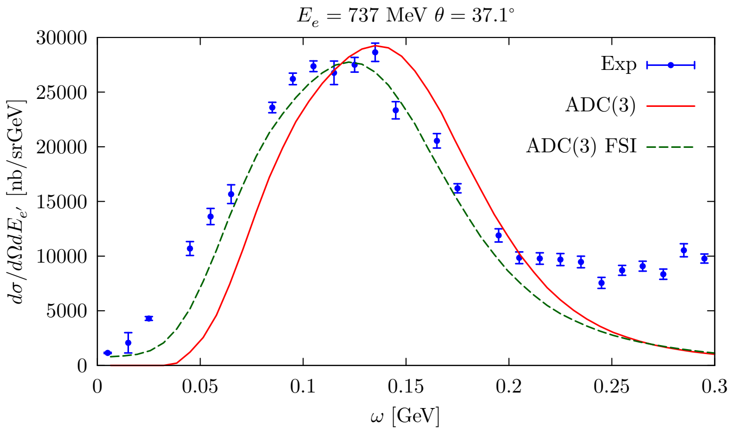
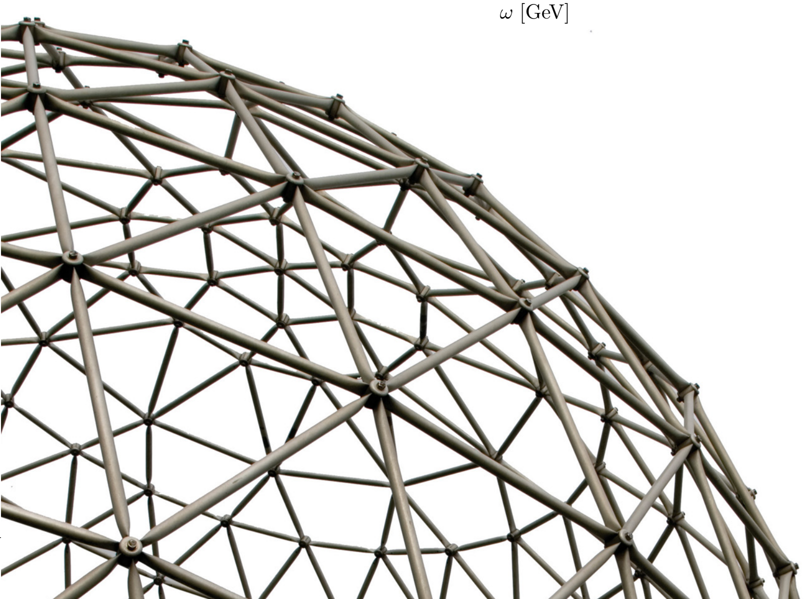
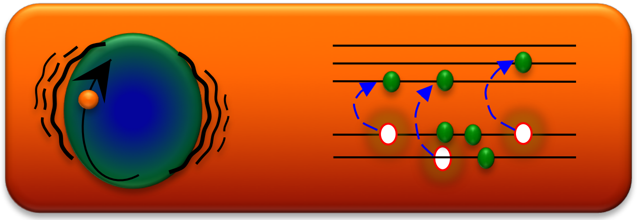
Ab Initio Approach to Correlations in Nuclei and their Applications

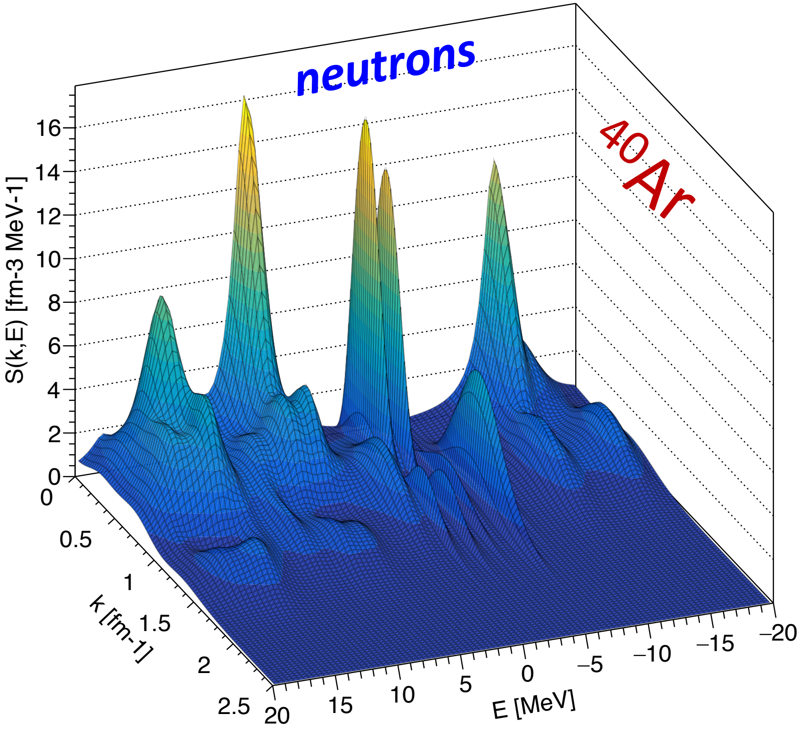
Carlo Barbieri — University of Surrey

28 February 2019









Outline

- The Self-Consistent Green's Funtion method (SCGF)

- Mid-mass nuclei with chiral interactions

- Neutrino Nucleus scattering (@ GeV energies)

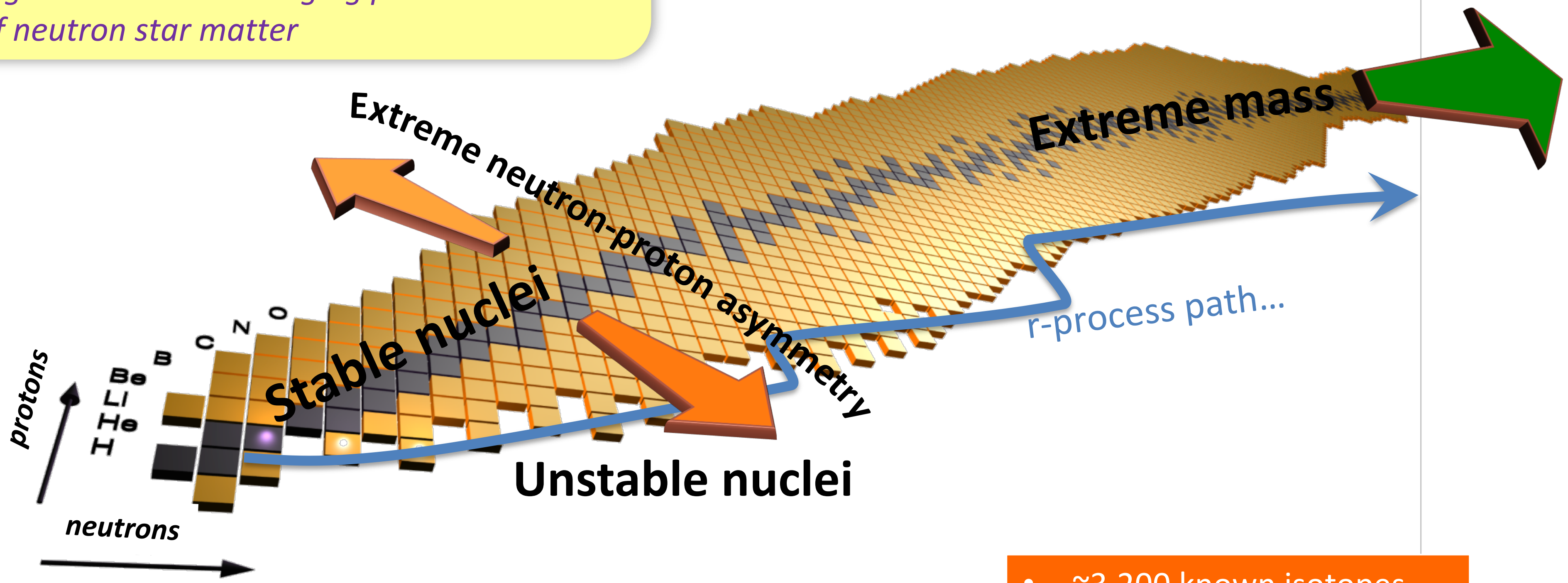
- Optical potnetials from ab initio

- (Hyper)nuclear ofrces from LQCD *(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…



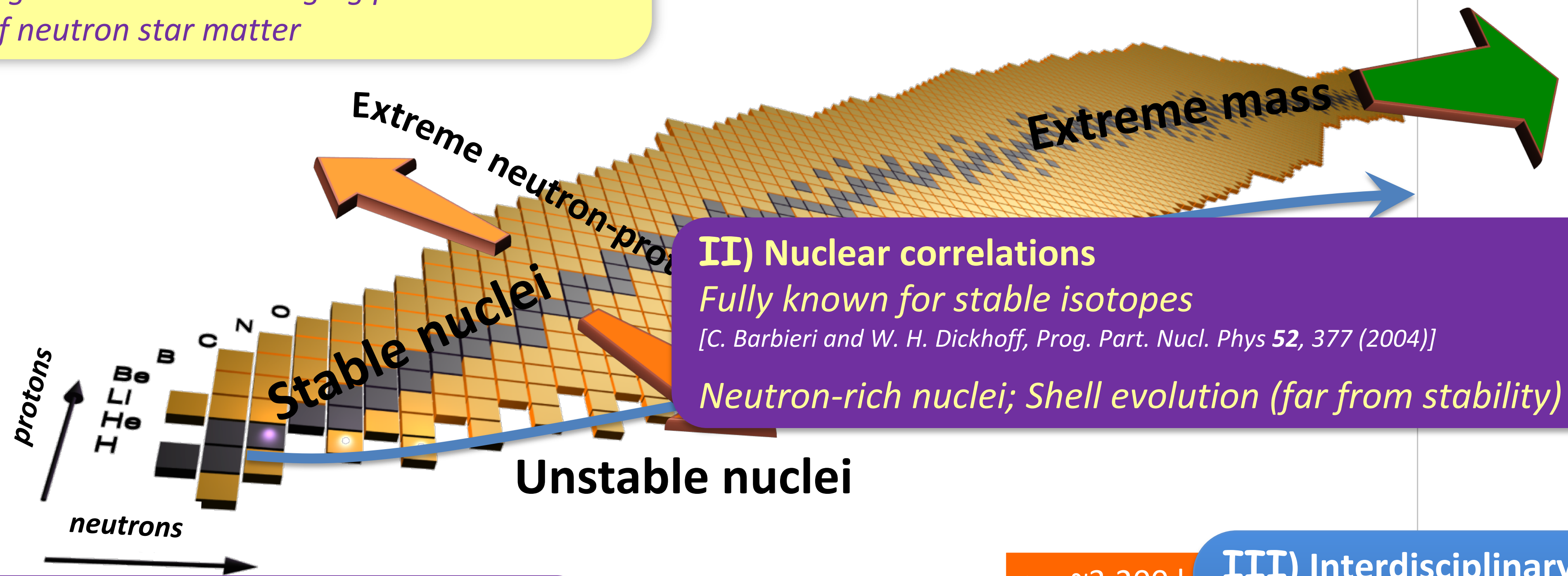
- ~3,200 known isotopes
- ~7,000 predicted to exist
- Correlation characterised in full for ~283 stable

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

Current Status of low-energy nuclear physics

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, 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

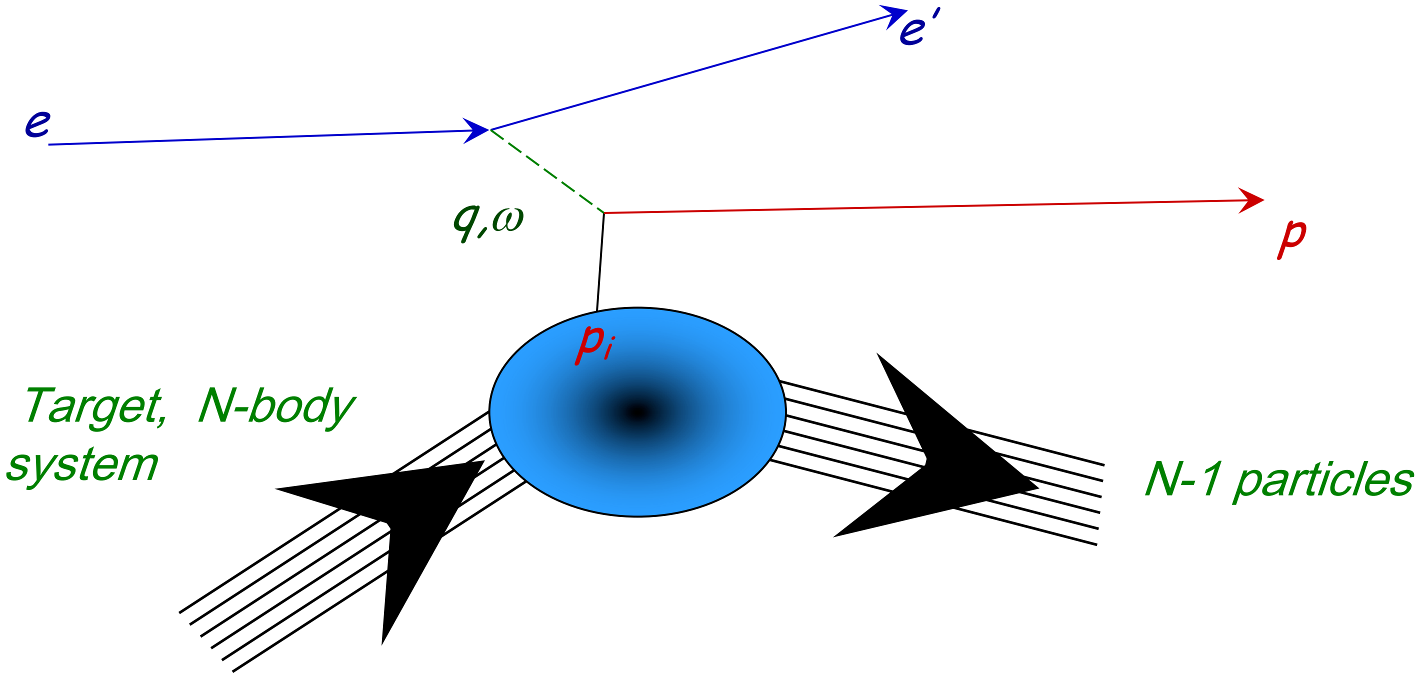
- ~3,200 k
- ~7,000 p
- Correlati
  in full fo

Nature **473**, 25

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

Spectroscopy via knock out reactions-basic idea

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



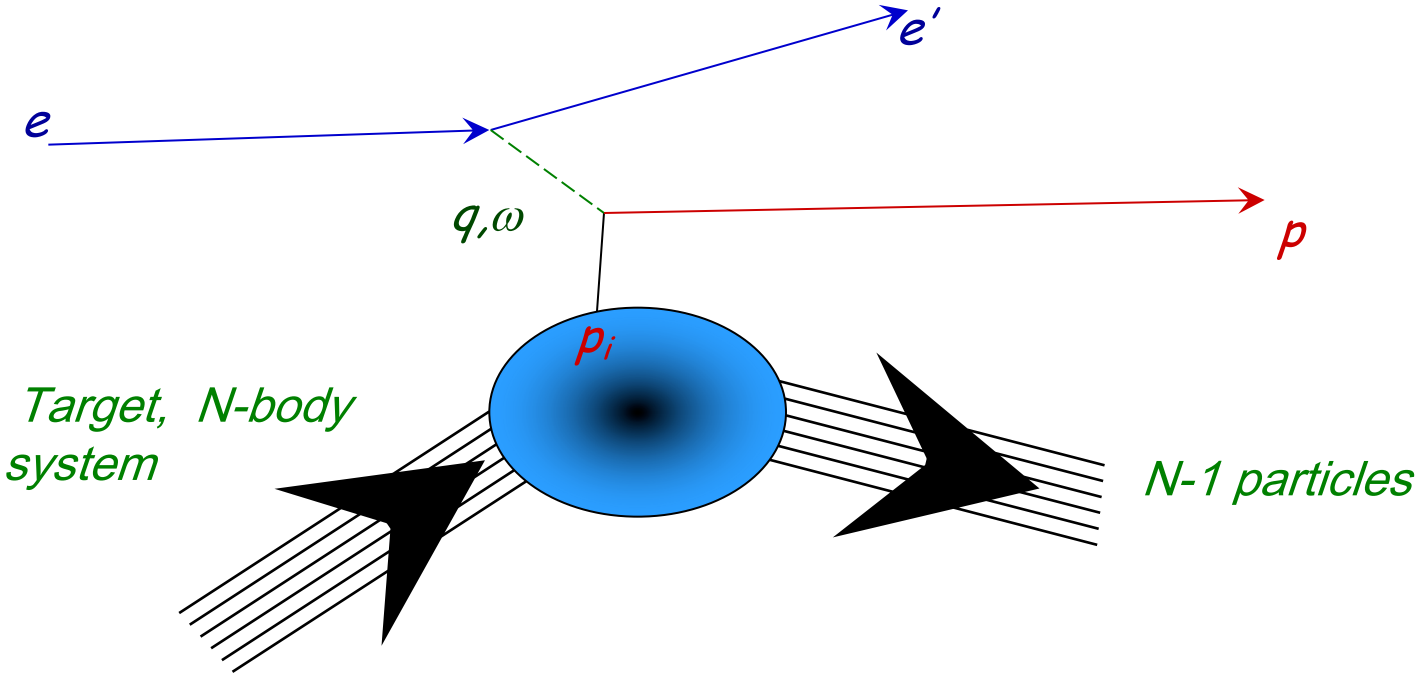
Basic idea:

- 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!!!

