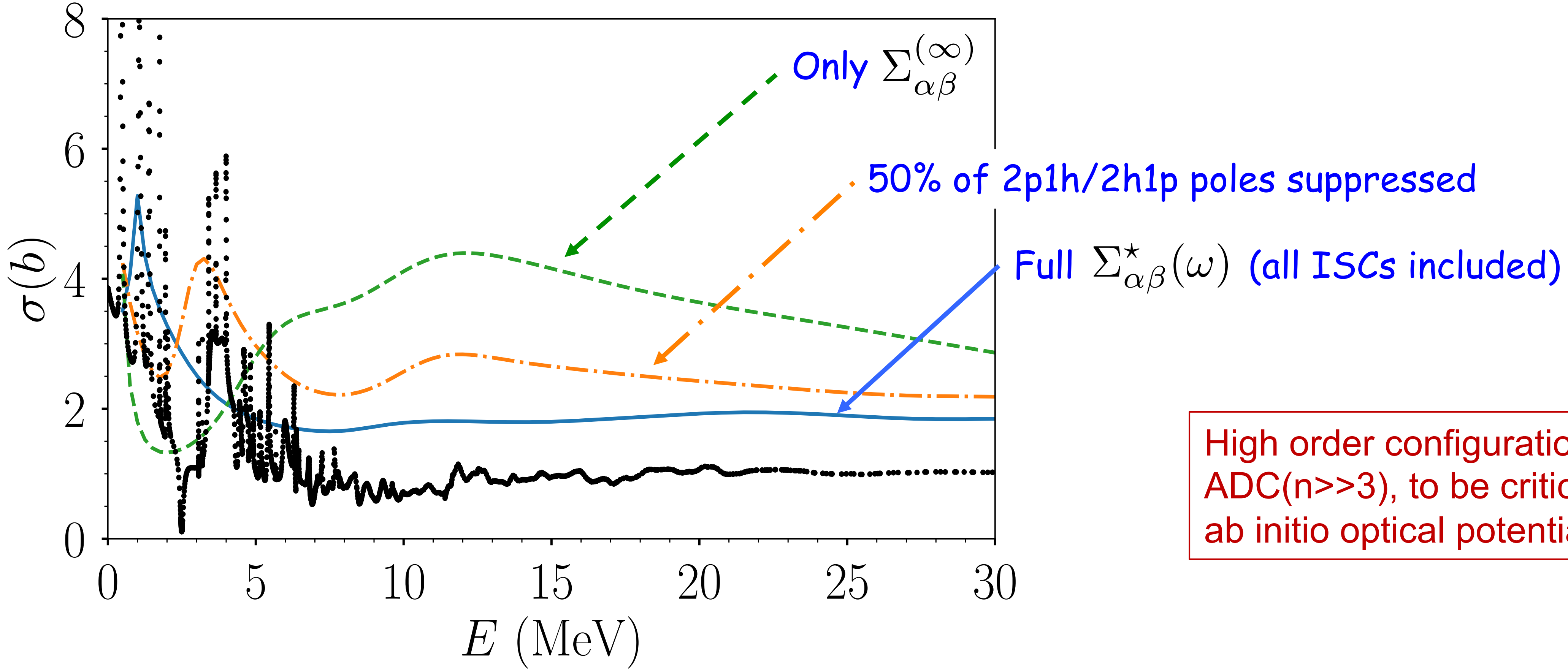




Role of intermediate state configurations (ISCs)

n-^{16}O, total elastic cross section

[A. Idini, CB, Navratil, Phys. Rev. Lett. **123**, 092501 (2019)]



High order configurations, or ADC(n>>3), to be critical for fully ab initio optical potentials

$$\Sigma^{\star}_{\alpha\beta}(\omega) = \Sigma^{(\infty)}_{\alpha\beta} + \sum_{i,j} \mathbf{M}^{\dagger}_{\alpha,i} \underbrace{\left[\frac{1}{E-(\mathbf{K}^{>}+\mathbf{C})+i\Gamma} \right]_{i,j}}_{\text{2p1h}} \mathbf{M}_{j,\beta} + \sum_{r,s} \mathbf{N}_{\alpha,r} \underbrace{\left[\frac{1}{E-(\mathbf{K}^{<}+\mathbf{D})-i\Gamma} \right]_{r,s}}_{\text{2h1p}} \mathbf{N}^{\dagger}_{s,\beta}$$

Reaching large isotopes

(electron scattering and charge radii)

P. Arthuis, CB, M. Vorabbi, P. Finelli, Phys. Rev. Lett. **125**, 182501 (2020)]

Electron-Ion Trap colliders…

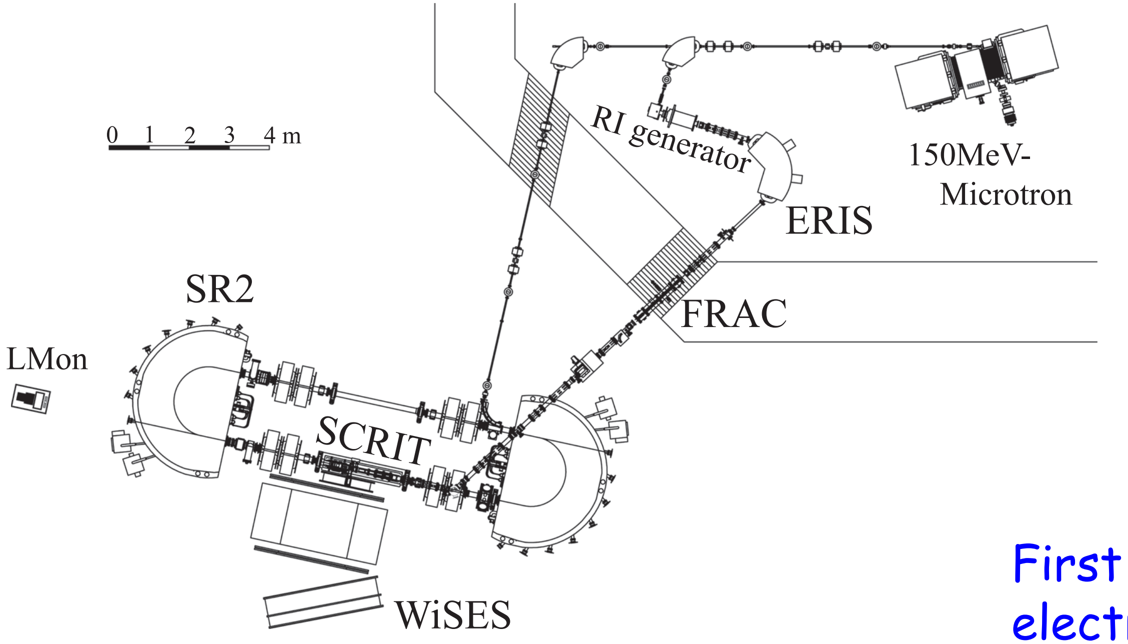


FIG. 1. Overview of the SCRIT electron scattering facility.

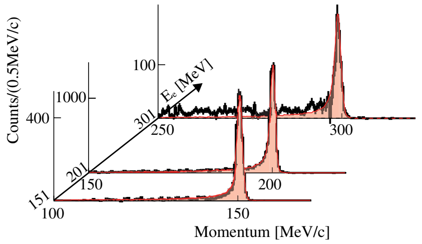
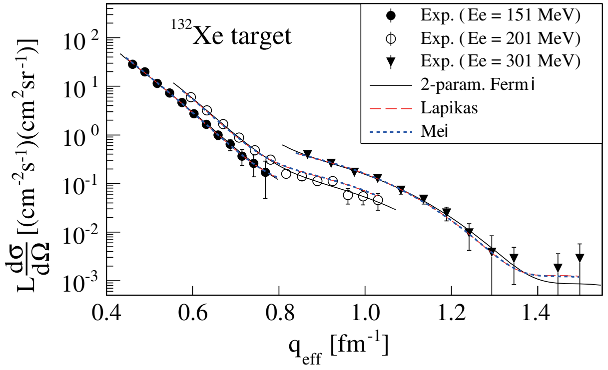


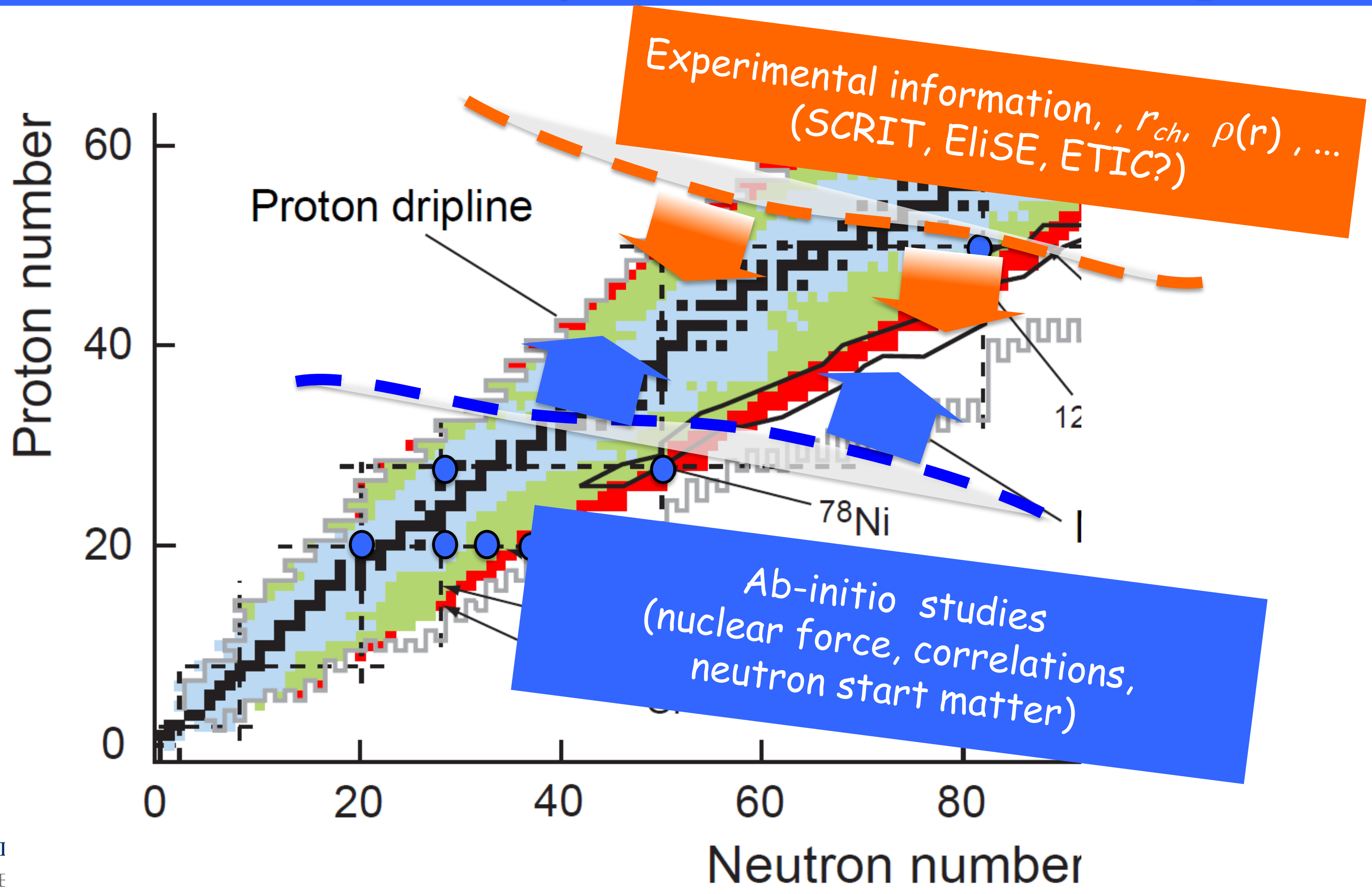
FIG. 3. Reconstructed momentum spectra of ^{132}Xe target after background subtraction. Red shaded lines are the simulated radiation tails following the elastic peaks.



First ever measurement of charge radii through electron scattering with and ion trap setting that *can be used on radioactive isotopes* !!

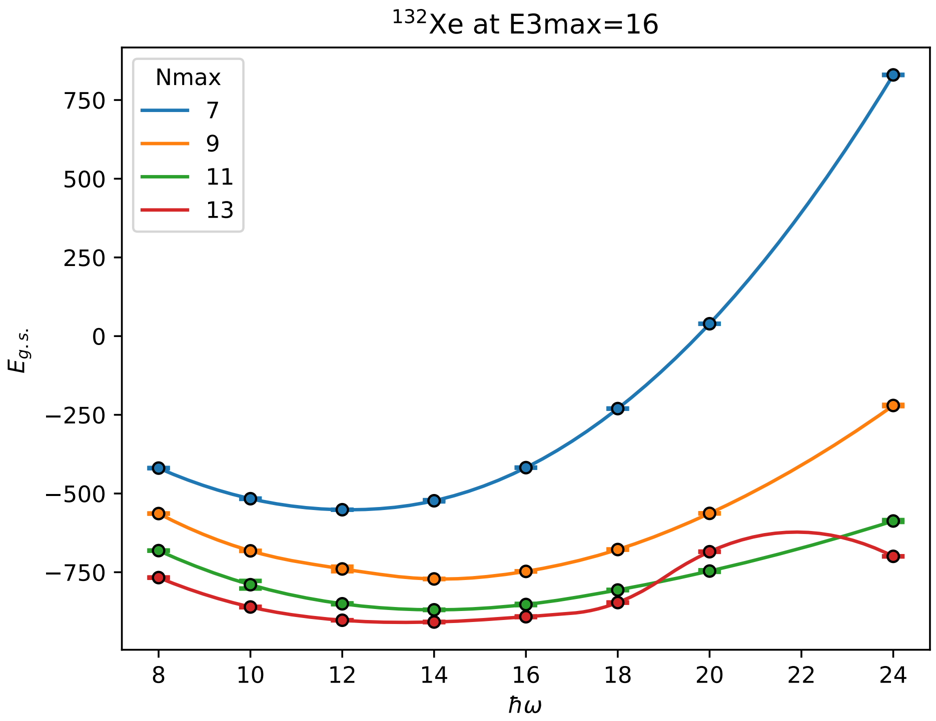
K. Tsukada *et al.*, Phy rev Lett **118**, 262501 (2017)

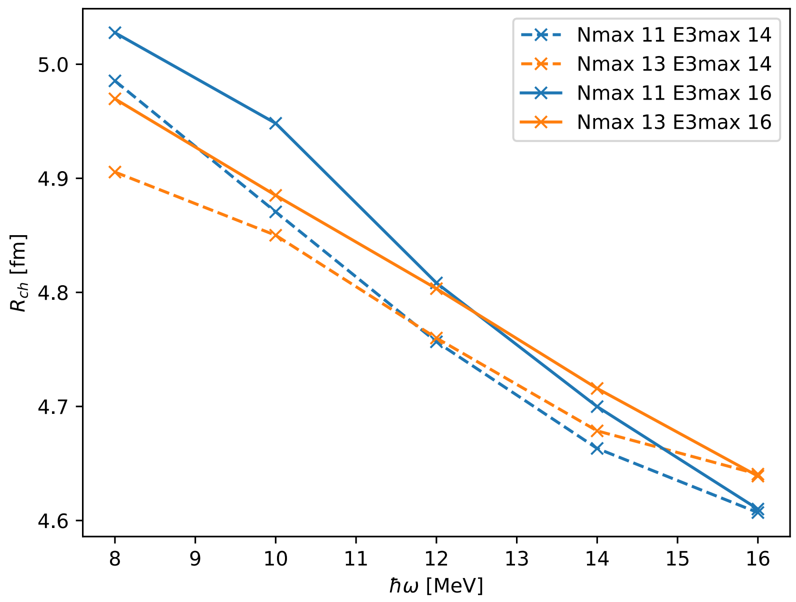
unstable isotopes from e⁻ scattering



Convergence in large isotopes – e.g. ^{132}Xe

Gorkov ADC(2) with NNLOsat Hamiltonian





Energies still badly converging…
- Nmax converges slowly…
- E3max (# of 3NFs elements) out of control

Radii converge much better and can be bracketed!

P. Arthuis, CB, M. Vorabbi, P. Finelli - arXiv:2002.02214

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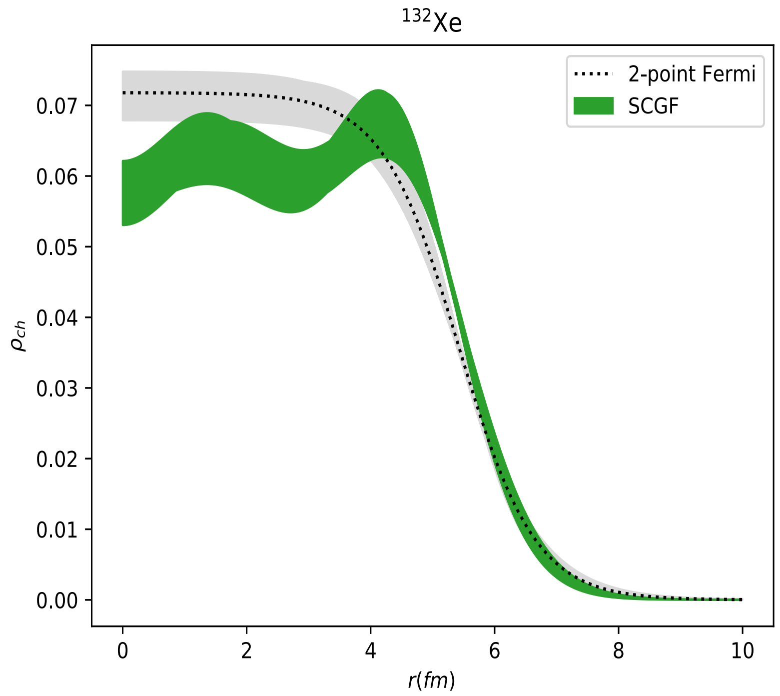
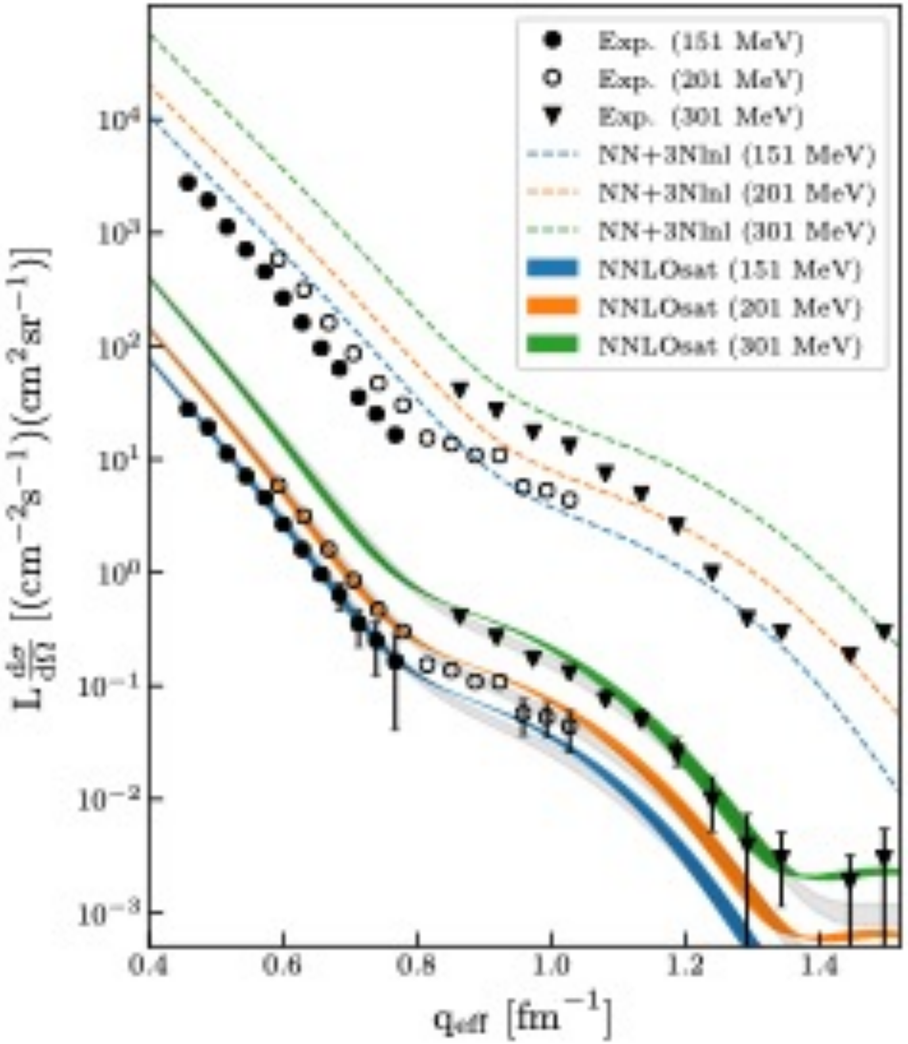
Convergence in large isotopes – e.g. ^{132}Xe