Spectroscopy via knock out reactions-basic idea

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



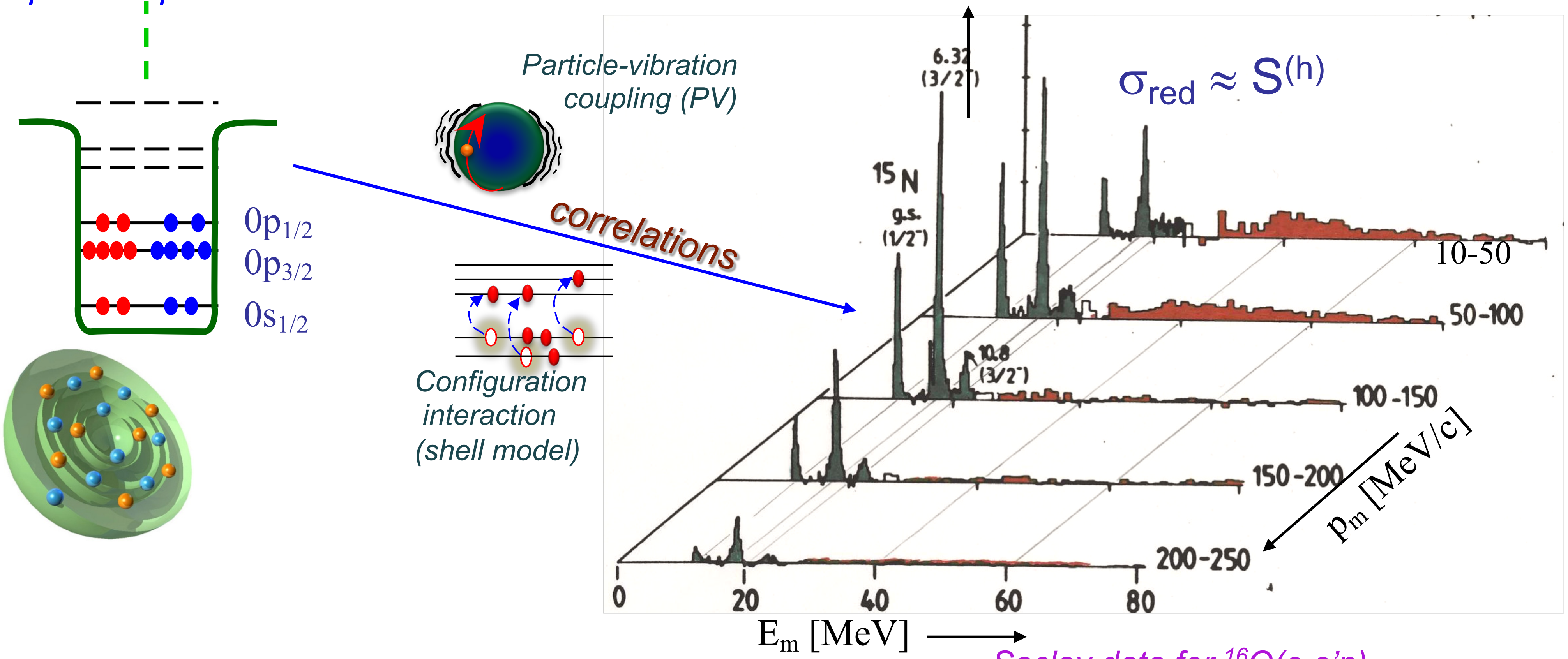
In plane wave impulse approximation (PWIA):

$$\frac{d\sigma_{(e,e'p)}}{dE_{e'}\,d\Omega_{e'}\,d\Omega_p} = \sigma_{ep} \times S^h(p_m, E_m)$$

Concept of correlations

independent particle picture

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)]

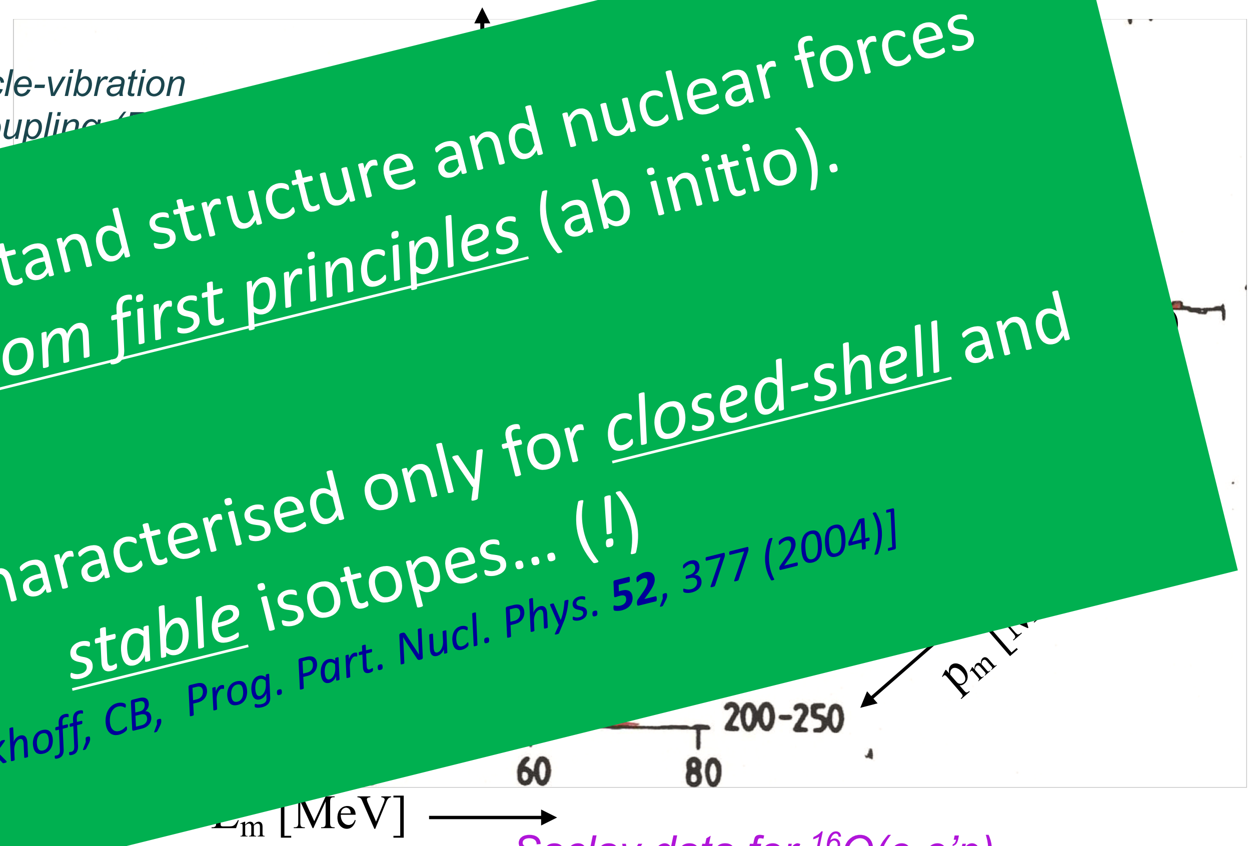
Understood for a few stable closed shells:

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

Concept of correlations

independent particle picture

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)]

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

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

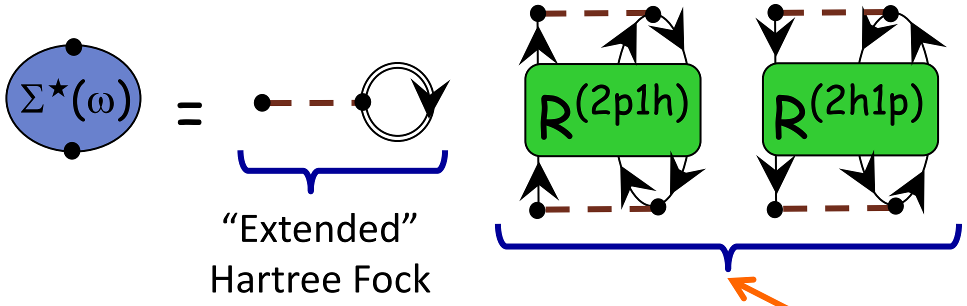
*[W. Dickhoff, CB, Prog. Part. Nucl. Phys. **52**, 377 (2004)]*

Understo… for a few stable closed shells:
*[CB and W. H. Dickhoff, 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…

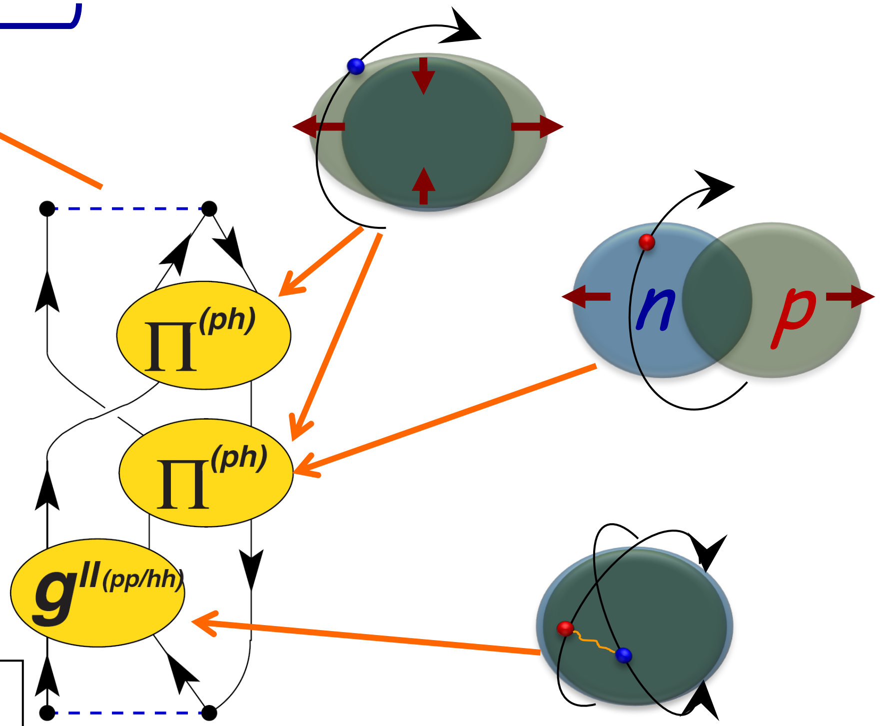
CB et al.,
Phys. Rev. C**63**, 034313 (2001)
Phys. Rev. A**76**, 052503 (2007)
Phys. Rev. C**79**, 064313 (2009)

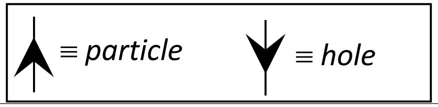


- A complete expansion requires *__all__* *__types__* of particle-vibration coupling

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

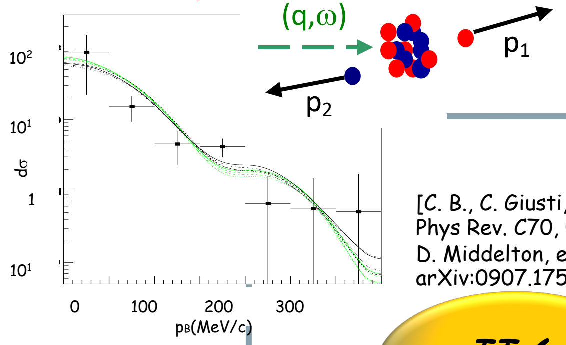
- The Self-energy $\Sigma^{\star}(\omega)$ yields *both* single-particle states and scattering





Self-Consistent Green's Function Approach

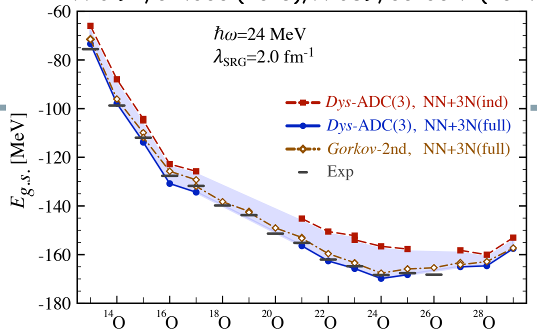
$^{16}O(e,e'pn)^{14}N$ @ MAINZ

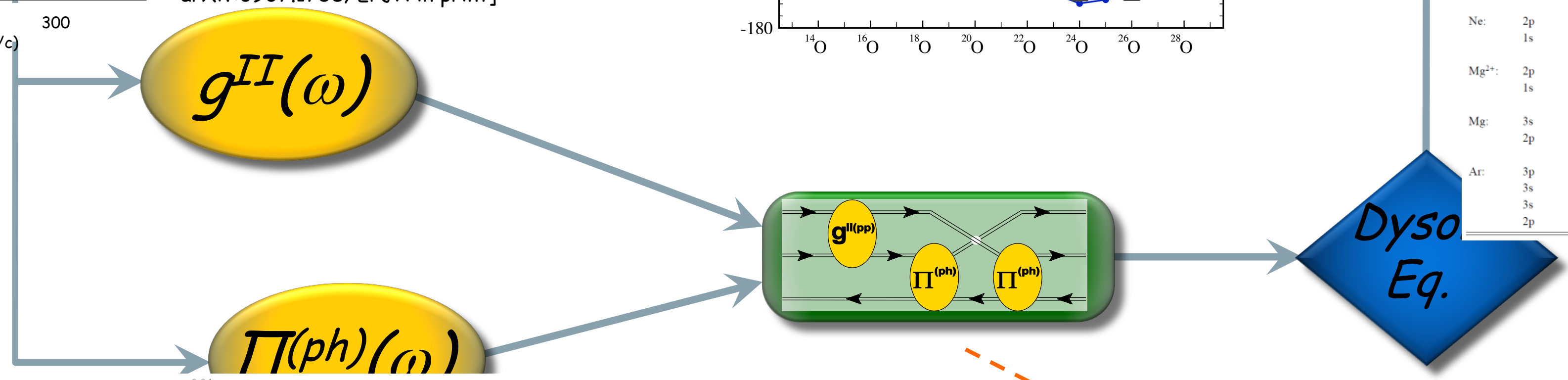


[C. B., C. Giusti, et al. Phys Rev. C70, 014606 (2004)
D. Middelton, et al. arXiv:0907.1758; EPJA in print]

Binding energies

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





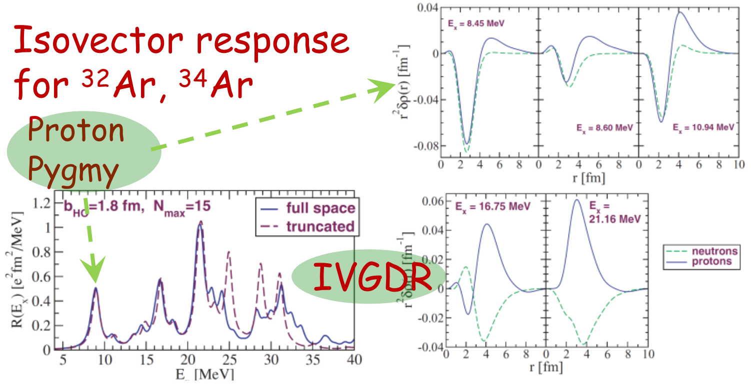
Ionization energies/ affinities, in atoms

[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

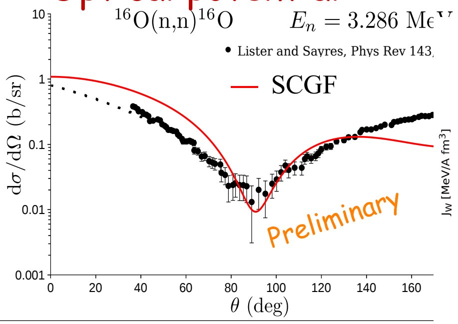
Isovector response for ^{32}Ar, ^{34}Ar

Proton Pygmy

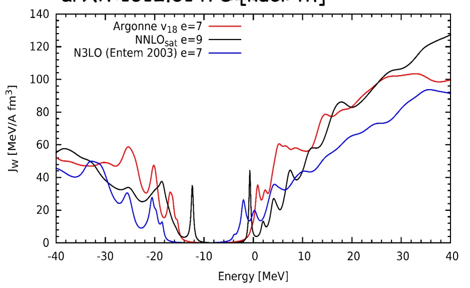


[C. B., K. Langanke, et al., Phys Rev. C77, 024304 (2008)]

Optical potential



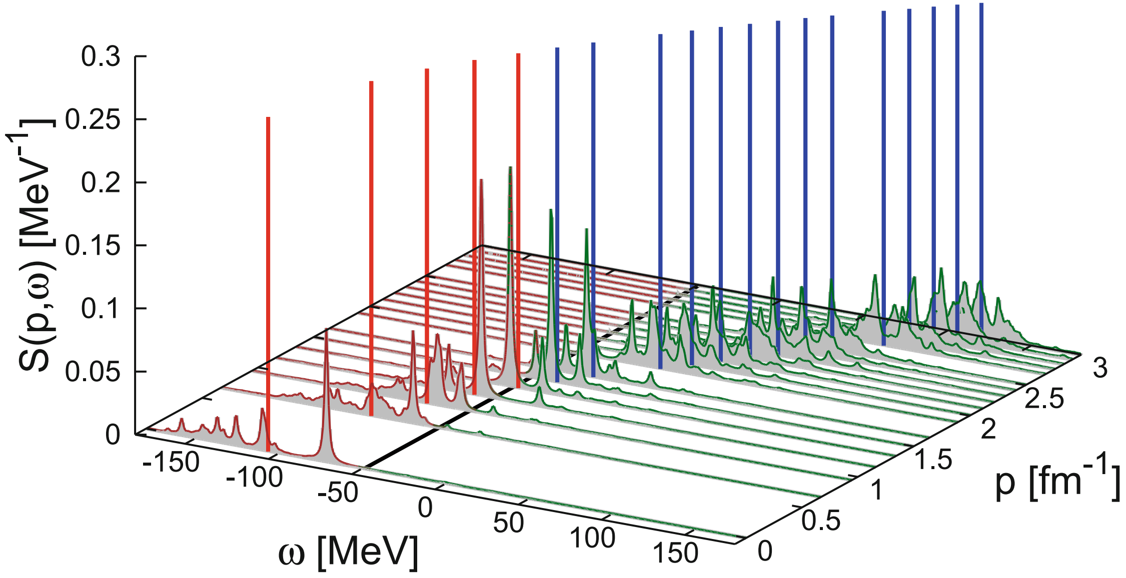
arXiv:1612.01478 [nucl-th]



Spectral function in matter and nuclei

Solve the Dyson eq. to obtain all the structure information probed by nucleon transfer (spectral function):