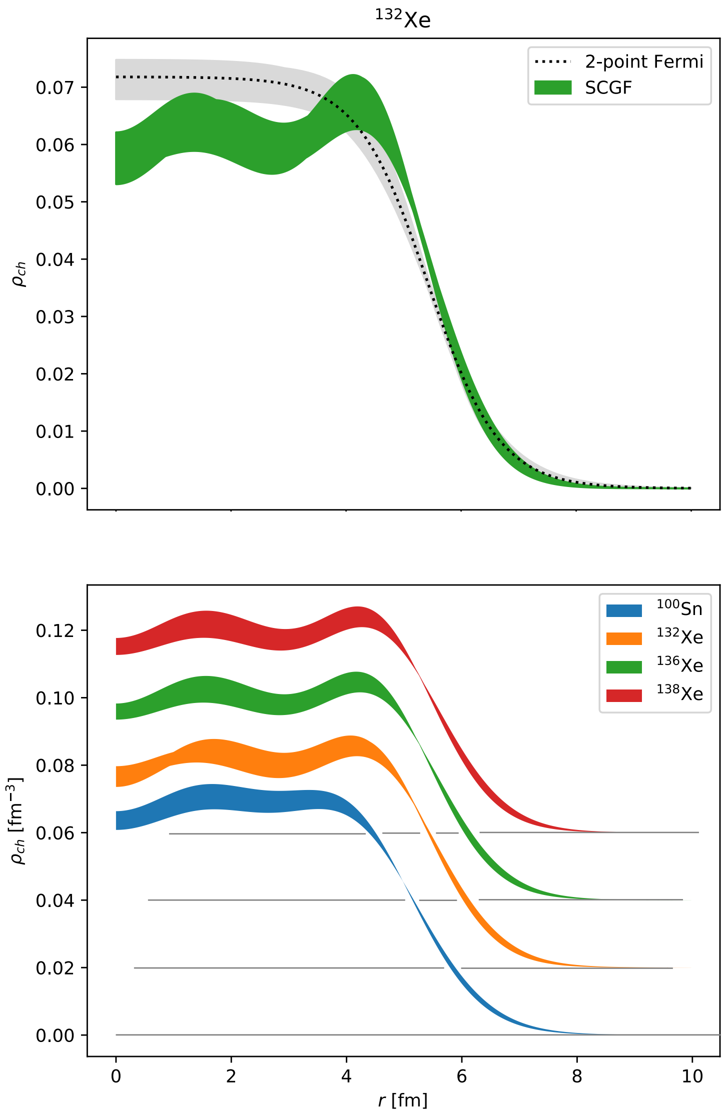
Gorkov ADC(2) with NNLOsat Hamiltonian





P. Arthuis, *CB*, *M. Vorabbi*, *P. Finelli* - arXiv:2002.02214

Sn and Xe isotopes



Gorkov ADC(2) and Dyson ADC(3) with NNLOsat Hamiltonian

	SCGF	Exp.
^{100}Sn	4.525 – 4.707	
^{132}Sn	4.725 – 4.956	4.7093
^{132}Xe	4.700 – 4.948	4.7859
^{136}Xe	4.715 – 4.928	4.7964
^{138}Xe	4.724 – 4.941	4.8279

P. Arthuis, CB, M. Vorabbi, P. Finelli - arXiv:2002.02214

Study of nuclear interactions from Lattice QCD

*C. McIlroy, CB et al. Phys. Rev. C**97**, 021303(R) (2018)*
D. Lonardoni et al. - in preparation

In collaboration with:

Hadrons to Atomic nuclei
HAL
from Lattice QCD

Why nuclear interactions on the Lattice???

- Alternative approach to EFT -- This is ”true” QCD, <u>not</u> a low-k expansion thereof
- Not based on a specific EFT momentum scale exploitable to high densities (e.g. Neutron stars)
- No need to worry about cutoffs,   no LECs to worry about   ...AND:
- Variation in potentials from variation in sink operators (estimate uncertainties, missing N-body terms, etc…)
- Direct derivation of hyperon-nucleon interactions
- Built to reproduce exactly QCD *NN, 3N,* observables *that would be computed with Lattice QCD.*
- Natural hierarchy of many-nucleon interactions (2NF, 3NF, etc…) occurs.
- Eigenstates below inelastic threshold all included in the interactions (no need to evolve DMC to the g.s.).

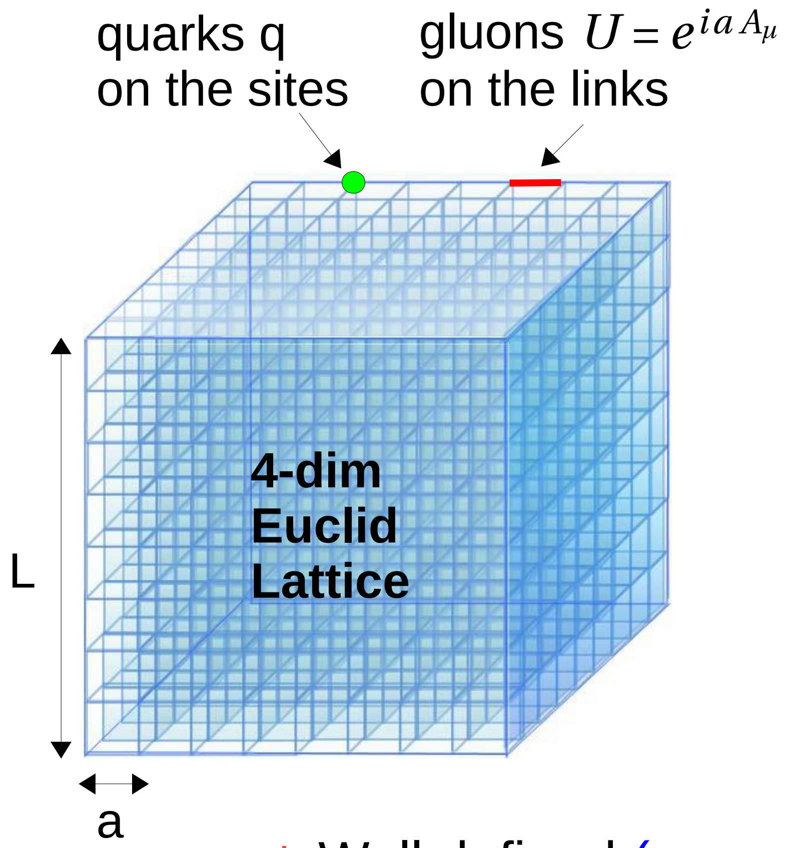
Challenges and limitations: *- Mostly LO terms of the NN force exploited so far (but being improved).*
- Physical pion mass limit underway (but it requires efforts).
- NNN only barely addressed.
- Strong short-range repulsion is a challenge to ab-initio approaches.

Hadrons to Atomic nuclei
HAL
from Lattice QCD

➔ *Need to develop appropriate many-body methods*

Lattice QCD

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



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

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

{ Ui } : 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

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:

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

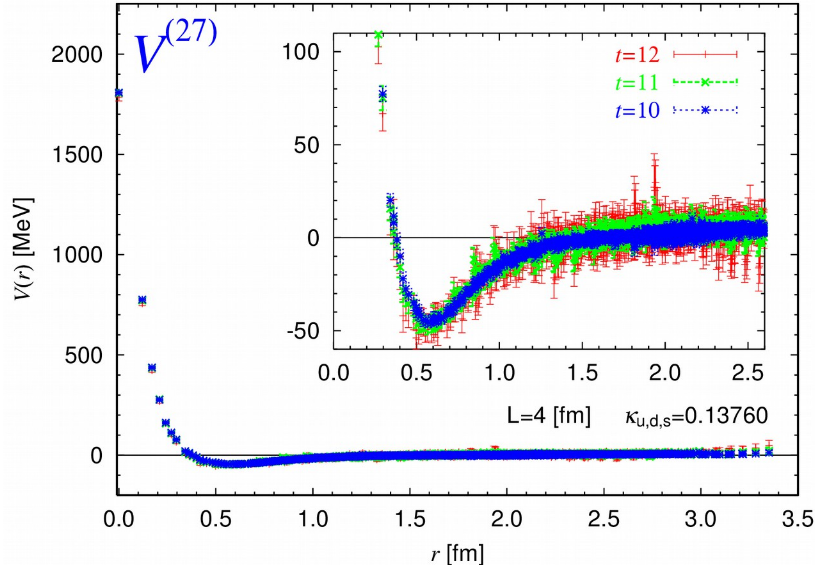
$$\Rightarrow\; V(\vec{r}) = \frac{1}{2\mu}\frac{\nabla^2\psi(\vec{r},t)}{\psi(\vec{r},t)} - \frac{\frac{\partial}{\partial t}\psi(\vec{r},t)}{\psi(\vec{r},t)} - 2M_B$$

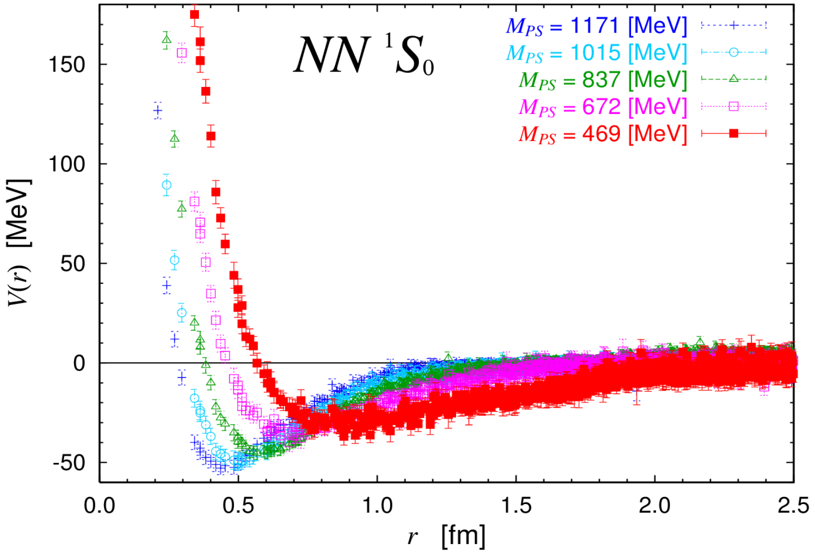
Tensor/Yukawa force in S-D

Spin-orbit force, P waves

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

Two-Nucleon HAL potentials in flavour SU(3) symm.





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

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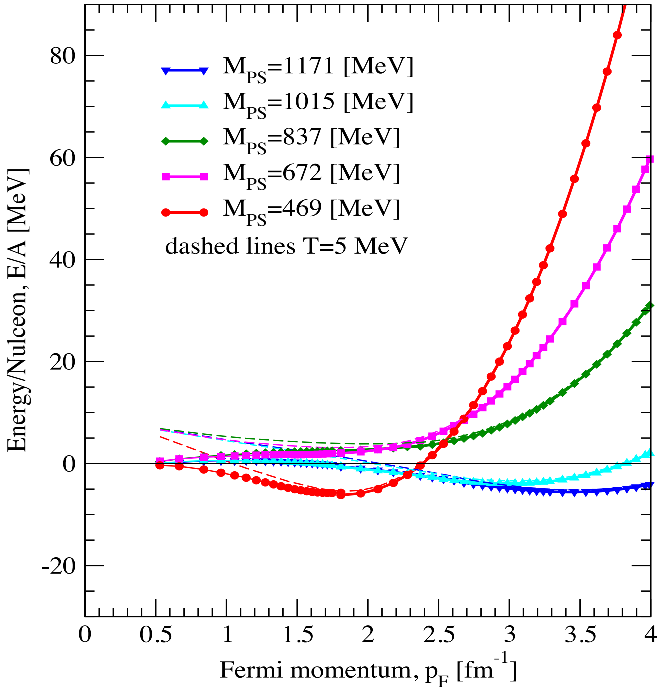
← HALQCD method; see talk from K. Sasaki, today!

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.

m_π =047Gev/C^2 binds nuclear matter:



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

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

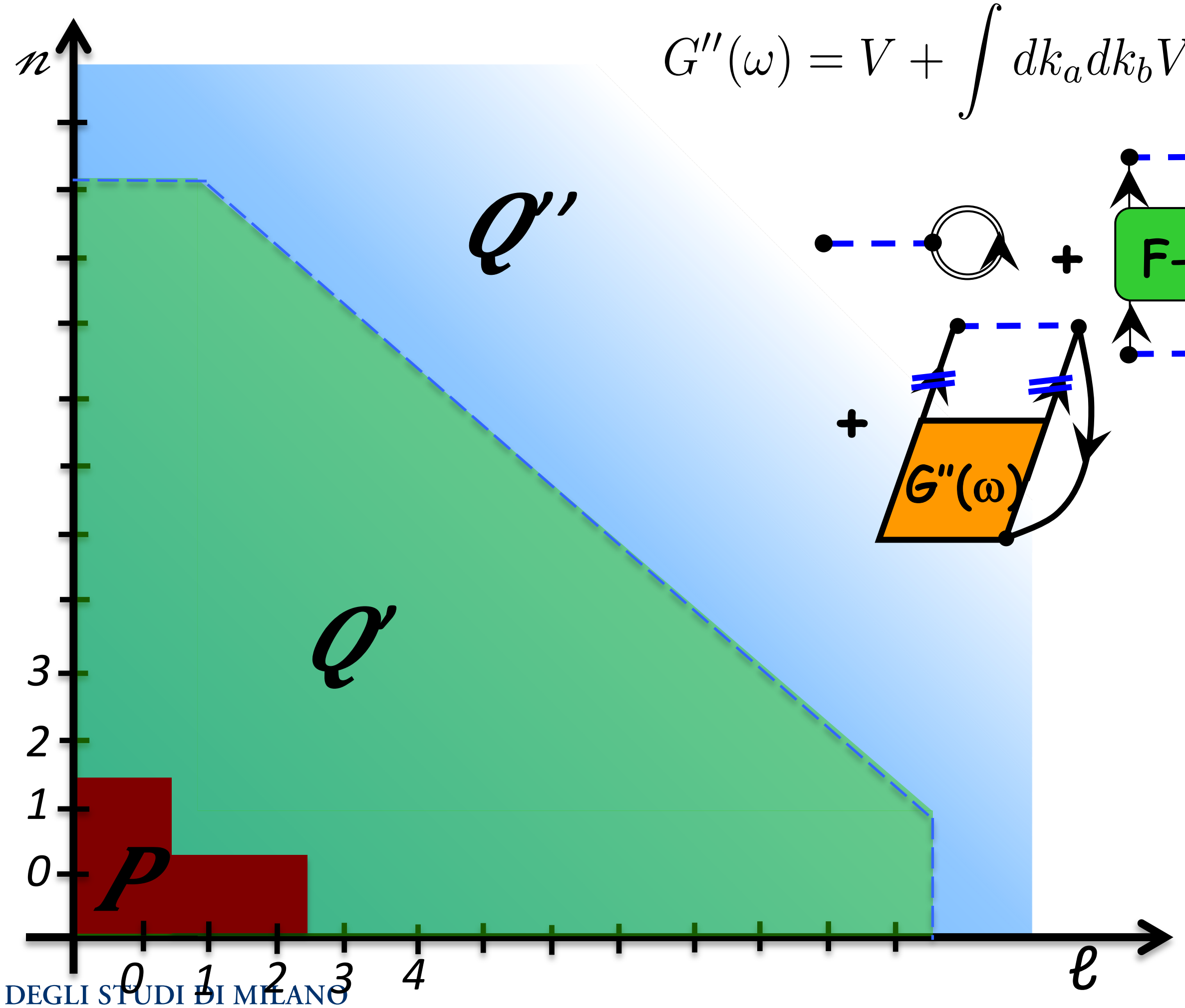
Application of microscopic (*ab initio*) SCGF to potentials with hard cores.

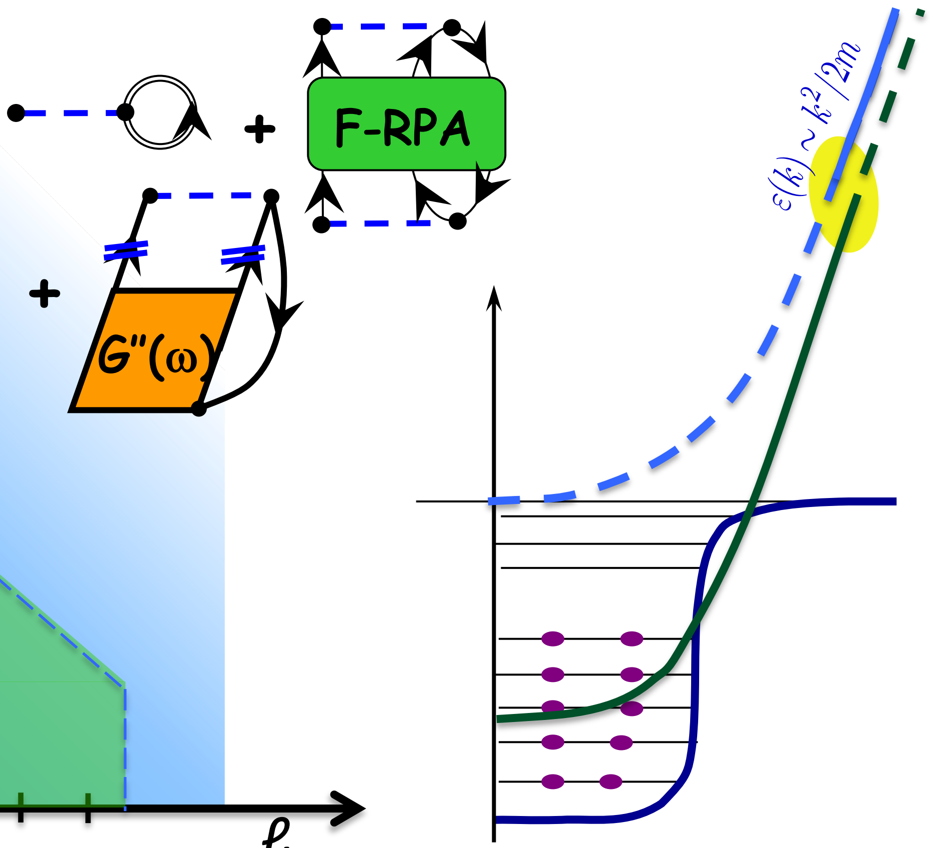
How do we do it?? → *With a G-matrix!*

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):

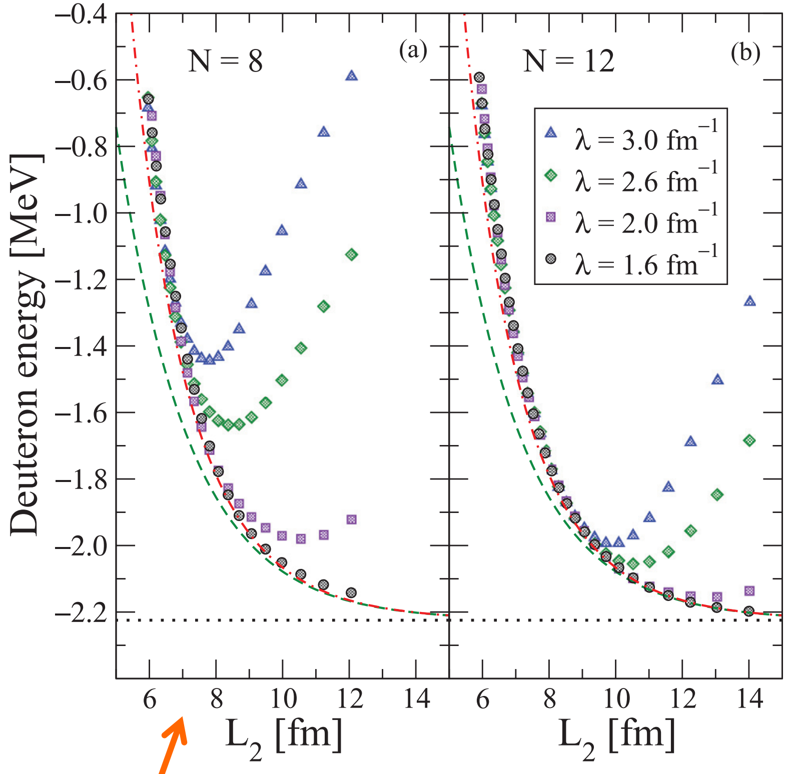
$$G''(\omega) = V + \int dk_a dk_b V \frac{\hat{Q}''}{\omega - \varepsilon(k_a) - \varepsilon(k_b) + i\eta} G''(\omega)$$