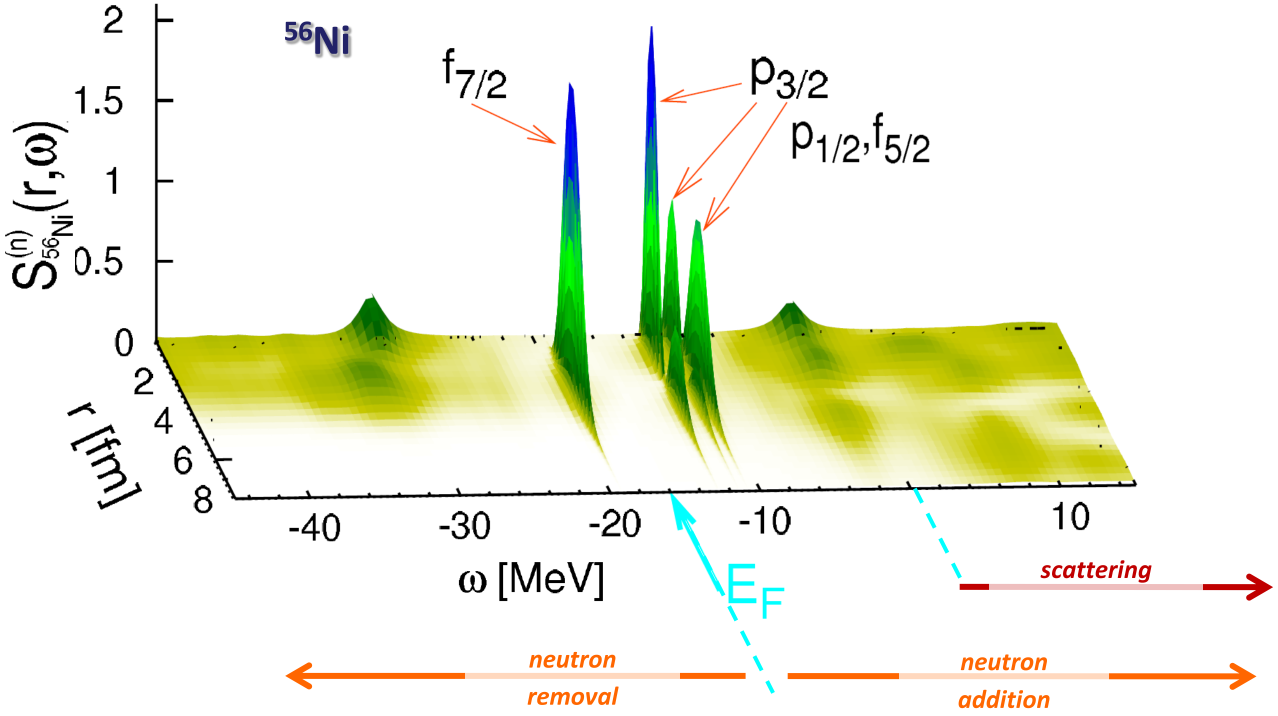
$$g_{\alpha\beta}(\omega) \;=\; g^{(0)}_{\alpha\beta}(\omega) \;+\; \sum_{\gamma\,\delta} g^{(0)}_{\alpha\gamma}(\omega)\Sigma^{\star}_{\gamma\delta}(\omega)g_{\delta\beta}(\omega)$$



$E_{qp}(p) \approx \frac{p^2}{2\,m} \;+\; U(p)$

and : uncorrelated Fermi gas

Nucleonic matter



Finite nuclei

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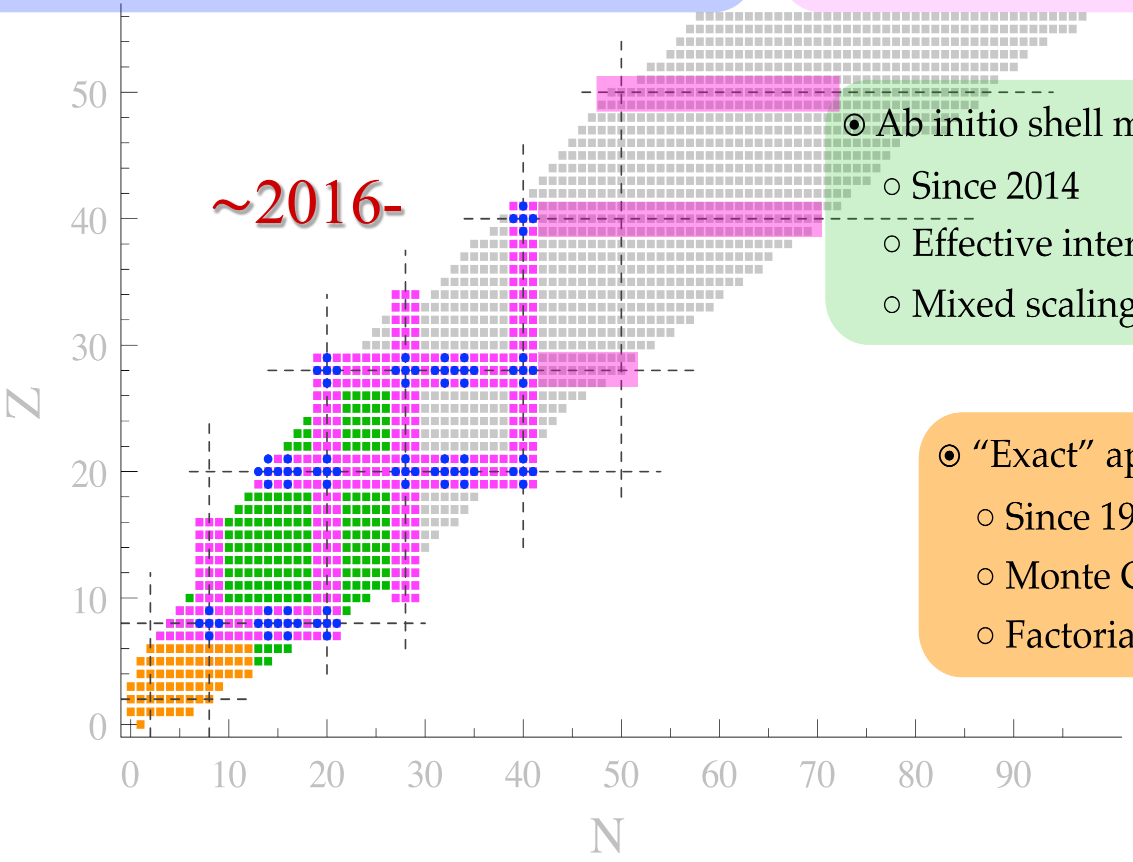
Reach of ab initio methods across the nuclear chart

- 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

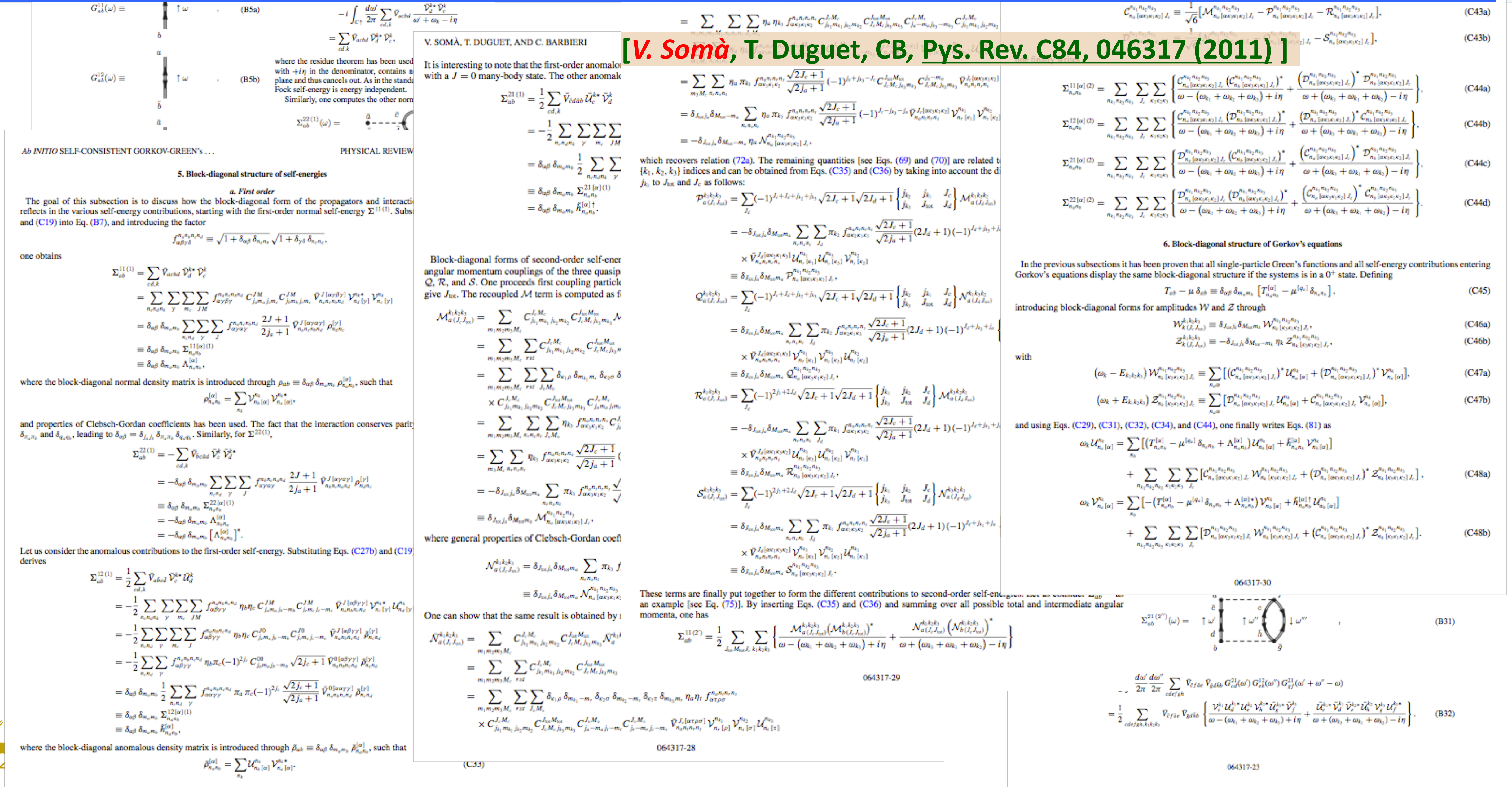
Deformation
???

Symmetry restoration
???

Slide, courtesy of V. Somà

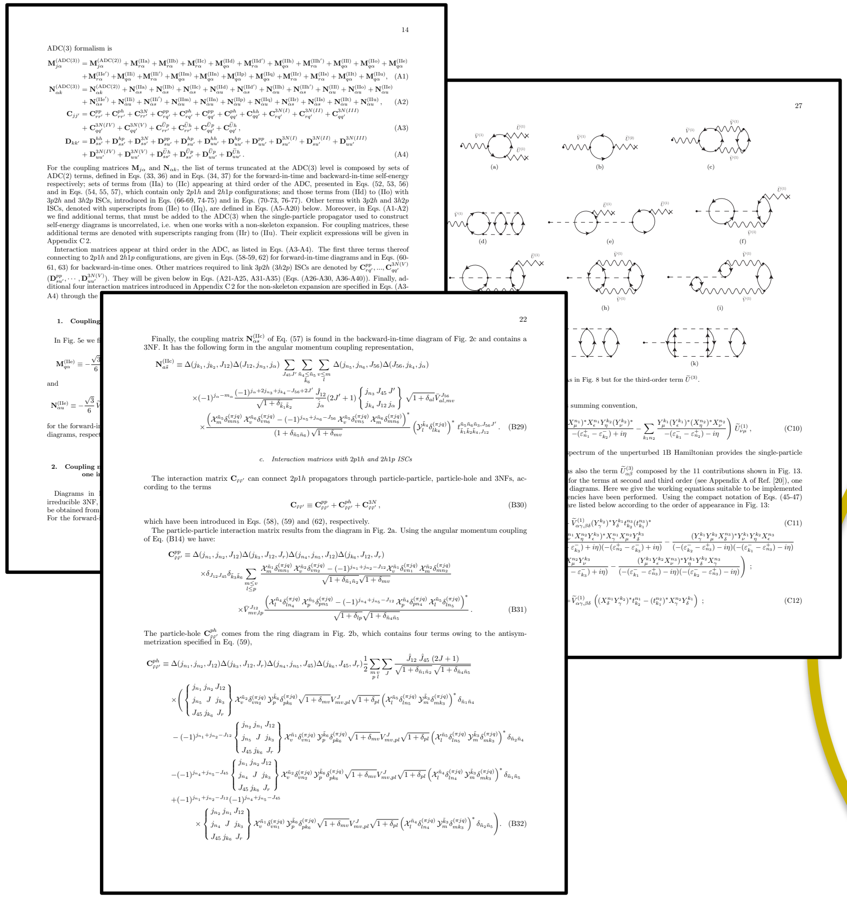
Espressions for 1st & 2nd order diagrams

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



Inclusion of NNN forces

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



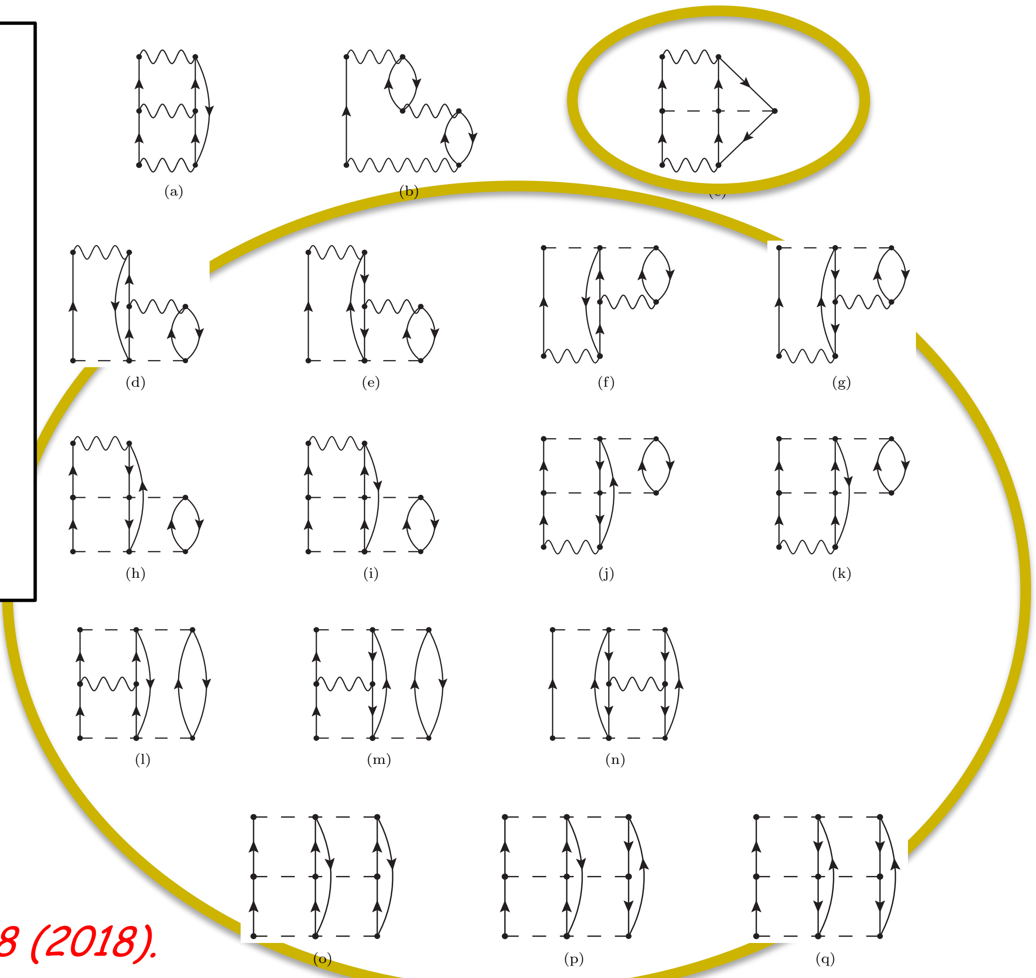


FIG. 5. 1PI, *skeleton* and *interaction irreducible* self-energy diagrams appearing at 3^{rd}-order in perturbative expansion (7), making use of the effective hamiltonian of Eq. (9).

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

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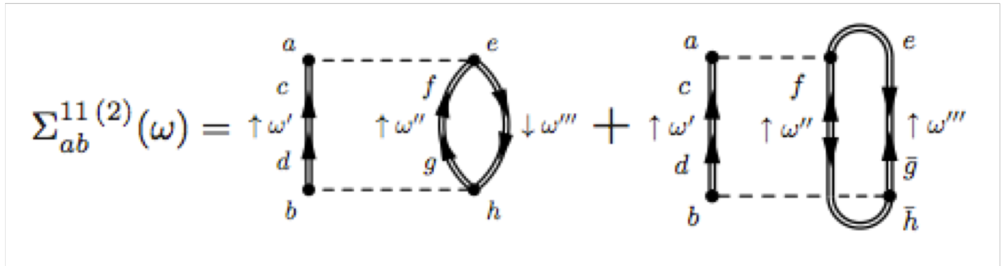
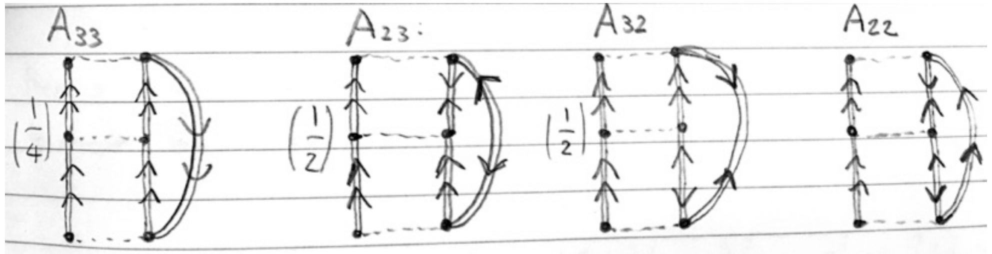
Reaching (Gorkov – 3NF – higher ordes…) is a mess

Gorkov at 2nd order and ONLY NN forces:

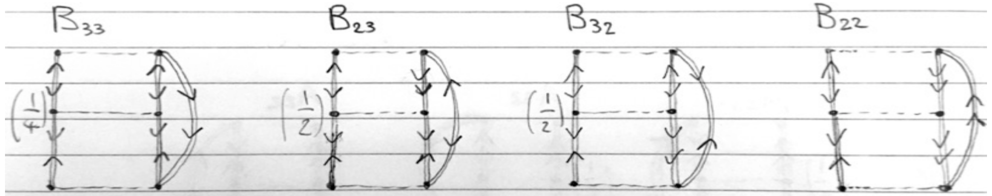


Gorkov at 3rd order and ONLY NN forces:

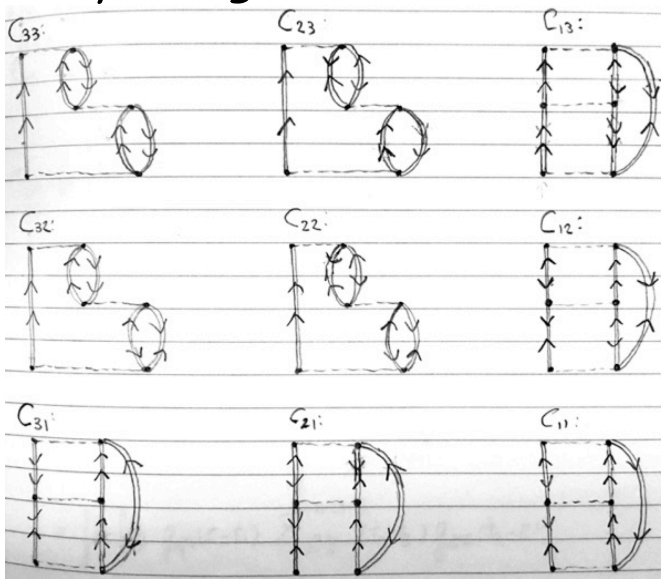
pp/hh-ladders:



hh-interactions (hh int. among pp ladders!!!)