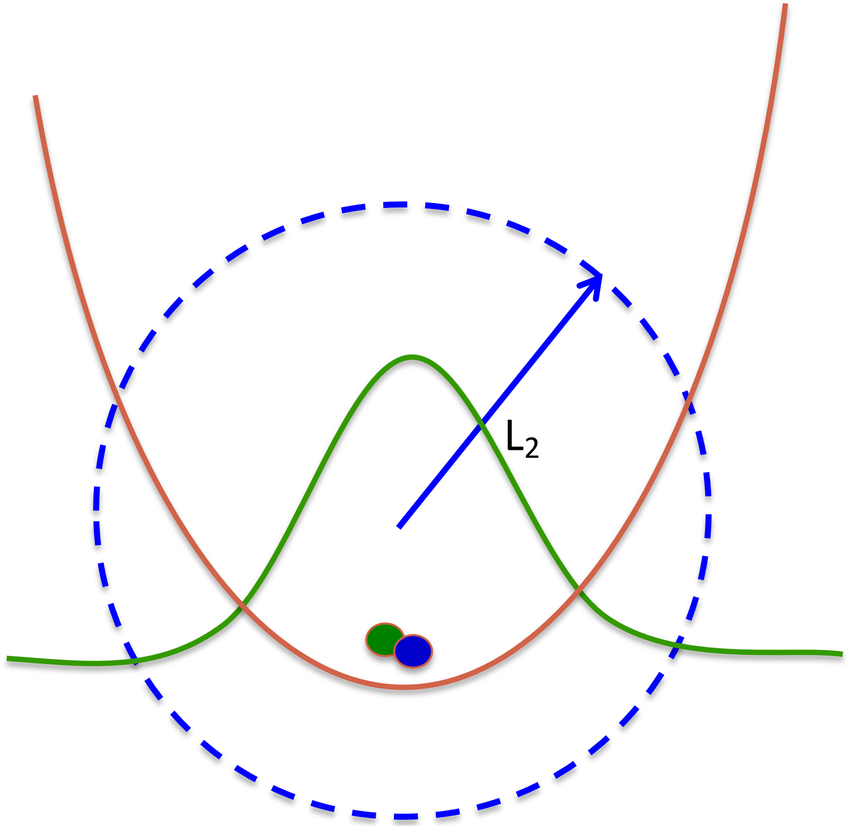




Infrared convergence

S. N. More et al., Phy. Rev. C**87**, 044326 (2013)



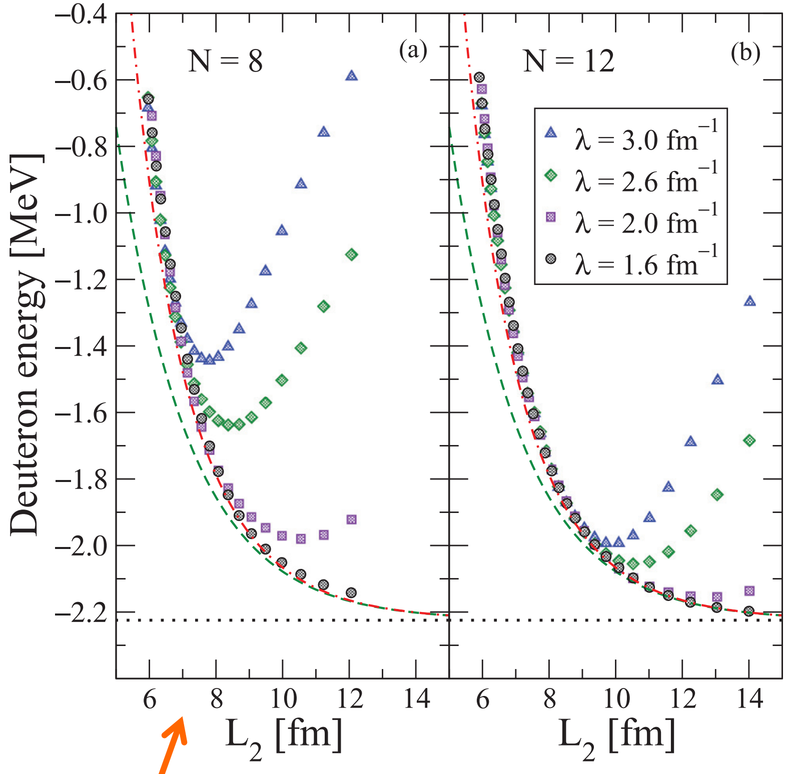


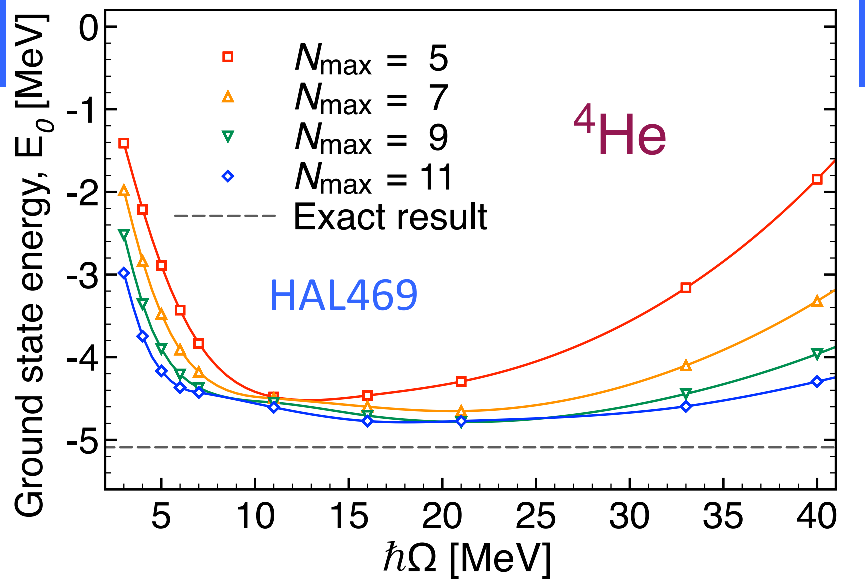
Deuteron g.s. Energy
EM(500) – N3LO two-nucleon force

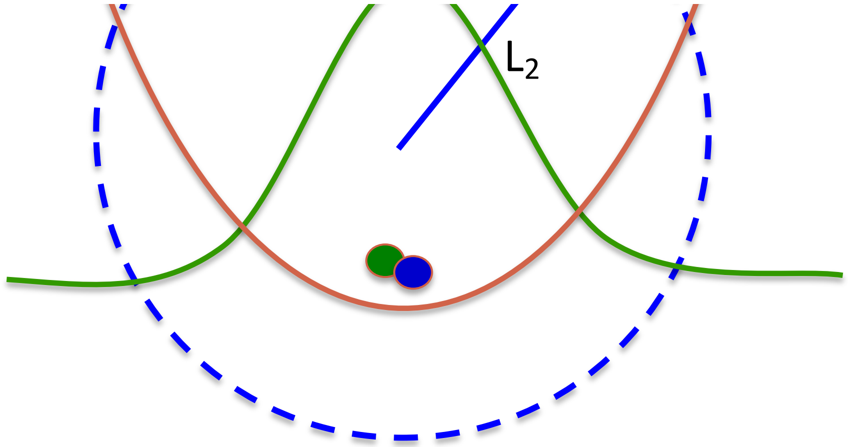
$$L_2 = \sqrt{2(N + 3/2 + 2)}b$$

Infrared convergence

S. N. More et al., Phy. Rev. C**87**, 044326 (2013)







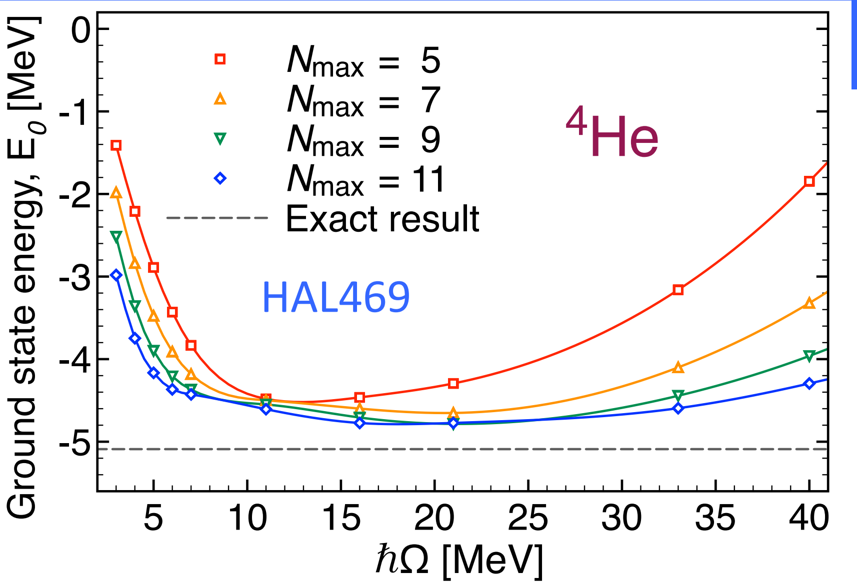
Deuteron g.s. Energy
EM(500) – N3LO two-nucleon force

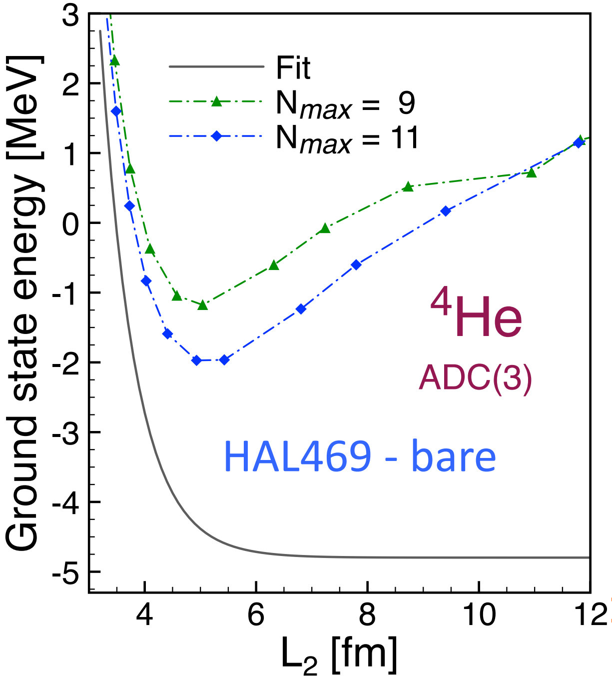
$$L_2 = \sqrt{2(N + 3/2 + 2)}b$$

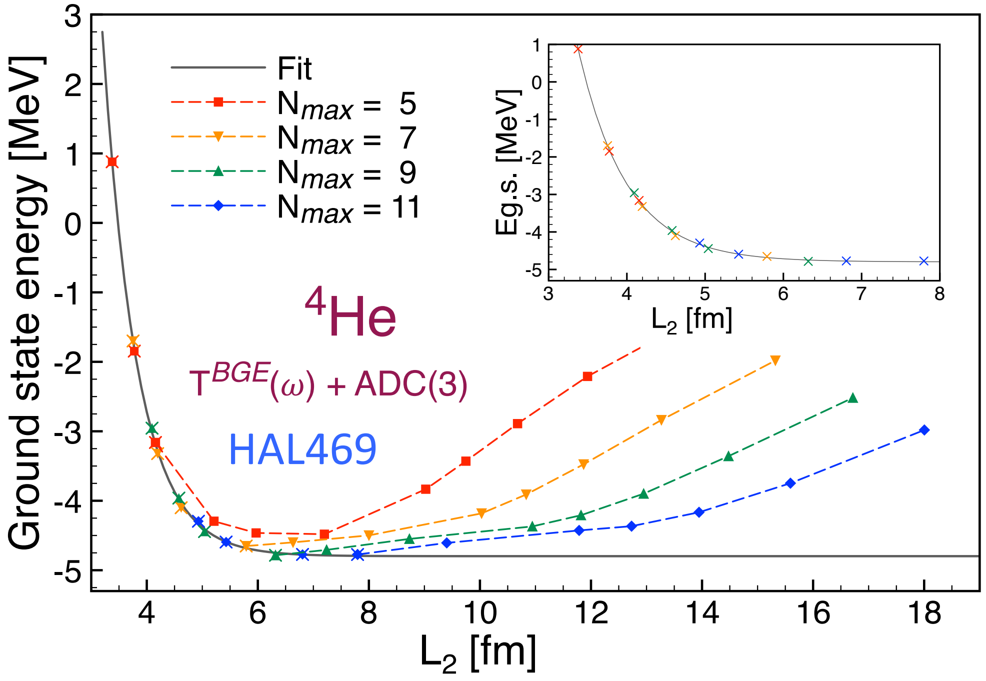
Infrared convergence

Short-range repulsion in the HALQCD-type potentials can be tamed correctly even for large nuclei.

C. McIlroy, CB, et al., Phys. Rev. C**97**, 021303(R) (2018)







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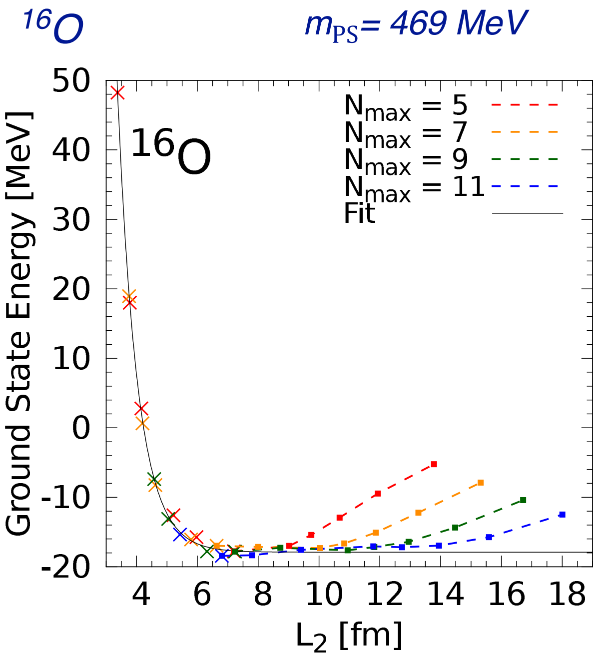
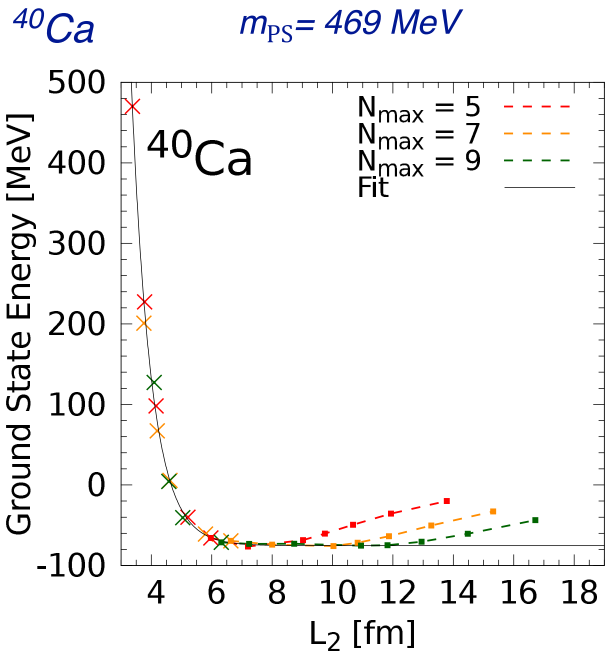
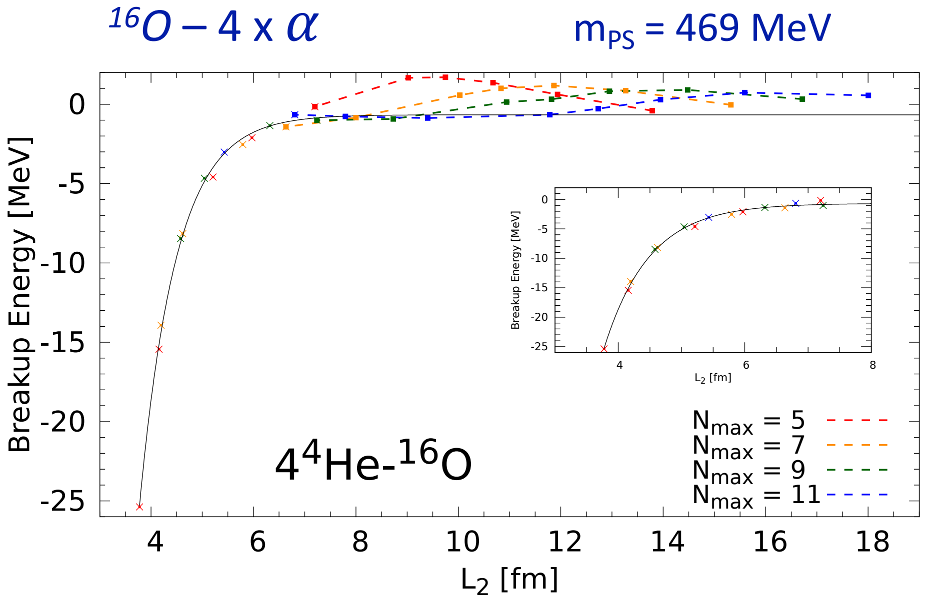
Binding of ^{16}O and ^{40}Ca:







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

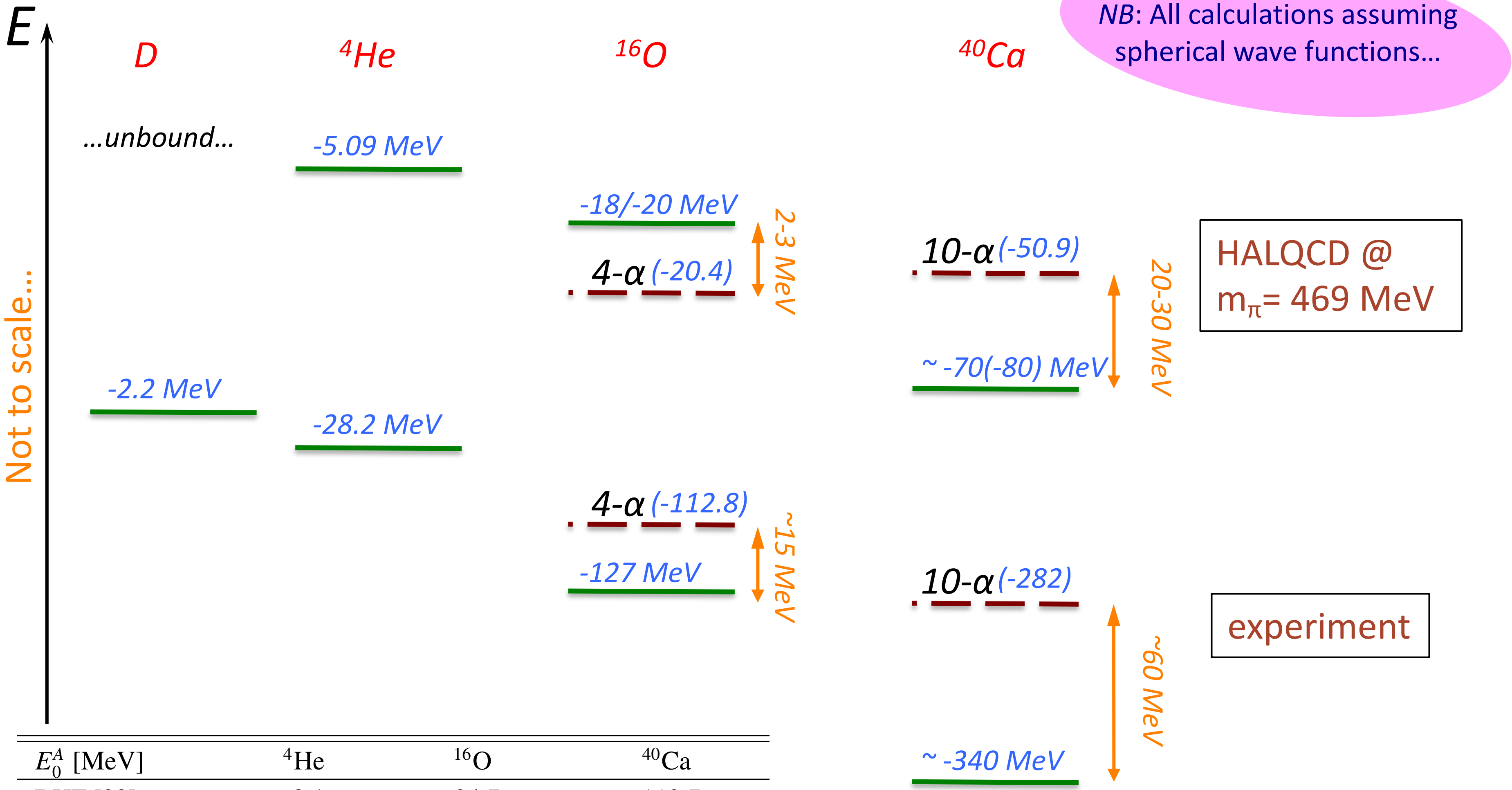
➔ ^{16}O at $m_\pi \approx$ 470 MeV is unstable toward 4-α breakup!

C. McIlroy, CB, et al., Phys. Rev. C**97**, 021303(R) (2018)

E_0^A [MeV]	^{4}He	^{16}O	^{40}Ca
BHF [22]	-8.1	-34.7	-112.7
G(ω) + ADC(3)	-4.80(0.03)	-17.9 (0.3) (1.8)	-75.4 (6.7) (7.5)
Exact Result [51]	-5.09	–	–
Separation into ^{4}He clusters:		-2.46 (0.3) (1.8)	24.5 (6.7) (7.5)

Results for binding

NB: All calculations assuming spherical wave functions…



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C. McIlroy, CB, et al., Phys. Rev. C**97**, 021303(R) (2018)

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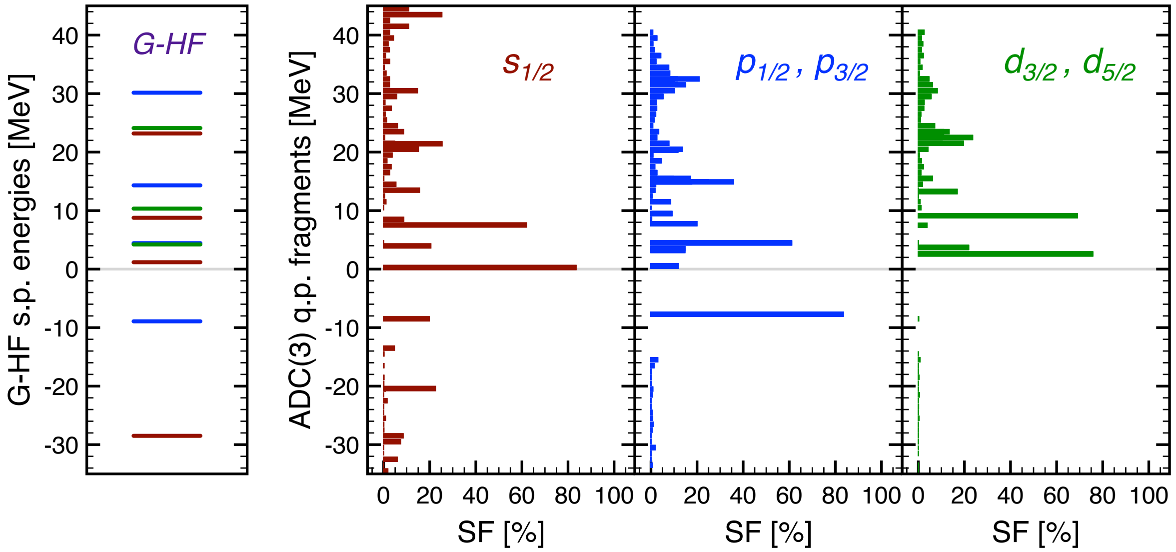
Spectral strength in ^{16}O and ^{40}Ca:

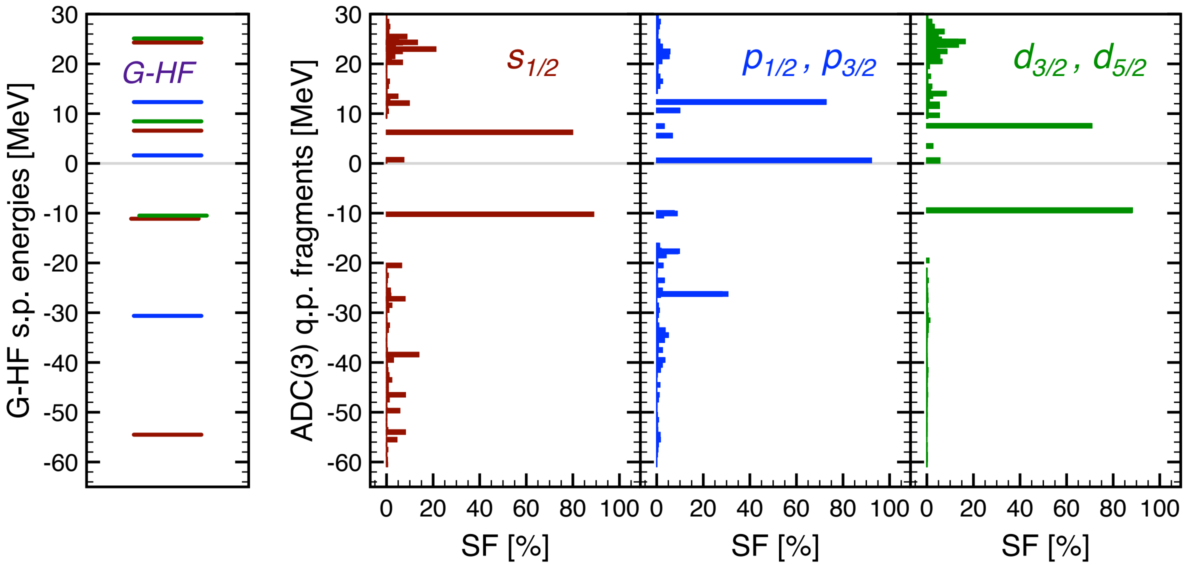


Particle-hole gaps:

^{16}O

m_π= 469 MeV: ~8 MeV

Expt (phys m_π): 11.5 MeV



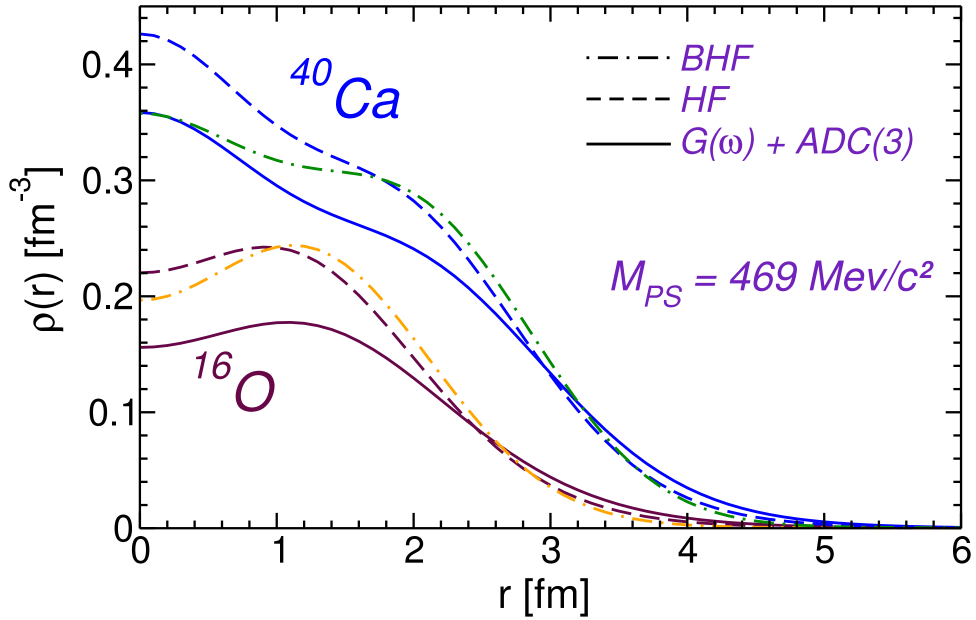
^{40}Ca

m_π= 469 MeV: ~10 MeV

Expt (phys m_π): 7.5 MeV

C. McIlroy, CB, et al., arXiv:1701.02607 [nucl-th]

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



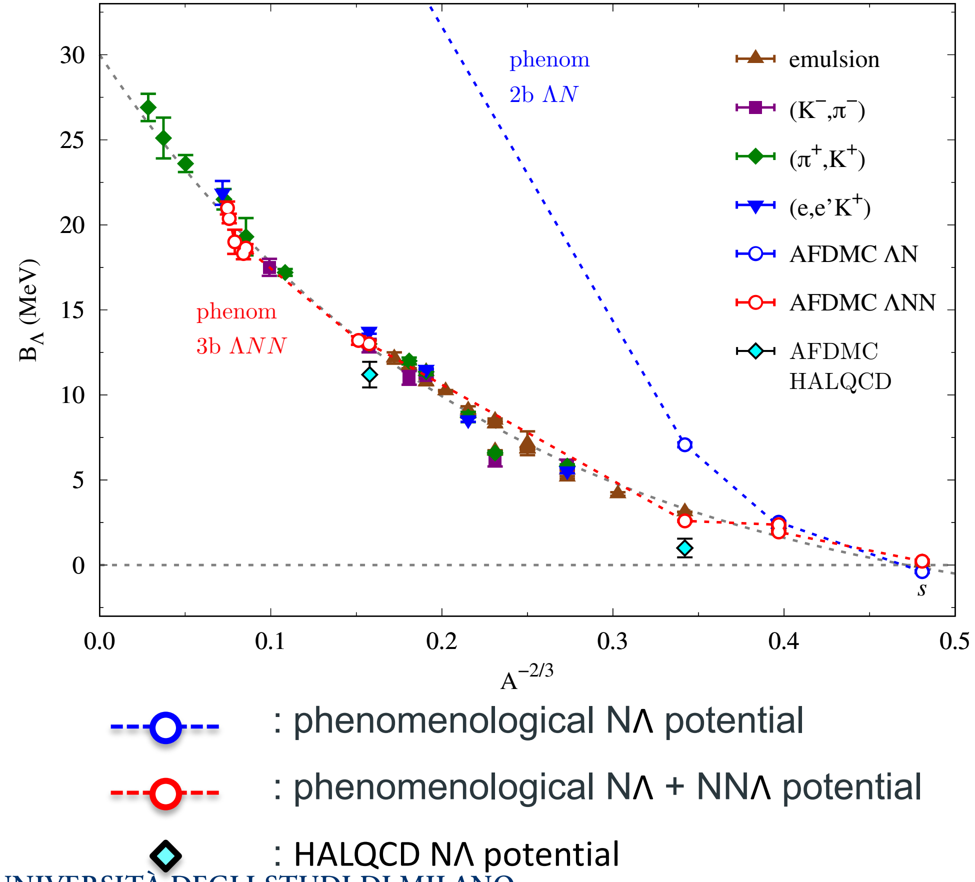
Calculated matter radii at $m_\pi \approx$ 470 MeV:

		^{16}O	^{40}Ca
$r_{pt-matter}$:	BHF [22]	2.35 fm	2.78 fm
	HF	2.39 fm	2.78 fm
	G(ω) + ADC(3)	2.64 fm	2.97 fm
r_{charge}:	G(ω) + ADC(3)	2.77 fm	3.08 fm
	Experiment [54, 55]	2.73 fm	3.48 fm

C. McIlroy, CB, et al., arXiv:1701.02607 [nucl-th]

Quantum MC calculations for Ys

- AV4' + UIX with phenomenological hypernuclear forces requires large ΛNN 3-baryon force
- Physical mass now under reach ($m_\pi \approx$ 145 MeV) for hyperons
- HALQCD ΛN 3-baryon force is already very close to experiment



$$H = -\frac{\hbar^2}{2m_N}\sum_i \nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} - \frac{\hbar^2}{2m_\Lambda}\nabla_\Lambda^2 + \sum_i v_{i\Lambda}$$

Argonne v_4' (AV4') nucleon-nucleon (NN) interaction $\quad v_{ij} = \sum_{p=1,4} v^p(r_{ij}) O_{ij}^p$

central component of the Urbana IX (UIX$_c$) $\quad V_{ijk} = A_R \sum_{cyc} T^2(m_\pi r_{ij}) T^2(m_\pi r_{ik})$

The hyperon-nucleon (YN) potential $\quad v_{i\Lambda} = \sum_{p=c,\sigma,t} v^p(r_{i\Lambda}) O_{i\Lambda}^p$

Diffusion Monte Carlo:

$$\langle X|\Psi_T\rangle = \langle X|\left(\prod_{i<j<k} U_{ijk}\right)\left(\prod_{i<j} F_{ij}\right)\left(\prod_i F_{i\Lambda}\right)|\Phi_{J^\pi,J_z,T_z}\rangle, \qquad |\Psi_0\rangle = e^{-(H-E_0)\tau}|\Psi_T\rangle$$

AFDMC: $$e^{-\lambda O^2\delta\tau/2} = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} dx\, e^{-x^2/2} e^{x\sqrt{-\lambda\delta\tau}\, O}$$

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D. Lonardoni, A. Lovato, et al, Phys. Rev. Lett. 114, 092301 (2015) & arXiv:1506.04042

Quantum MC calculations for Ys

- HALQCD96 Hyperon Nucleon potential (@ $m_\pi \approx 145$ MeV) for hyperons

$$v_{i\Lambda} = \sum_{p=c,\sigma,t} v^p(r_{i\Lambda})\, O^p_{i\Lambda}$$

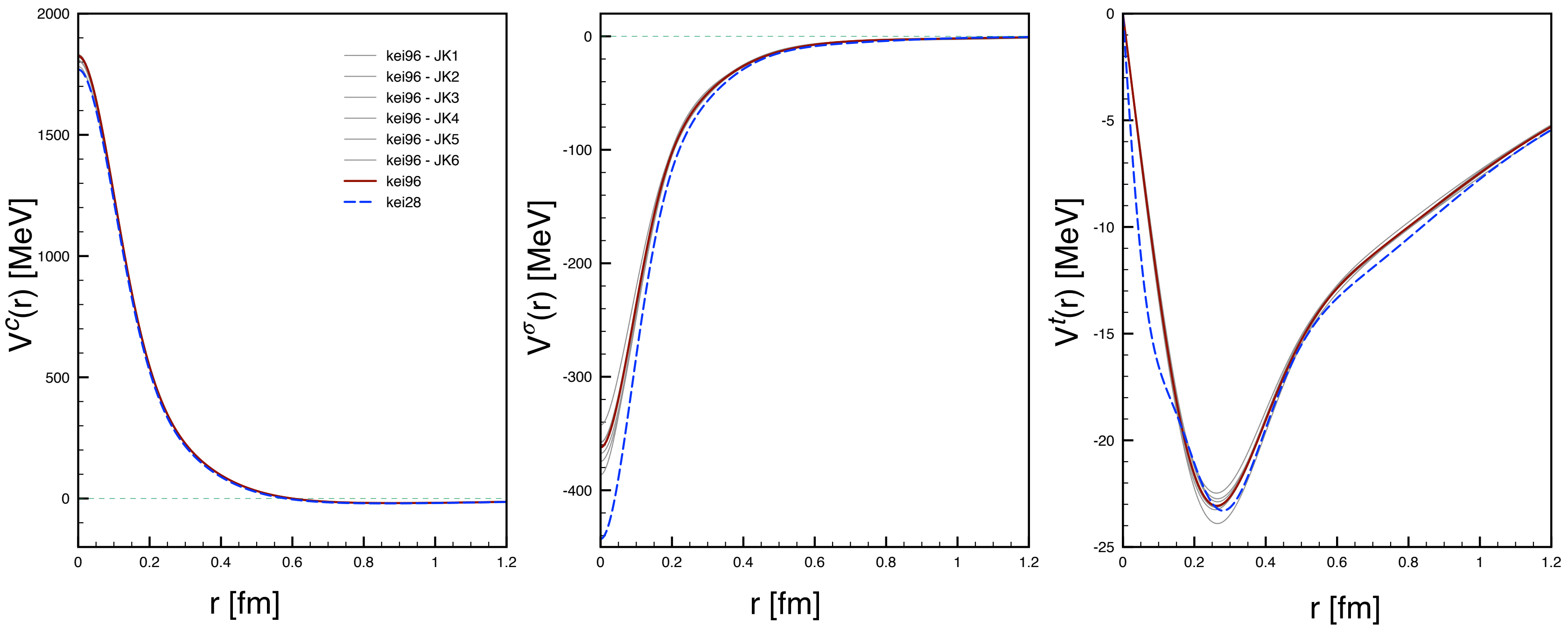

Figure 1: Central $v_c(r)$, spin $v_\sigma(r)$, and tensor $v_t(r)$ components of the ΛN potential.