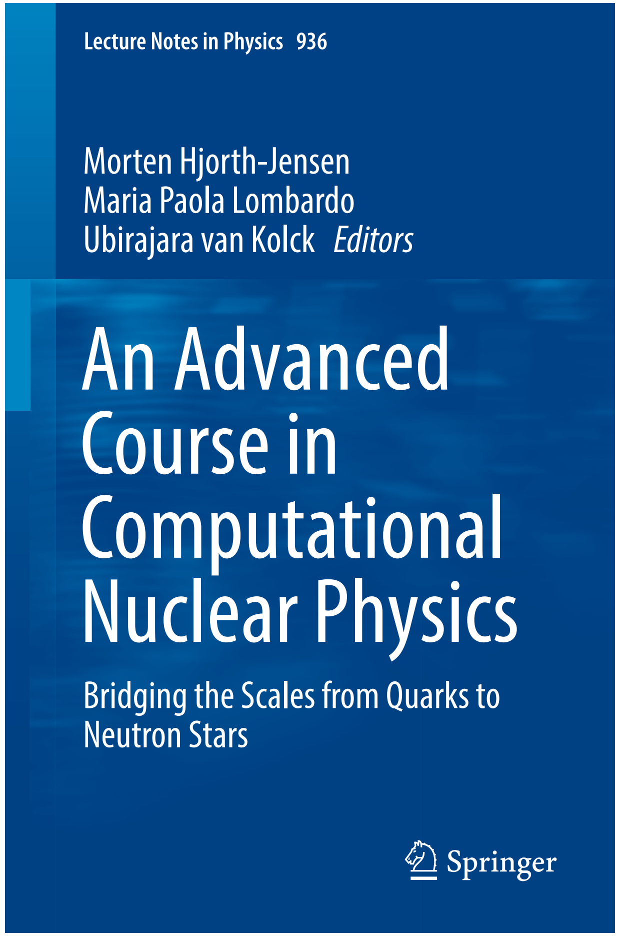


ph-rings:



Automatic generation of diagram needed for 3NF and beyond…

→ F. Raimondi and P. Arthuis, in progress…



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

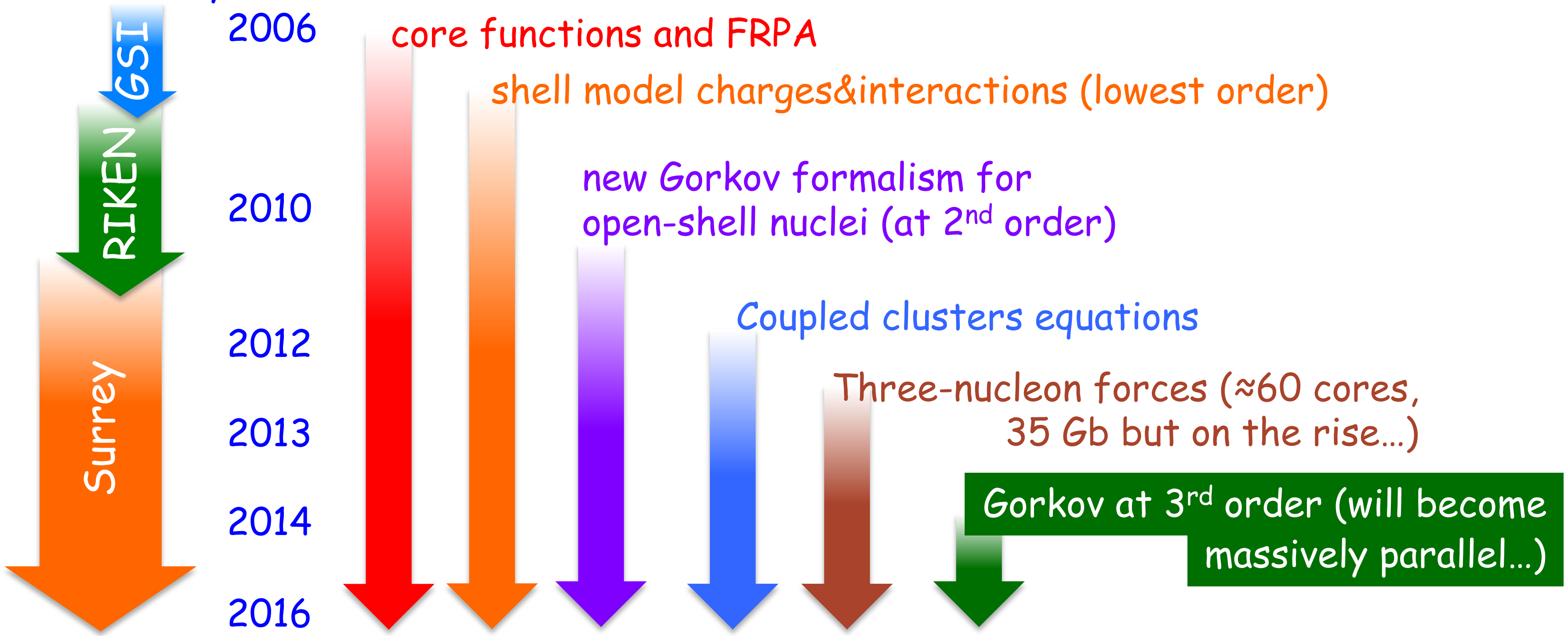
CB and A. Carbone,
chapter 11 of
Lecture Notes in Physics 936 (2017)

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:

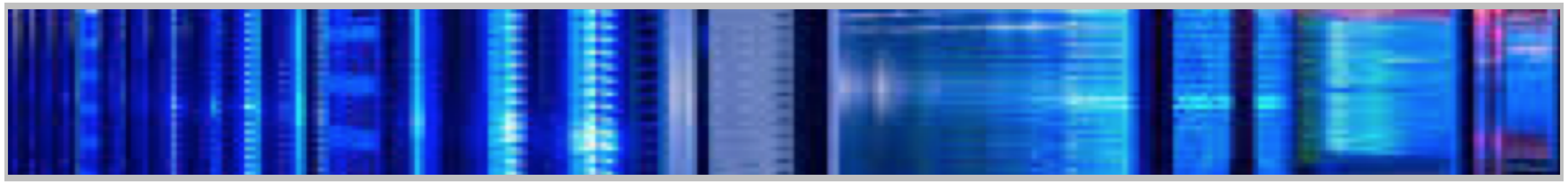


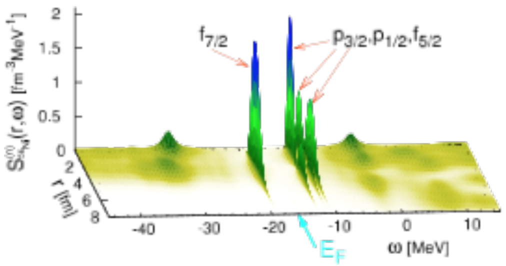
… applications …

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:

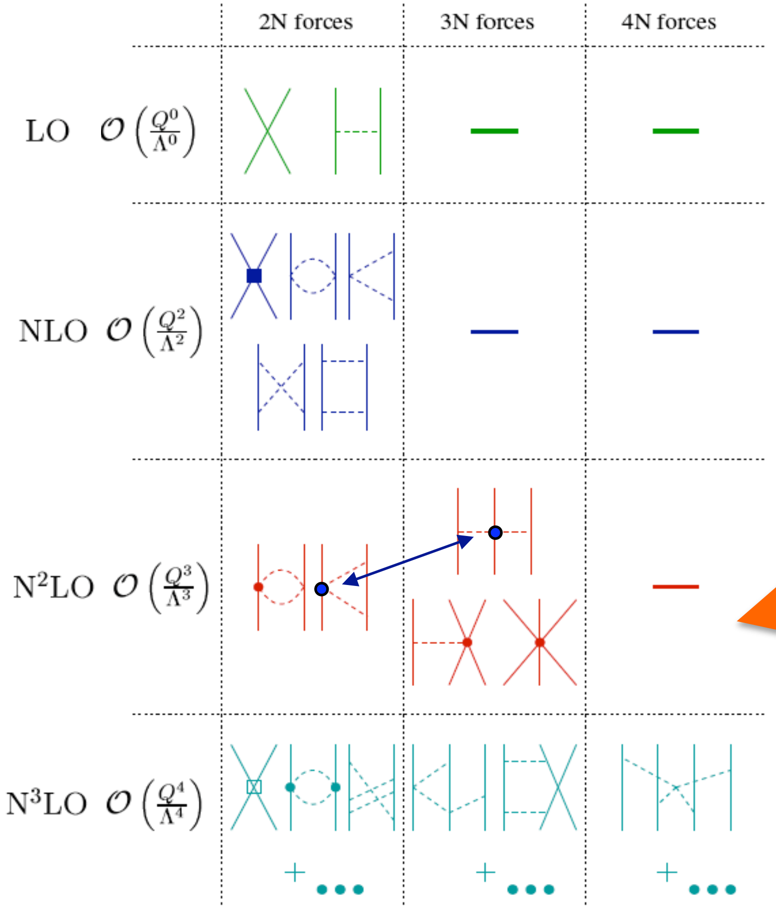
Prog. Part. Nucl. Phys. 52, p. 377 (2004),
Phys. Rev. A76, 052503 (2007),
Phys. Rev. C79, 064313 (2009),
Phys. Rev. C89, 024323 (2014)

Chiral EFT interactions
and
3-nucleon forces

in mid-mass isotopes

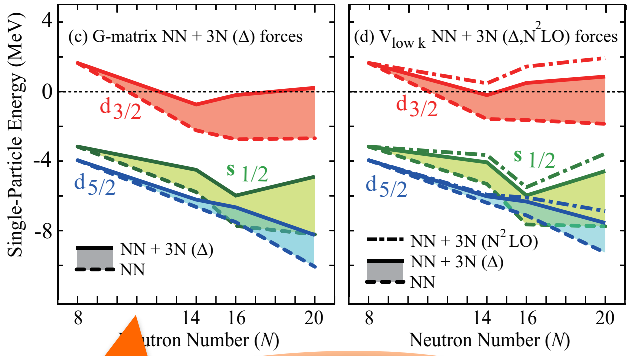
Realistic nuclear forces form Chiral EFT

Chiral EFT for nuclear forces:



(3NFs arise naturally at N2LO)

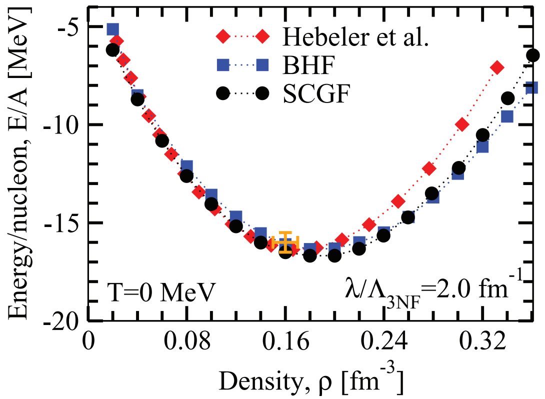
Single particle spectrum at E_{fermi}:



[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)]

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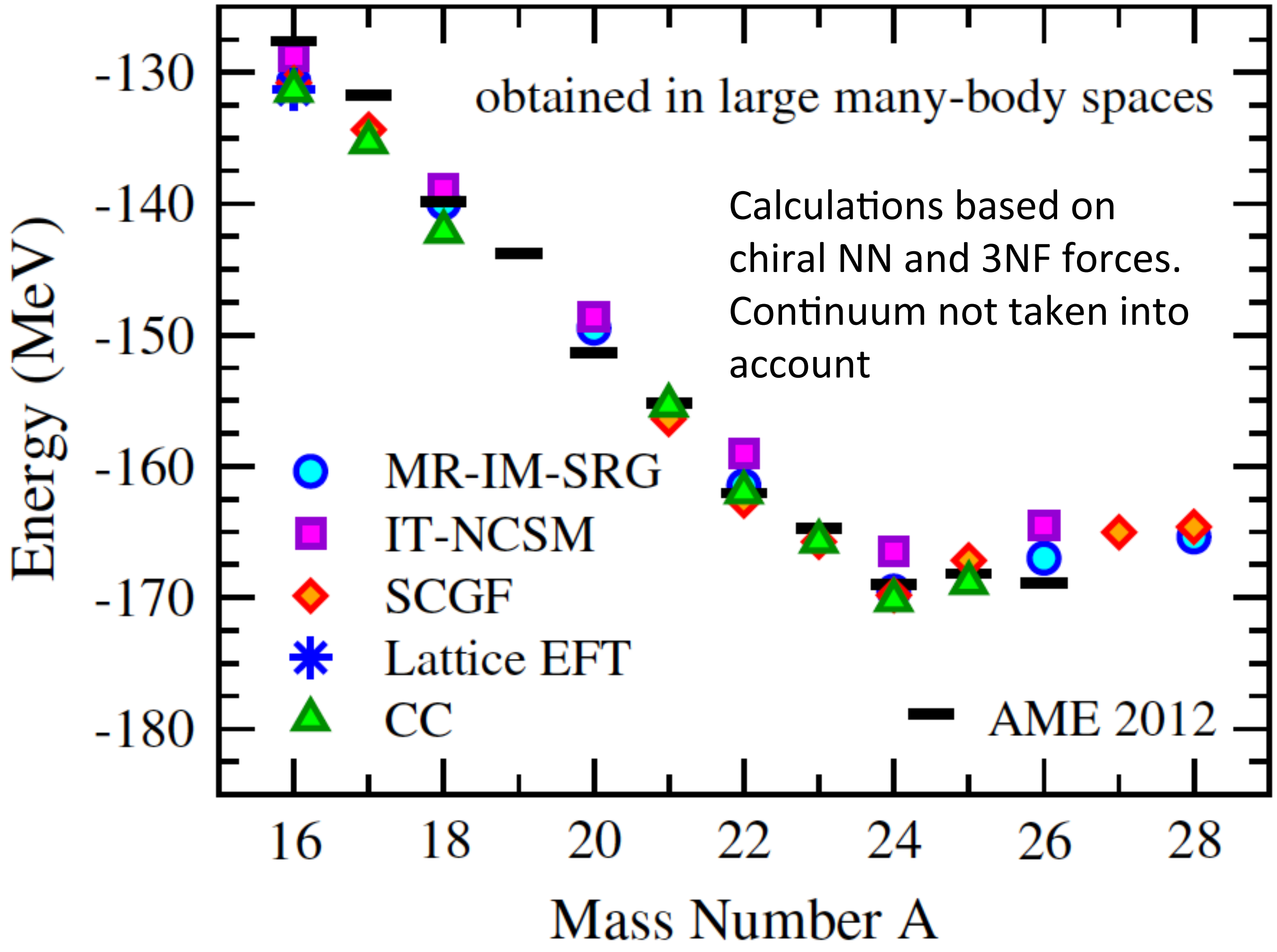
Benchmark of ab-initio methods for oxygen isotopic chain



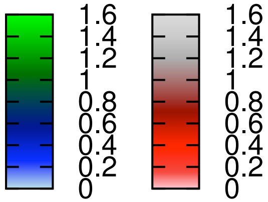
Hebeler, Holt, Menendez, Schwenk, Ann. Rev. Nucl. Part. Sci. in press (2015)

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

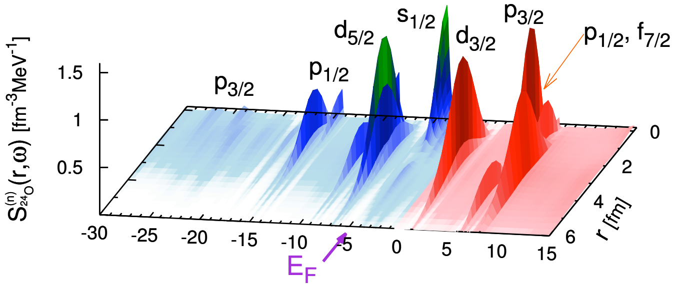
N2LO (Λ = 400Mev/c) chiral 3N interaction evolved (2.0fm^{-1})

Neutron spectral function of Oxygens

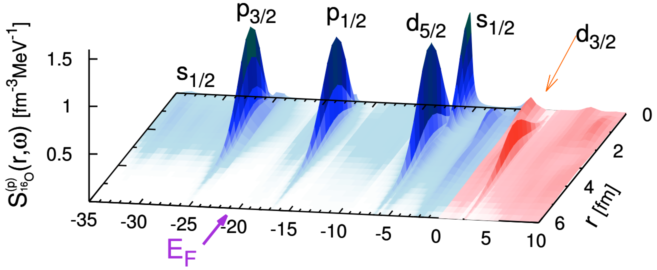
A. Cipollone, CB, P. Navrátil, *Phys. Rev. C* ***92**, 014306 (2015)*



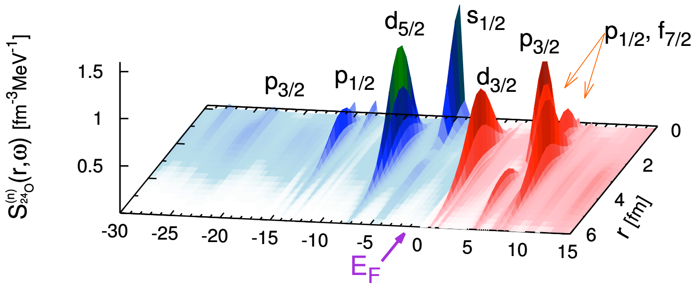
^{22}O:



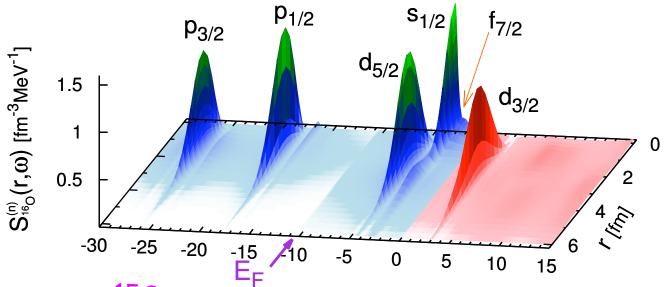
^{14}O:



^{24}O:

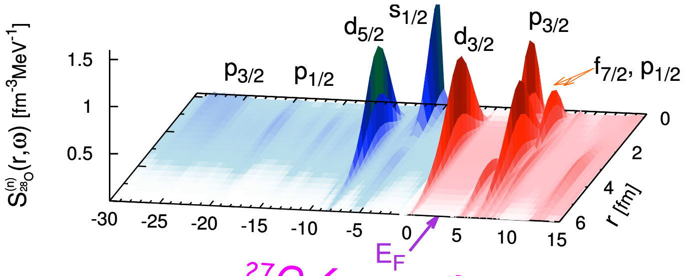


^{16}O:



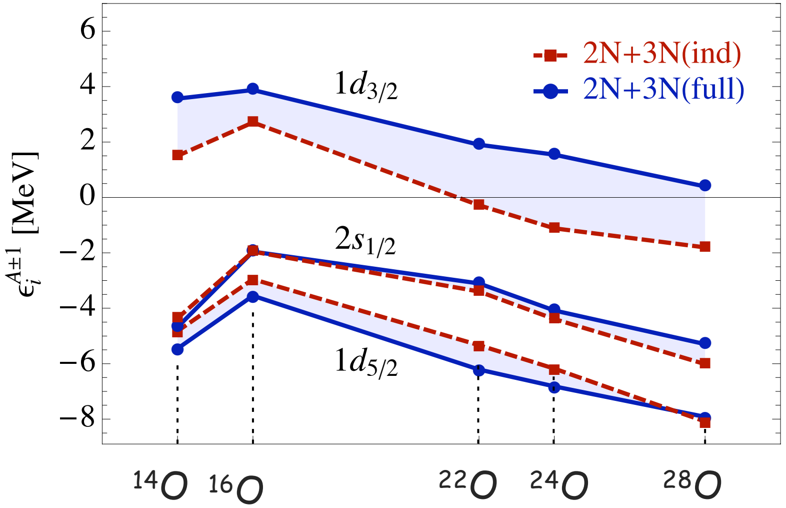
^{15}O ← → ^{17}O

^{28}O:



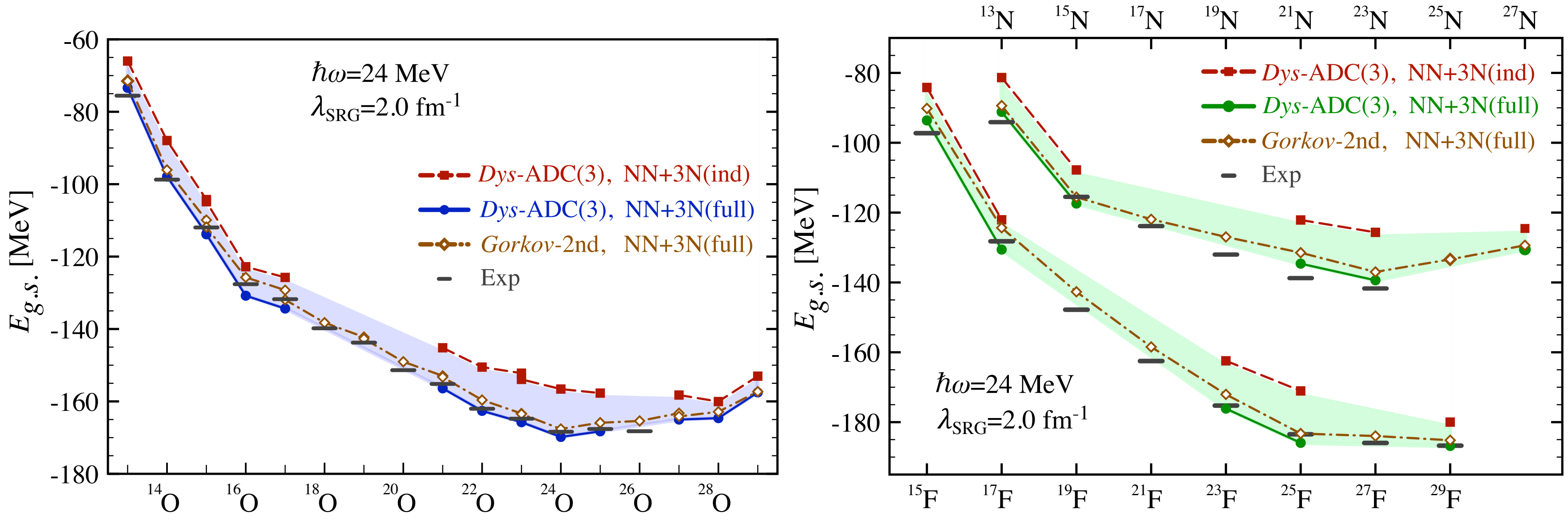
^{27}O ← → ^{29}O

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)



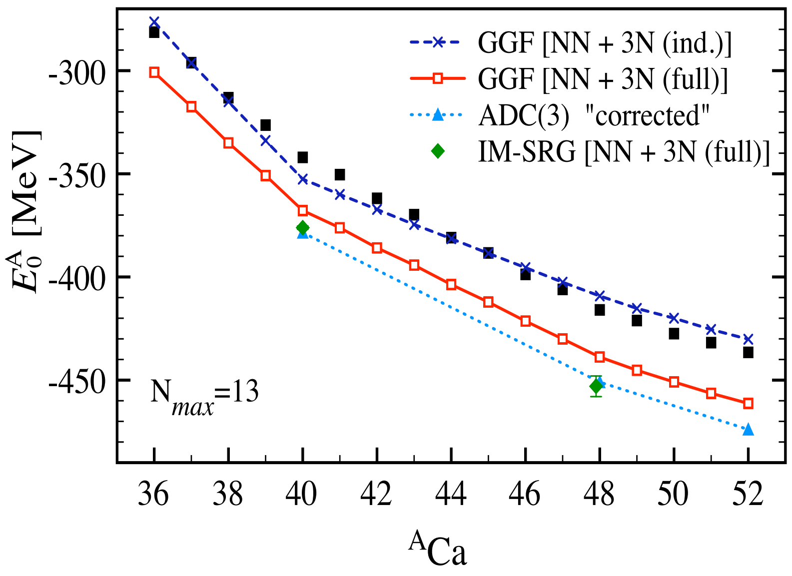
→ 3NF crucial for reproducing binding energies and driplines around oxygen

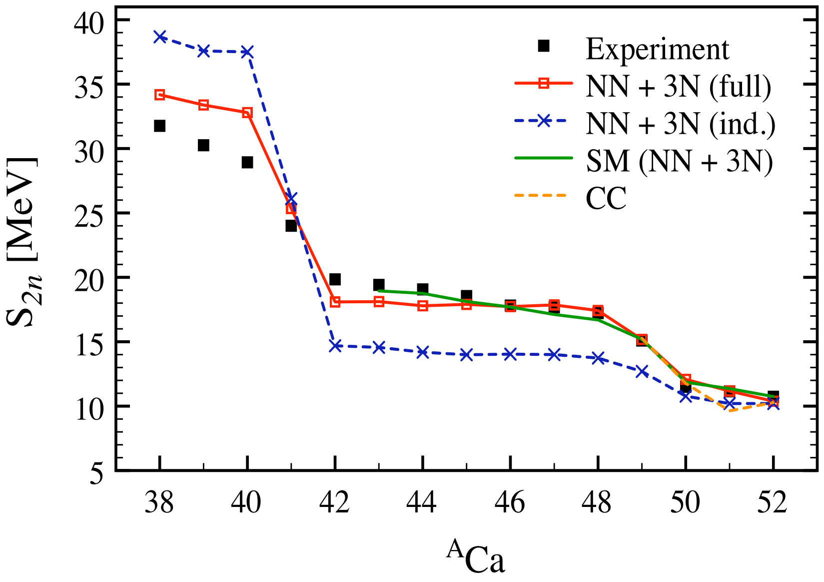
→ cf. microscopic shell model [Otsuka et al, PRL**105**, 032501 (2010).]

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})

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)

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

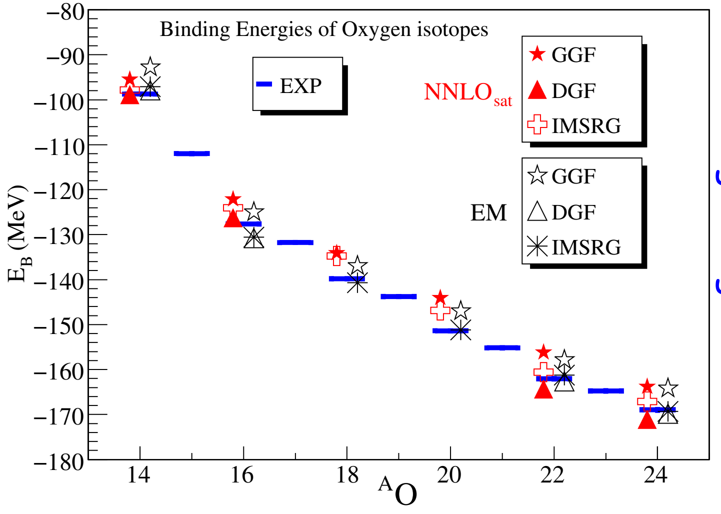
Radii and Binding Energies in Oxygen Isotopes: A Challenge for Nuclear Forces

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

NNLO-sat interaction
Phys.Rev. C91, 051301 ('15)

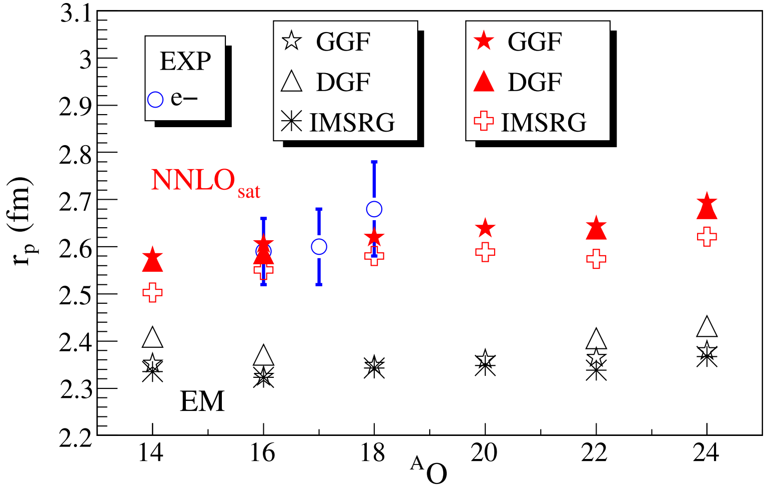
- New fits of chiral interactions (NNLOsat) highly improve comparison to data

- Deficiencies remain for neutron rich isotopes

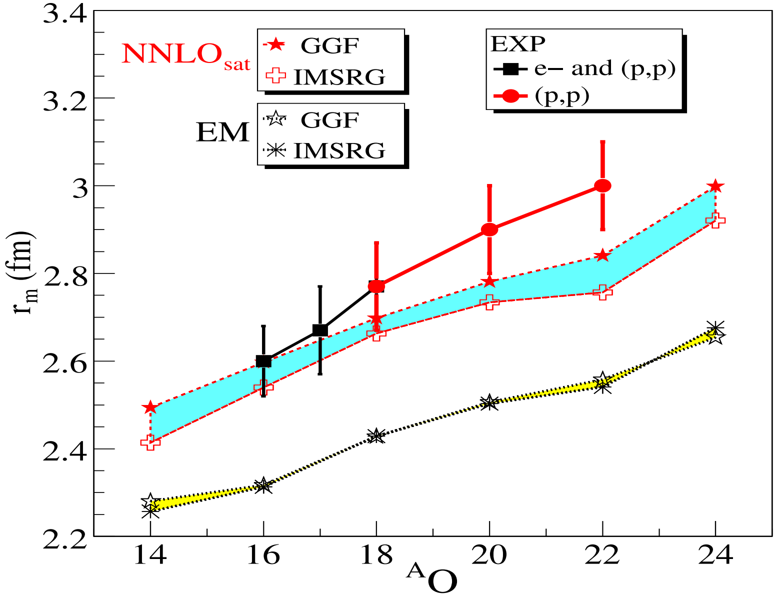


binding energies

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.

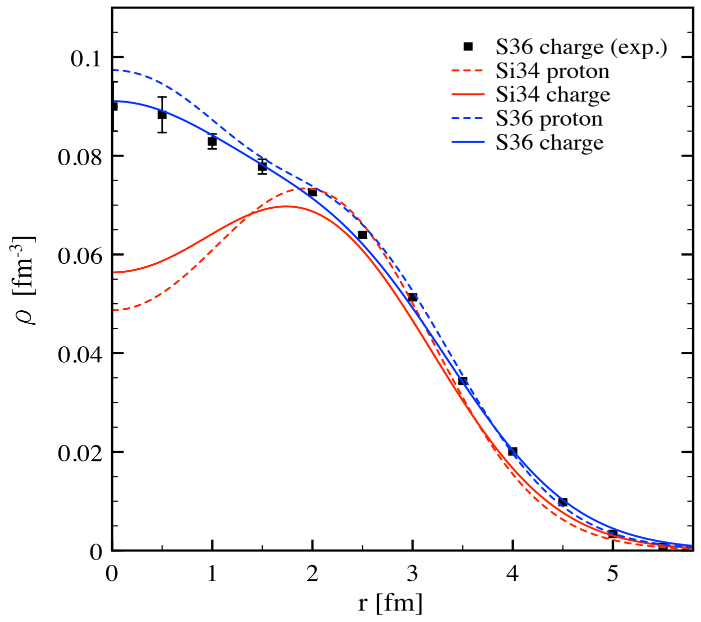


proton radii



matter radii

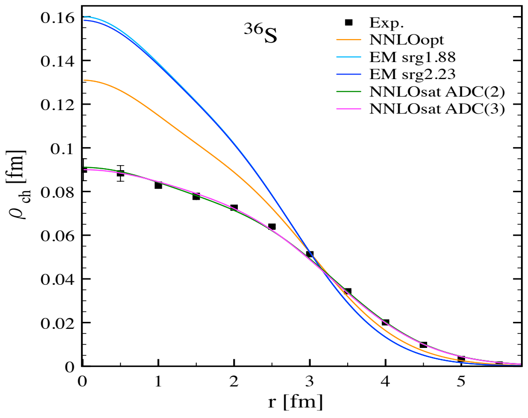
Bubble nuclei… ^{34}Si prediction

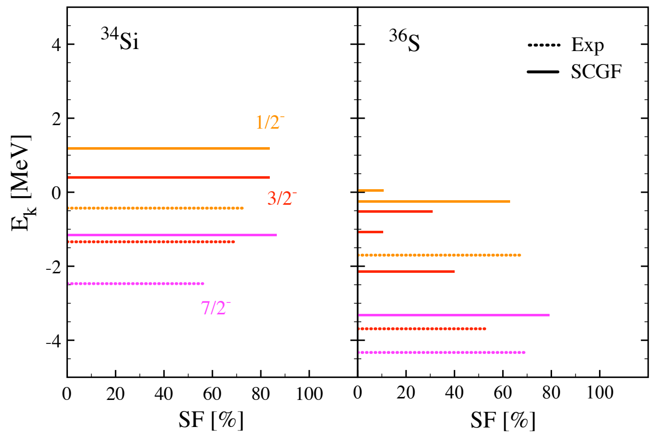


Duguet, Somà, Lecuse, CB, Navrátil,
Phys.Rev. C**95**, 034319 (2017)

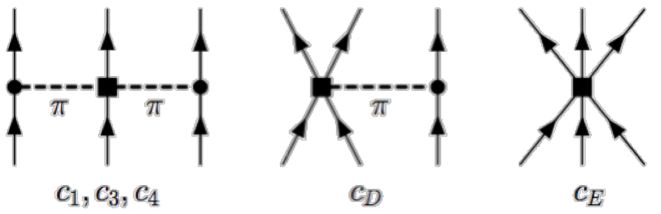
- ^{34}Si is unstable, charge distribution is still unknown
- Suggested central depletion from mean-field simulations
- *Ab-initio* theory confirms predictions
- Other theoretical and experimental evidence:
  Phys. Rev. ***C 79****, 034318 (2009),*
  Nature Physics ***13****, 152–156 (2017).*

Validated by charge distributions and neutron quasiparticle spectra:

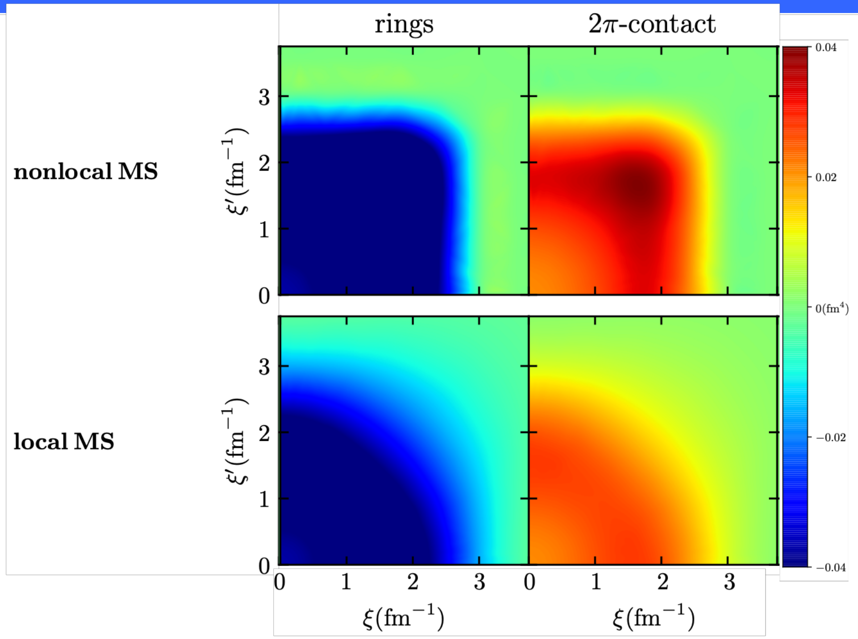




Local vs. non-local chiral N²LO NNN interaction — by P. Navrátil



$$\xi^2 = p^2 + 3/4q^2$$ ≈ 3-nucleon tot. kinetic energy



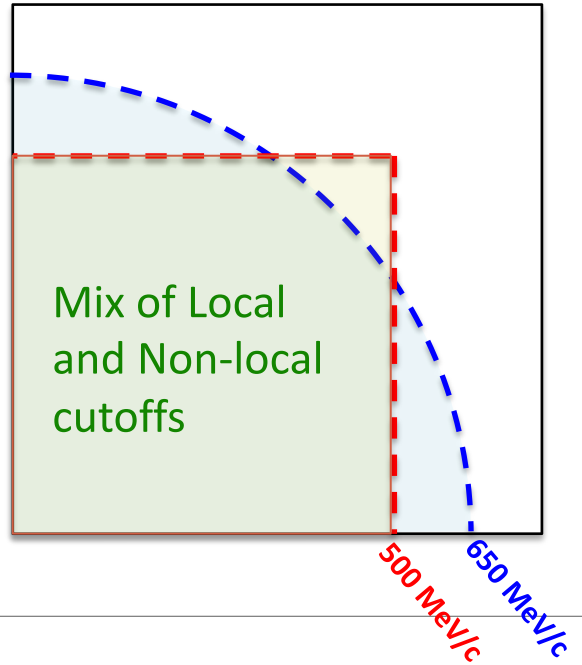
$$f_\Lambda^{\text{long}}(\mathbf{p},\mathbf{q}) = \exp\left[-((\mathbf{p}^2 + 3/4\,\mathbf{q}^2)/\Lambda^2)^n\right]$$

$$\left\langle \mathbf{p}'\mathbf{q}' | V_{3N}^{\text{reg}} | \mathbf{pq} \right\rangle = f_R(\mathbf{p}',\mathbf{q}')\,\langle \mathbf{p}'\mathbf{q}' | V_{3N} | \mathbf{pq}\rangle\, f_R(\mathbf{p},\mathbf{q})$$

$$f_\Lambda^{\text{long}}(\mathbf{Q}_i) = \exp\left[-(\mathbf{Q}_i^2/\Lambda^2)^2\right]$$

$$\left\langle \mathbf{p}'\mathbf{q}' | V_{3N}^{\text{reg}} | \mathbf{pq} \right\rangle = \langle \mathbf{p}'\mathbf{q}' | V_{3N} | \mathbf{pq}\rangle \prod_i f_R(\mathbf{Q}_i)$$

- Local: chiral N³LO NN+ N²LO 3N500
  - c_D=-0.2 c_E=-0.205 (^{3}H E_{gs}=-8.48 MeV)
- Non-local: chiral N²LO$_{sat}$ NN+3N
  - c_D=+0.8168 c_E=-0.0396 (^{3}H E_{gs}=-8.53 MeV)
- Local/Non-local: chiral N³LO NN+ N²LO
  - c_D=+0.7 c_E=-0.06 (^{3}H E_{gs}=-8.44 MeV)



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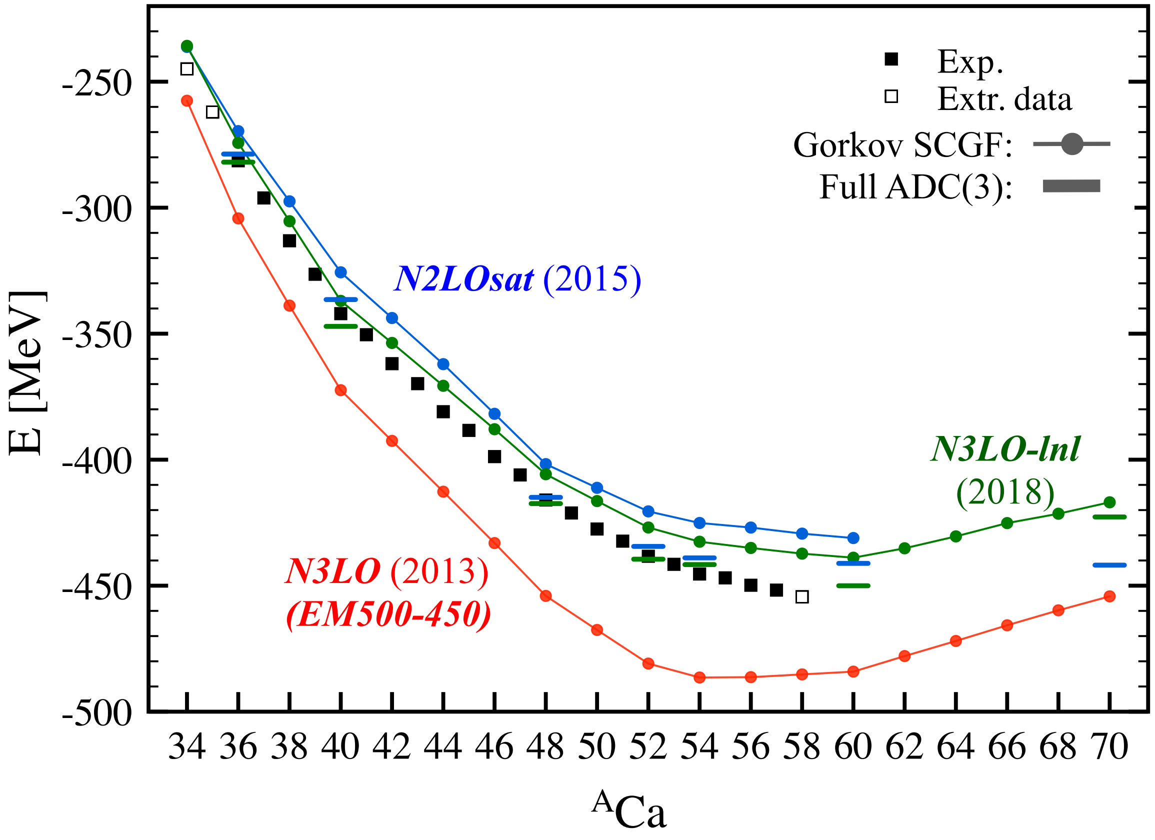
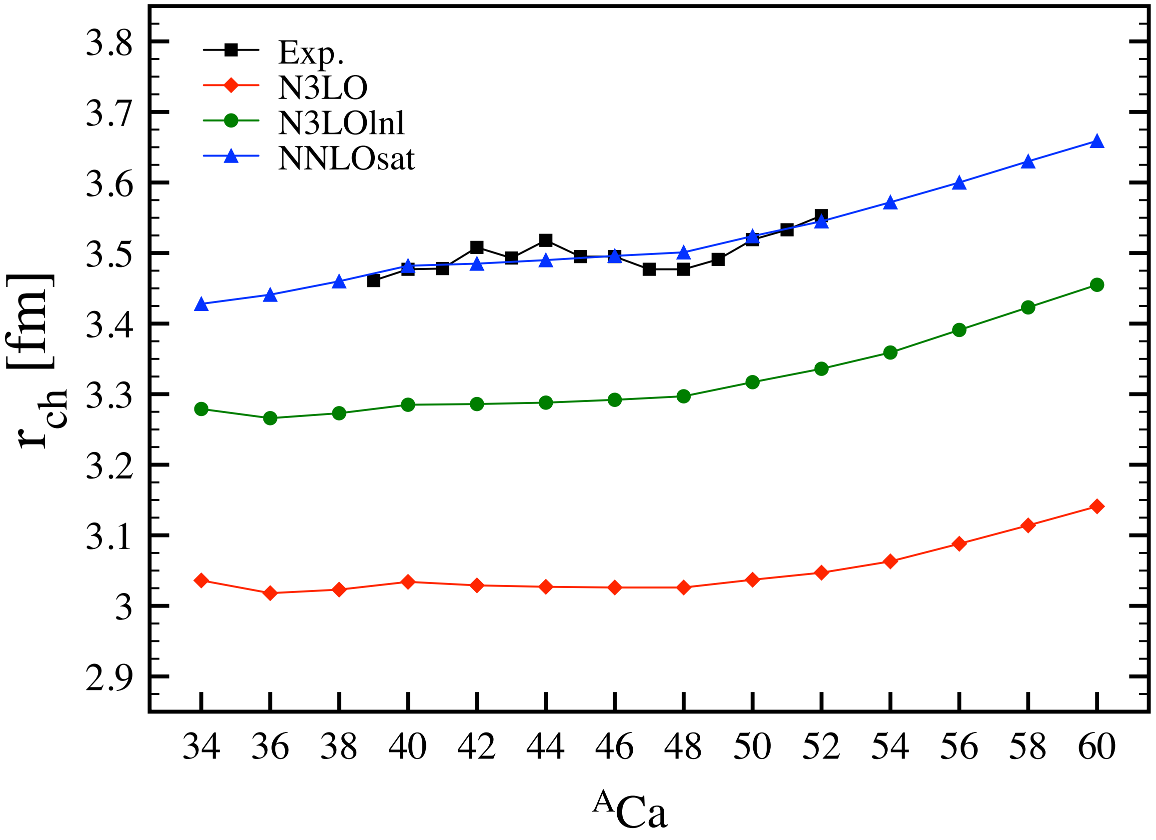
Plots courtesy of K. Hebeler (from his Tuesday's morning talk)

Comparison of nuclear forces - ^{A}Ca





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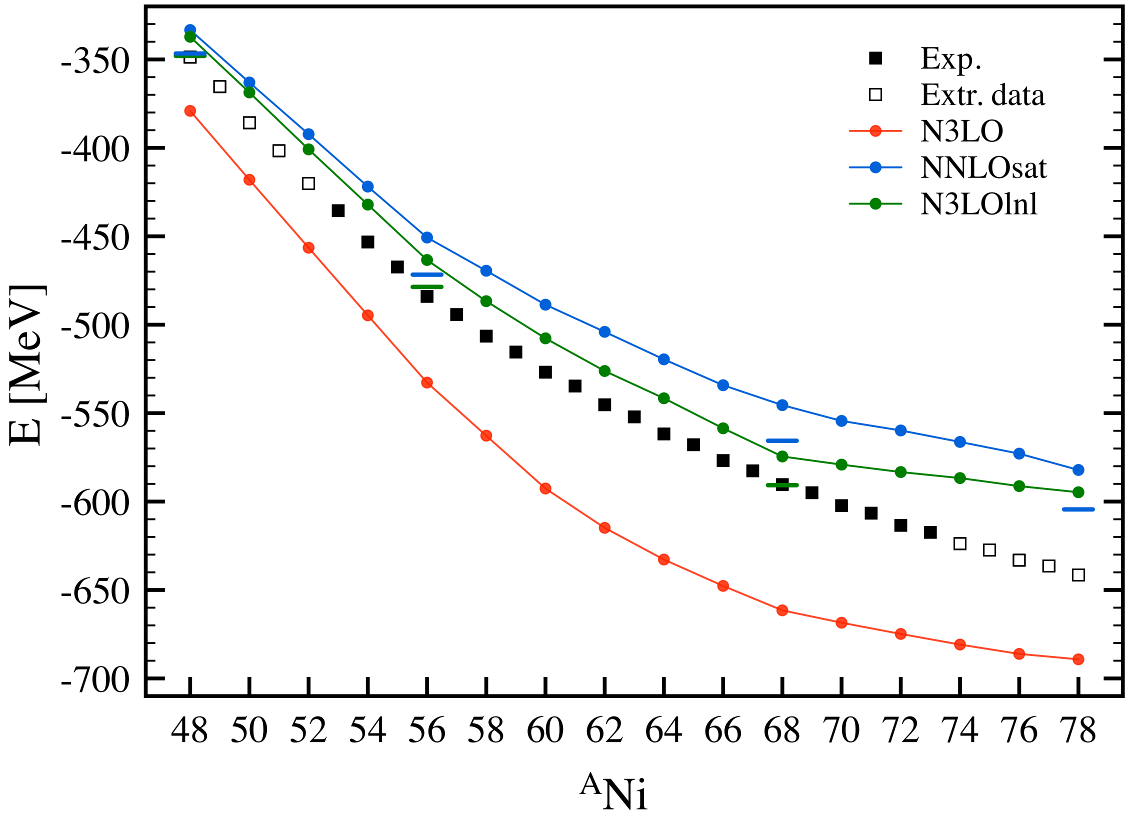
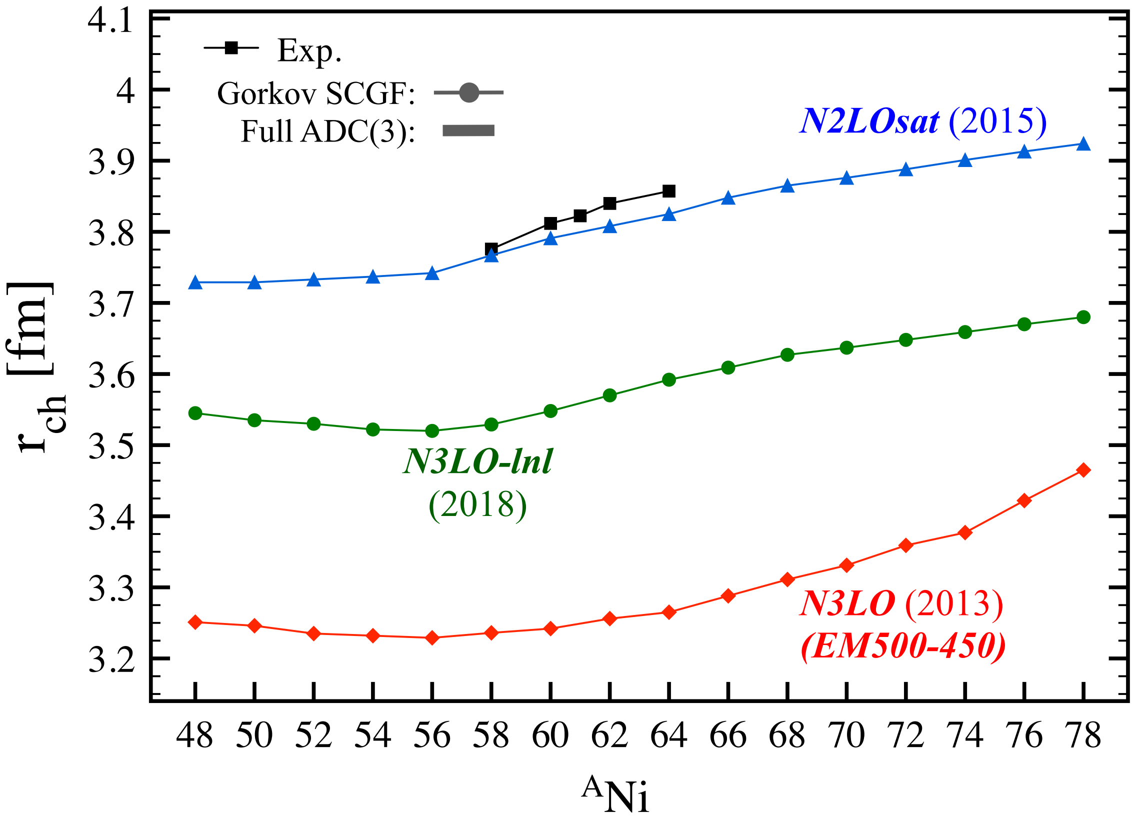
V. Somà, F. Raimondi, CB, P. Navrátil, T. Duguet, in preparation – arXiv:1903:xxyyzz

Comparison of nuclear forces – ^{A}Ni

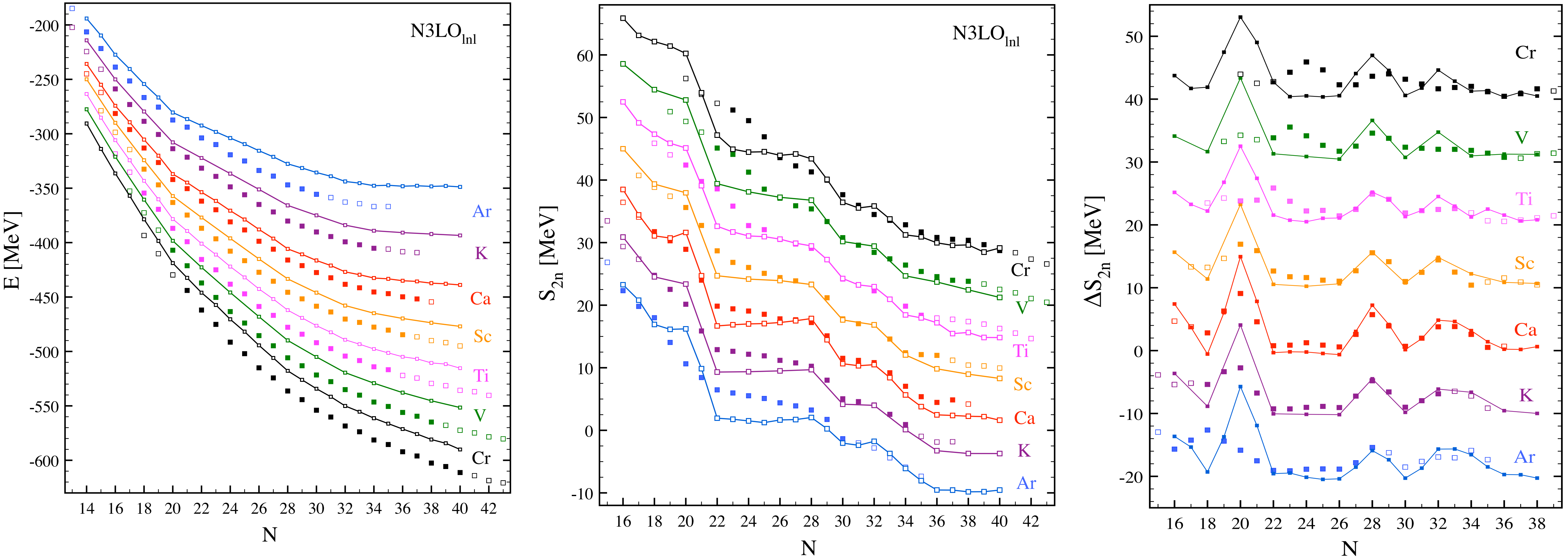




V. Somà, F. Raimondi, CB, P. Navrátil, T. Duguet, in preparation – arXiv:1903:xxyyzz

N3LO(500) + nln 3NF

SCGF – Gorkov-ADC(2)



V. Somà, F. Raimondi, CB, P. Navrátil, T. Duguet, in preparation – arXiv:1903:xxyyzz

Masses in the Ti isotopic chain

- High precision measurements at TITAN (TRIUMF):
  Newly developed Multiple-Reflection Time-of-Flight Mass Spectrometer (MR-TOF-MS)

- Weak shell closure at N=32 (quenched w.r.t. ^{52}Ca)

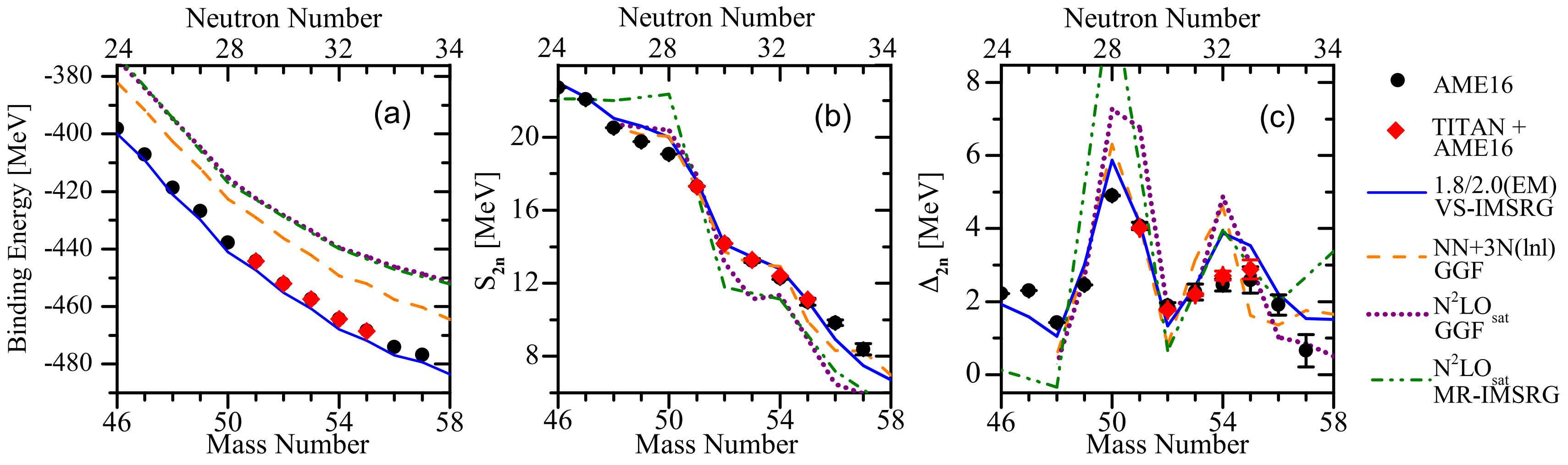


FIG. 4. The mass landscape of titanium isotopes is shown from three perspectives: (a) absolute masses (shown in binding energy format), (b) its first "derivative" as two-neutron separation energies (S_{2n}), and (c) its second "derivative" as empirical neutron-shell gaps (Δ_{2n}). Both theoretical *ab-initio* calculations (lines) and experimental values (points) are shown.