Quantum MC calculations for Ys

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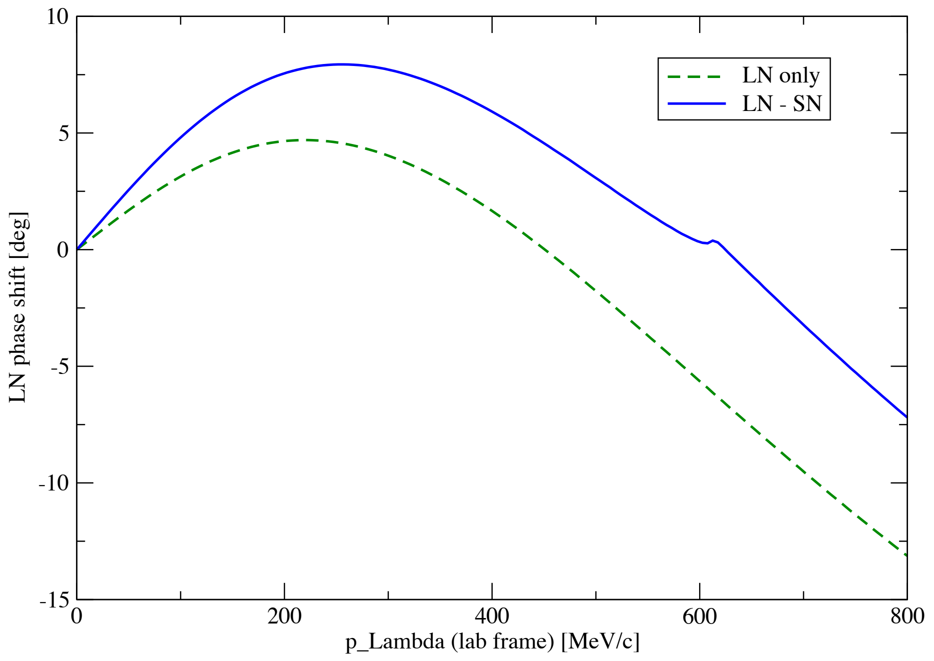
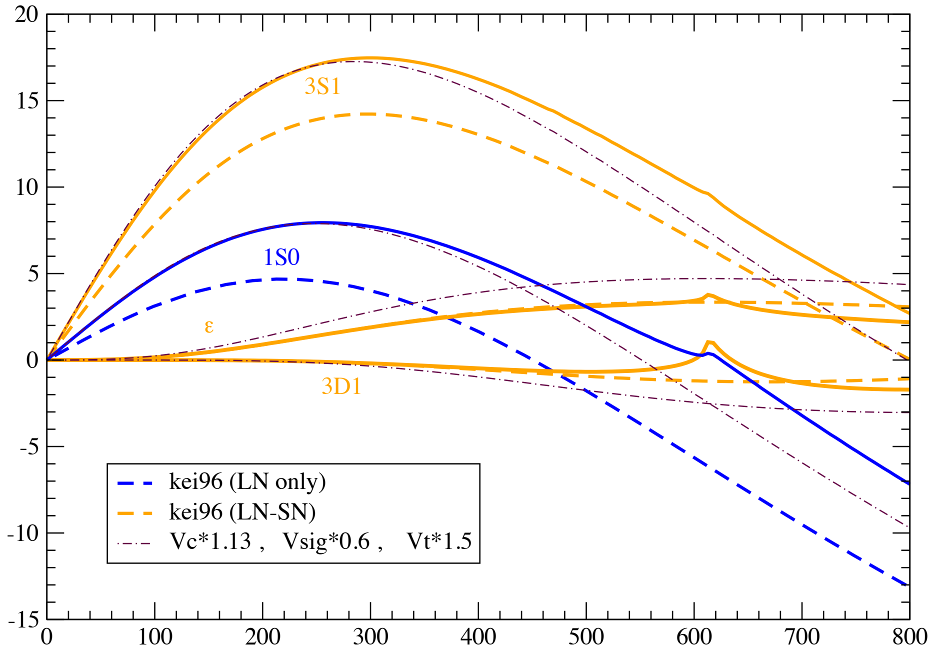
Lambda-nucleon phse shift in 1S0 (with and without virtual Sigma hyperon)



phase shifts LN, LN-SN and correceted LN

HAL145, kei96 potential



We modified the tree components of the HALQCD potential to effectively take into account the virtual ∑

Future application for Ys in nuclei now possible

- AV4' + UIX requires very large with phenomenological hypernuclear forces requires large ΛNN 3-baryon force
- Physical mass now under reach ($m_\pi \approx$ 145 MeV) for hyperons
- HALQCD ΛN 3-baryon force is already very close to experiment

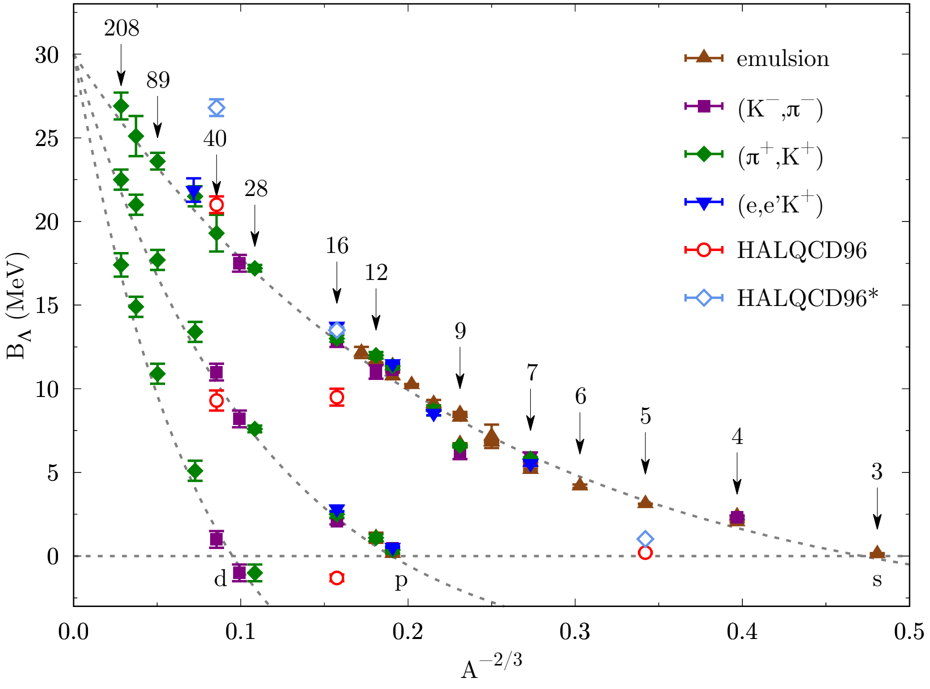


Table 1: Λ separation energies (in MeV) for different hypernuclei with the hyperon in different single-particle states. Second column reports the AFDMC results using the original HALQCD96 Λ*N* potential. Third column shows the results for the modified HALQCD96 Λ*N* potential (see text for details). In the last column, the available experimental data [] are reported.

$^{A}_{\Lambda}Z$	J^π (state)	HALQCD96	HALQCD96*	Exp
$^{5}_{\Lambda}$He	$1/2^+$ (*s*)	0.21(5)	1.02(3)	3.12(2)
$^{16}_{\Lambda}$O	1^- (*s*)	9.5(5)	13.5(2)	13.4(4)
	2^+ (*p*)	−1.3(2)	0.5(1)	2.5(2)
$^{40}_{\Lambda}$Ca	2^+ (*s*)	21.0(5)	26.8(5)	19.3(1.1)
	3^- (*p*)	9.3(6)	13.7(6)	11.0(5)

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D. Lonardoni, A. Lovato, CB, T. Inoue, HALQCD coll

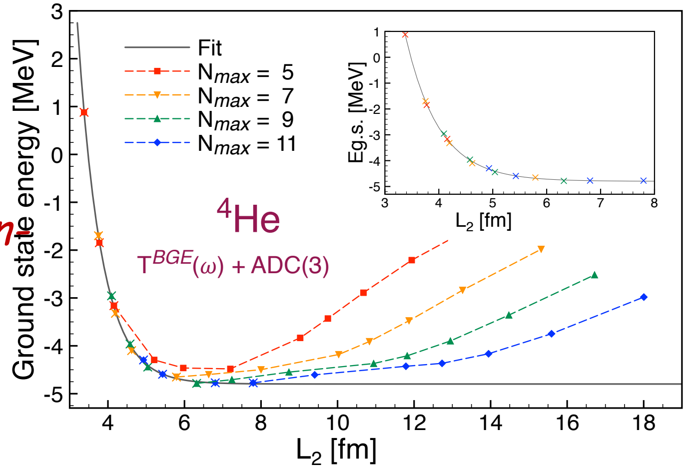
Summary

Thank you for your attention!!!

Applications to structure and reactions in medium-mass nuclei:

→ Description of nuclear g.s. in the pf shell is improved-especially in the trends w.r.t. iso-sopin asymmetry.

→ Higher accuracy, density of scattering states and absorption(for optical potentials), etc…. all require new formalisms and automatic generation of diagrams.



HALQCD Nuclear forces:

→ Strong short range behavior calls for new ideas in ab initio many-body methods.

→ The analysis of IR convergence tell us that short-range D.O.F. can be removed effectively. Diagram resummation through G-matrix is <u>good</u> starting point (to be extended).

→ At m_π=469MeV, closed shell 4He, 16O and 40Ca are bound. But oxygen is unstable toward 4-α break up, calcium stays bound. Underestimation of radii increases with A do to large saturation density (as for EM(500)+NLO3NF).

→ Preliminary forces for Lambda-nucleon are now available near the physical pion mass (m_π = 145 MeV/c^2). Preliminary studies are very promising!