E. Leistenschneider *et al.*, *CB*, Phy. Rev. Lett. **120**, 062503 (2018) – ***TITAN*** coll. @ TRIUMF

Electron and neutrino scattering off nuclei

N. Rocco, CB, Phys. Rev. C**98**, 025501 (2018).

N. Rocco, CB, O. Benhar, A. De Pace, A. Lovato, Phys. Rev. C**99**, 025502 (2019)

Lepton-nucleon cross section

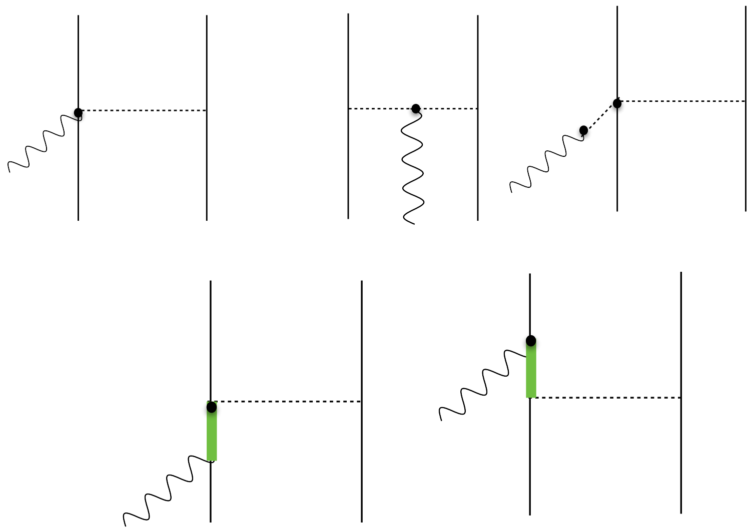
$$\left(\frac{d\sigma}{dT'd\cos\theta'}\right)_{\nu/\bar{\nu}} = \frac{G^2}{2\pi}\frac{k'}{2E_\nu}\left[\hat{L}_{CC}R_{CC} + 2\hat{L}_{CL}R_{CL} + \hat{L}_{LL}R_{LL} + \hat{L}_{T}R_{T} \pm 2\hat{L}_{T'}R_{T'}\right] ,$$

Nuclear structure is in the hadronic tensor:

$$\begin{aligned} W^{\mu\nu}(\mathbf{q},\omega) = \int \frac{d^3k}{(2\pi)^3} dE\, P_h(\mathbf{k},E) \frac{m^2}{e(\mathbf{k})e(\mathbf{k}+\mathbf{q})} \\ \times \sum_i \langle k|j_i^{\mu\,\dagger}|k+q\rangle\langle k+q|j_i^\nu|k\rangle \\ \times\, \delta(\omega + E - e(\mathbf{k}+\mathbf{q}))\,, \end{aligned}$$

$$\begin{aligned} W_{2\mathrm{b}}^{\mu\nu}(\mathbf{q},\omega) = \frac{V}{2}\int d\tilde{E}\frac{d^3k}{(2\pi)^3}d\tilde{E}'\frac{d^3k'}{(2\pi)^3}\frac{d^3p}{(2\pi)^3} \\ \times \frac{m^4}{e(\mathbf{k})e(\mathbf{k}')e(\mathbf{p})e(\mathbf{p}')} P_h^{\mathrm{NM}}(\mathbf{k},\tilde{E})P_h^{\mathrm{NM}}(\mathbf{k}',\tilde{E}') \\ \times \sum_{ij}\langle k\,k'|j_{ij}^{\mu\,\dagger}|p\,p'\rangle\langle p\,p'|j_{ij}^{\nu}|k\,k'\rangle \\ \times\, \delta(\omega + \tilde{E} + \tilde{E}' - e(\mathbf{p}) - e(\mathbf{p}'))\,. \qquad (41) \end{aligned}$$

Two-body diagrams contributing to the axial and vector responses



N. Rocco, CB, O. Benhar, de Pace , A. Lovato, Phys. Rev. C**99**, 025502 (2019)

Lepton-nucleon cross section

$$\left(\frac{d\sigma}{dT' d\cos\theta'}\right)_{\nu/\bar\nu} = \frac{G^2}{2\pi}\frac{k'}{2E_\nu}\left[\hat L_{CC}R_{CC} + 2\hat L_{CL}R_{CL} + \hat L_{LL}R_{LL} + \hat L_T R_T \pm 2\hat L_{T'}R_{T'}\right] ,$$

Nuclear structure is in the hadronic tensor:

$$W^{\mu\nu}(\mathbf{q},\omega) = \int \frac{d^3k}{(2\pi)^3} dE\, P_h(\mathbf{k},E) \frac{m^2}{e(\mathbf{k})e(\mathbf{k}+\mathbf{q})} \times \sum_i \langle k|j_i^{\mu\,\dagger}|k+q\rangle\langle k+q|j_i^\nu|k\rangle \times \delta(\omega + E - e(\mathbf{k}+\mathbf{q})) ,$$

$$W^{\mu\nu}_{2b}(\mathbf{q},\omega) = \frac{V}{2}\int d\tilde E \frac{d^3k}{(2\pi)^3} d\tilde E' \frac{d^3k'}{(2\pi)^3}\frac{d^3p}{(2\pi)^3} \times \frac{m^4}{e(\mathbf{k})e(\mathbf{k}')e(\mathbf{p})e(\mathbf{p}')} P_h^{\rm NM}(\mathbf{k},\tilde E)P_h^{\rm NM}(\mathbf{k}',\tilde E') \times \sum_{ij}\langle k\,k'|j_{ij}^{\mu\,\dagger}|p\,p'\rangle\langle p\,p'|j_{ij}^\nu|k\,k'\rangle \times \delta(\omega + \tilde E + \tilde E' - e(\mathbf{p}) - e(\mathbf{p}')) . \quad (41)$$

Two models of the Spectral function

$$P_h(\mathbf{k},E) = \frac{1}{\pi}\sum_{\alpha\beta}\tilde\Phi^*_\beta(\mathbf{k})\tilde\Phi_\alpha(\mathbf{k}) \times {\rm Im}\langle\psi_0^A|a_\beta^\dagger \frac{1}{E + (H - E_0^A) - i\epsilon} a_\alpha|\psi_0^A\rangle$$

SCGF/ADC(3) using chiral NNLOsat

$$P_h(\mathbf{k},E) = P_h^{1h}(\mathbf{k},E) + P_h^{\rm corr}(\mathbf{k},E) .$$

$$P_h^{1h}(\mathbf{k},E) = \sum_{\alpha\in\{F\}} Z_\alpha|\phi_\alpha(\mathbf{k})|^2 F_\alpha(E - e_\alpha)$$

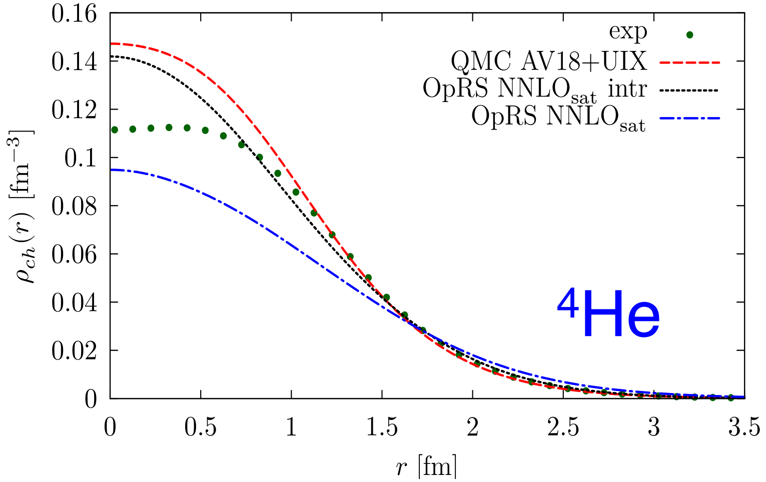
$$P_h^{\rm corr}(\mathbf{k},E) = \int d^3R\, \rho_A(\mathbf{R}) P^{\rm corr}_{h,\,NM}(\mathbf{k},E;\rho_A(\mathbf{R}))$$

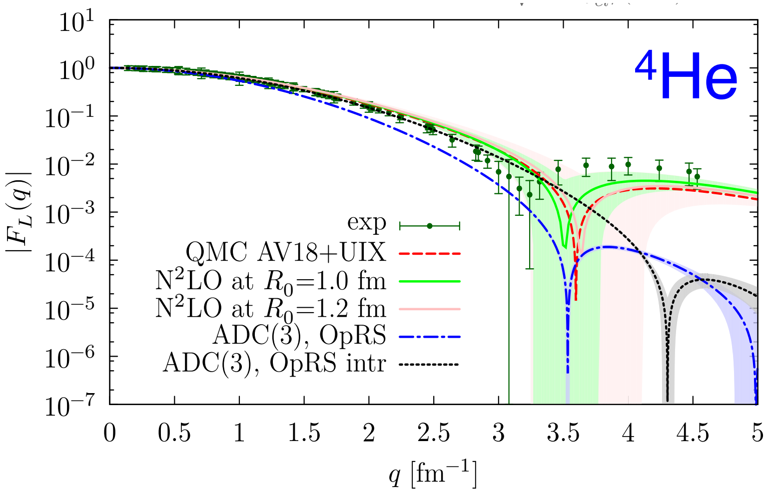
CBF using AV18+UIX (see Benhar's talk)

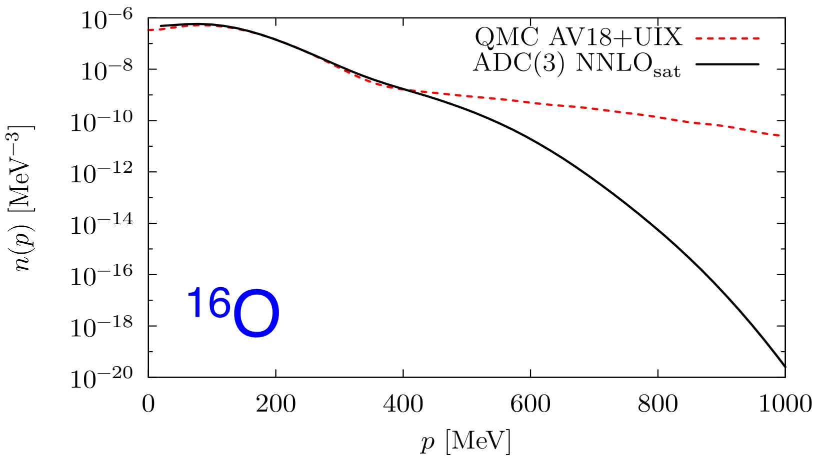
N. Rocco, CB, O. Benhar, de Pace , A. Lovato, Phys. Rev. C**99**, 025502 (2019)

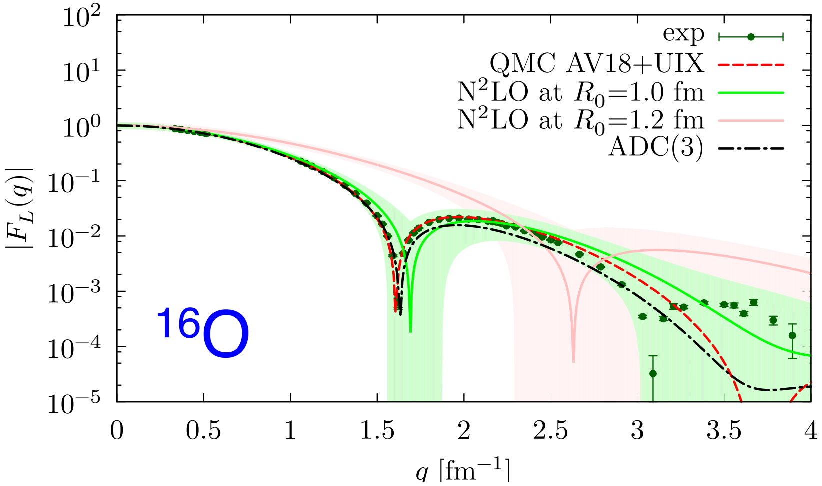
Prediction for chrg./mom. distributions and form factors

$$F_L(\mathbf{q}) = \frac{1}{Z}\frac{G_E^p(Q_{el}^2)\tilde{\rho}_p(q) + G_E^n(Q_{el}^2)\tilde{\rho}_n(q)}{\sqrt{1+Q_{el}^2/(4m^2)}}$$









- Calculations from the spectral functions obtained using SCGF
- Based on the saturating chiral N2LO-sat nuclear force
- Comparison to QMC calculations based on local chiral forces and/or AV18+UIX [PRC96, 024326 ('17) PRC96, 054007 ('17) PRC97, 044318 ('18)]

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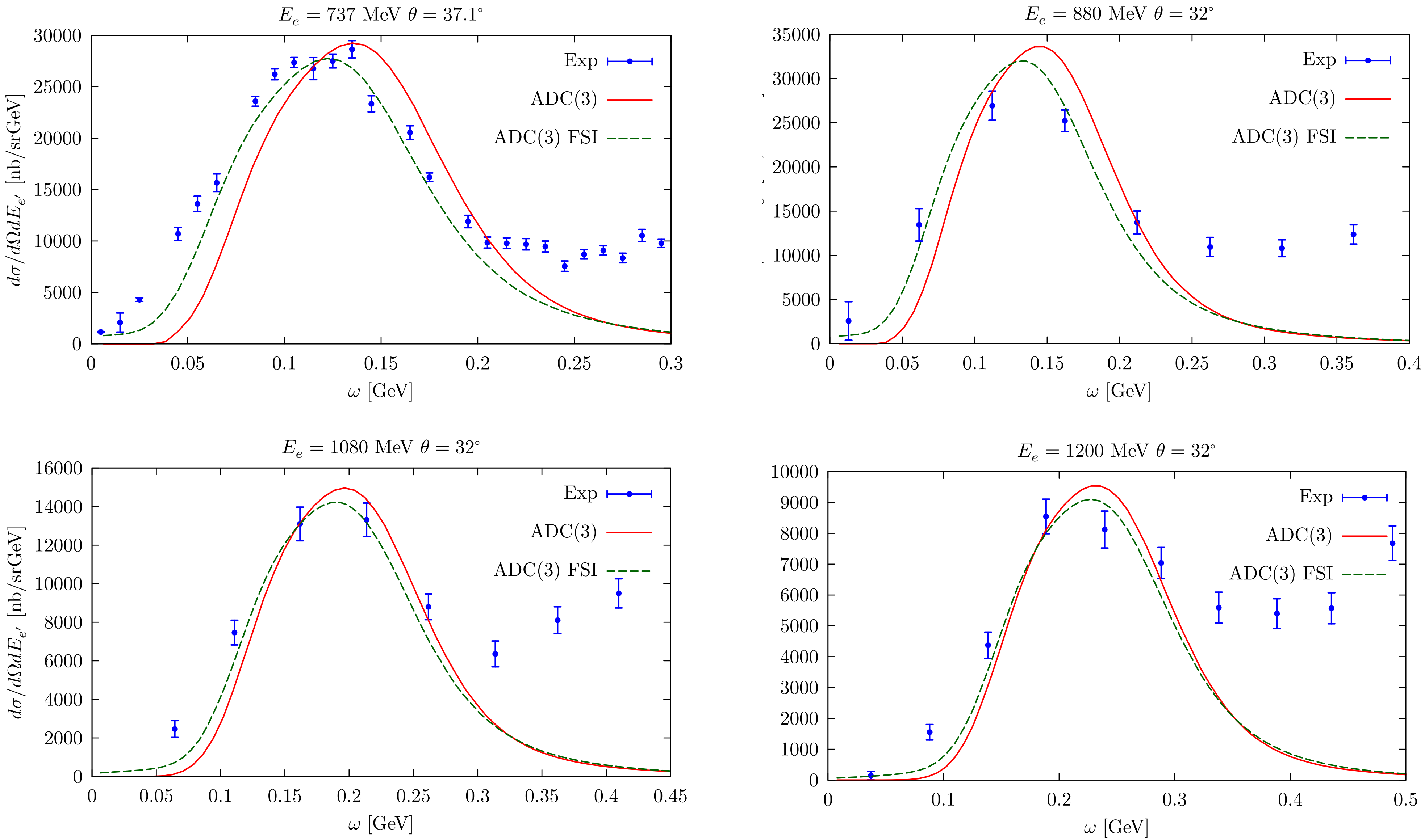
N. Rocco, CB, Phys. Rev. C**98**, 025501 (2018).

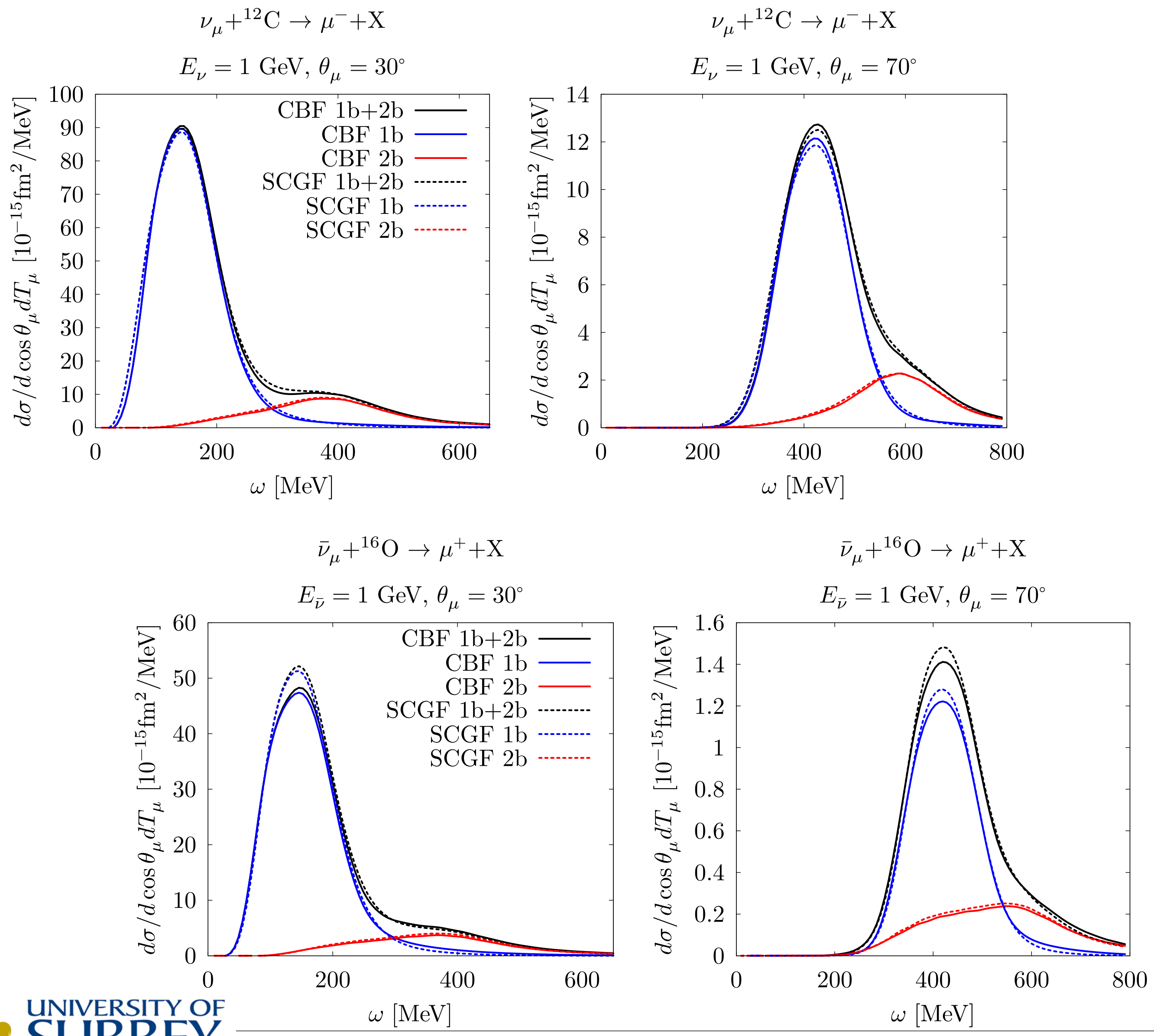
^{16}O-e$^-$ cross sections from the SCGF Spect. Fnct.



Based on the saturating chiral N2LO-sat nuclear force

N. Rocco, CB, Phys. Rev. C**98**, 025501 (2018).

Charged-current reaction for 1 GeV neutrinos



One-body current describe quasi elastic peak

Difference between CBF(AV18) and SCGF(NNLOsat) from 1-b terms

Two-body currents fiull up dip region

Missing Delta and meson emission contributions

X-sec. droppin with scattering angle

N. Rocco, CB, O. Benhar, de Pace , A. Lovato, Phys. Rev. C**99**, 025502 (2019)

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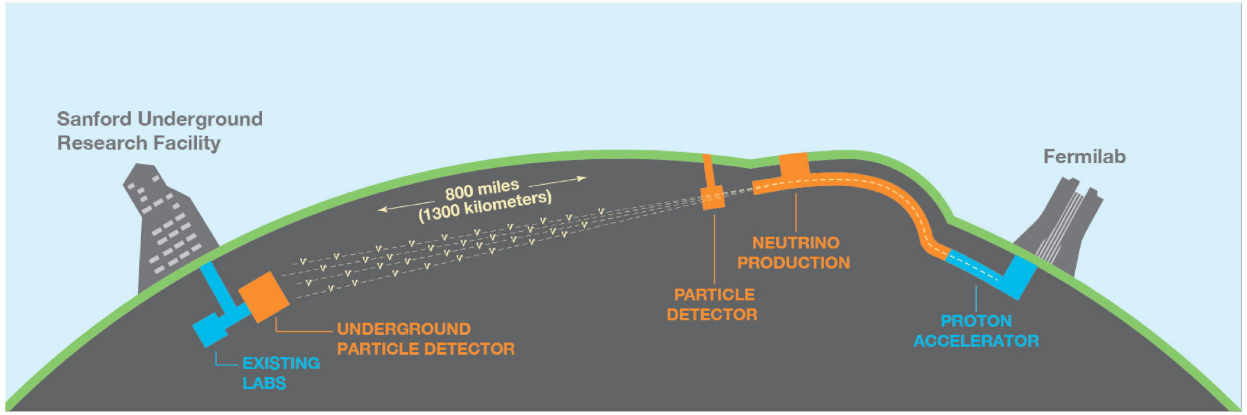
Neutrino Oscillations – next generation experiments



DUNE experiment will measure long base line neutrino oscillations to:

- Resolve neutrino mass hierarchy
- Search for CP violation in weak interaction
- Search for other physics beyond SM

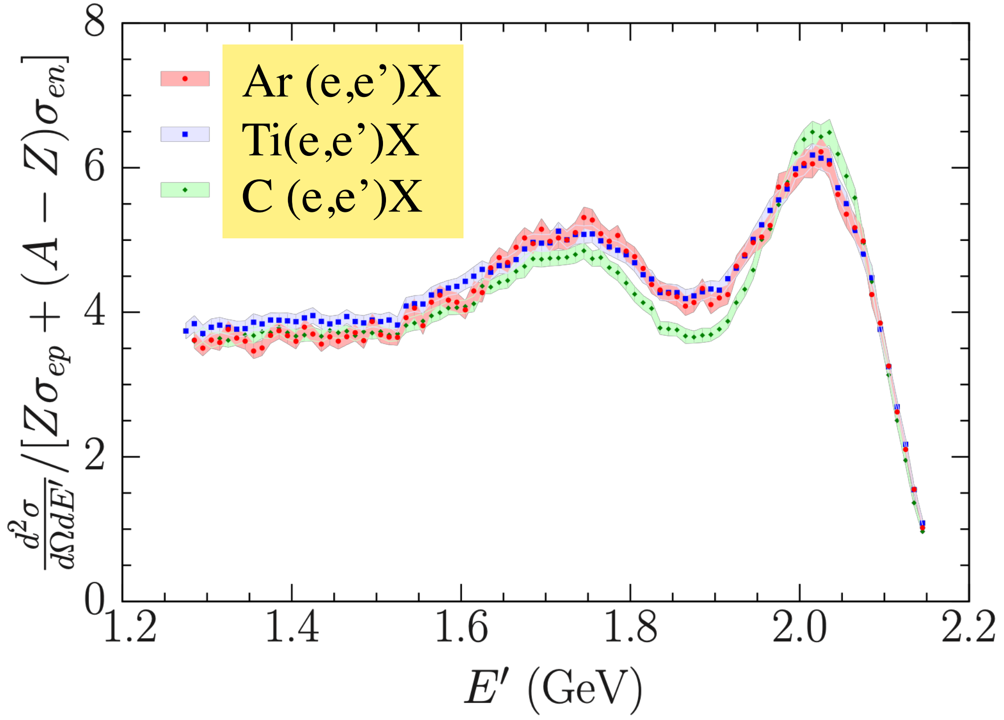
Liquid Argon projection chamber is being used. It will require one order of magnitude (20% → 2%) improvement in theoretical prediction for ν-^{40}Ar cross sections to achieve proper event reconstruction.

➔ **Need good knowledge of ^{40}Ar spectral functions and consistent structure-scattering theories.**

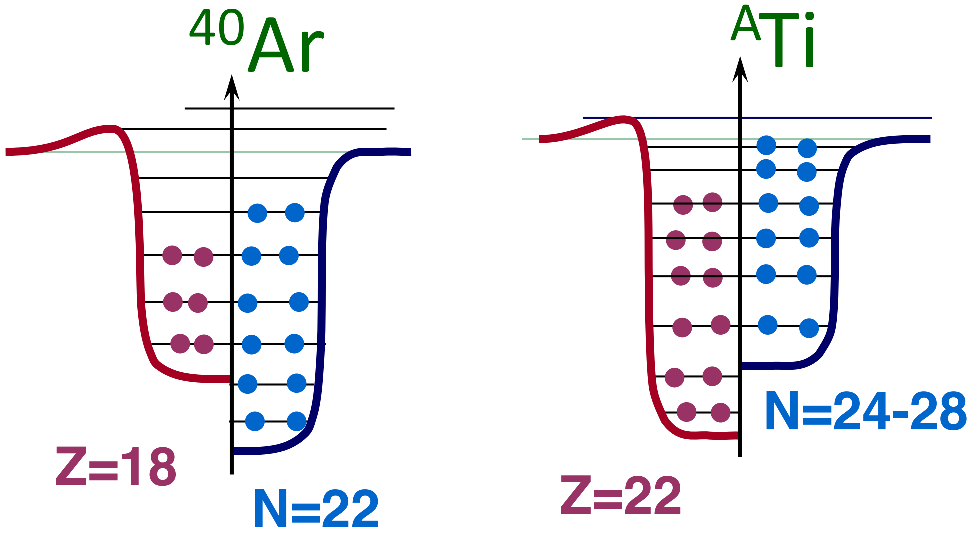
Spectral function for ^{40}Ar and Ti

Jlab experiment E12-14-012 (Hall A)

Phys. Rev. C 98, 014617 (2018); arXiv:1810.10575

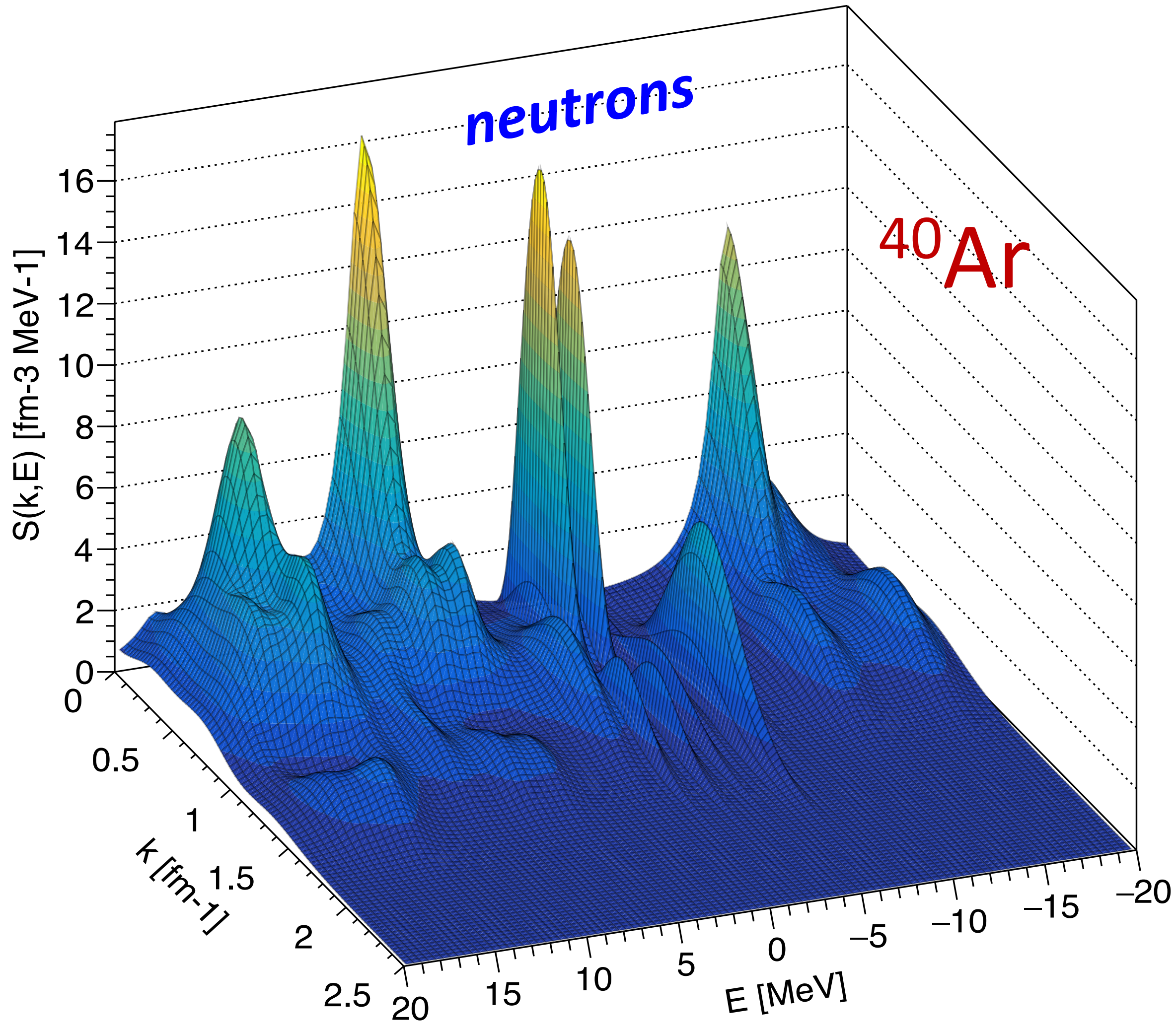


^{40}Ar(e,e'p) and Ti(e,e'p) data being analyzed



Proton distribution in Ti similar to neutron in ^{40}Ar ??

Spectral function for ^{40}Ar



- Experimental datat now available from Jlab: H. Dai et al., arXiv:1803.01910/ 1810.10575
- Ab initio simulations based on the ADC(2) truncation of the N2LO-sat Hamiltoninan

➔ Want validation of initial state correlation before they are implementer in neutrino-^{40}Ar simulations

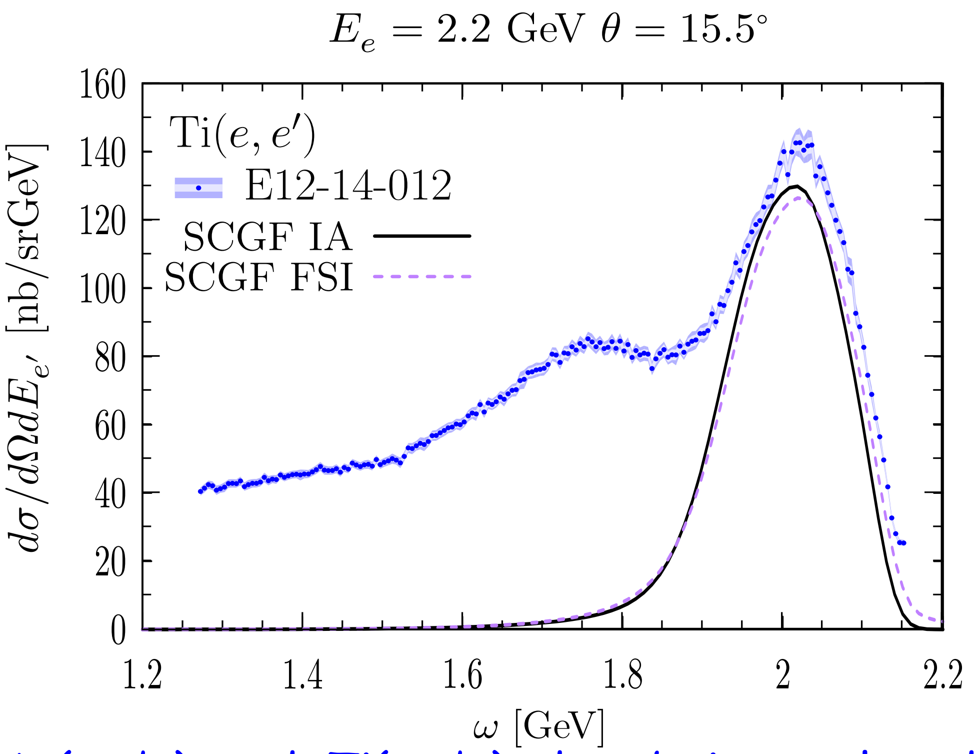
N. Rocco, V. Somà, CB, in preparation

UNIVERSITY OF SURREY Figure courtesy of V. Somà

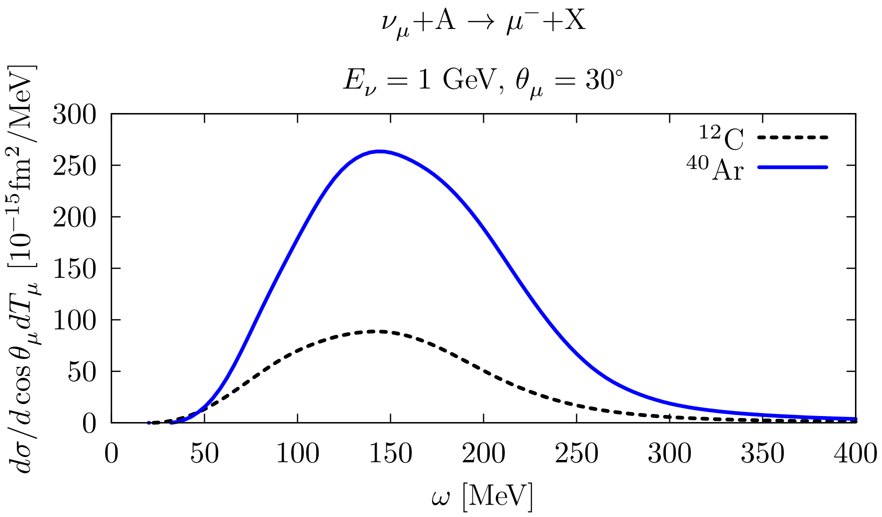
Electron and ν scattering on ^{40}Ar and Ti

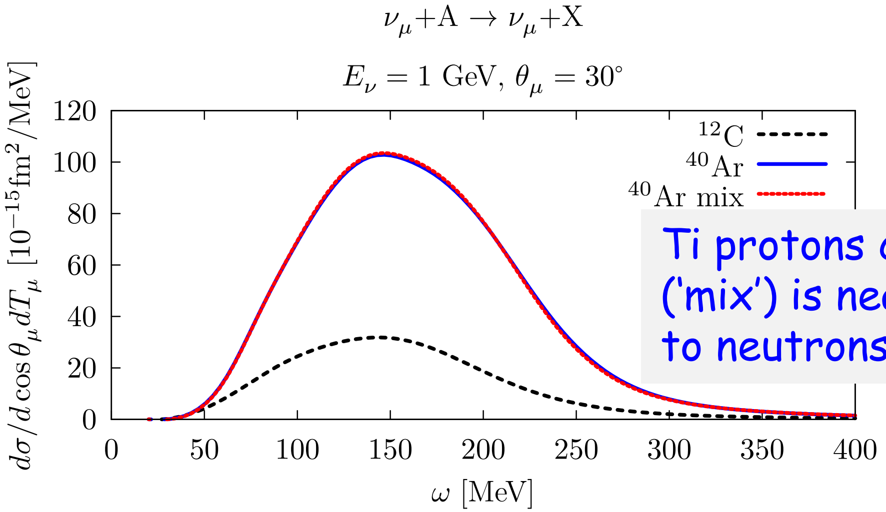
Jlab experiment E12-14-012 (Hall A)

Phys. Rev. C 98, 014617 (2018)



^{40}Ar(e,e'p) and Ti(e,e'p) data being analyzed





Ti protons contribution ('mix') is nearly identical to neutrons in ^{40}Ar.

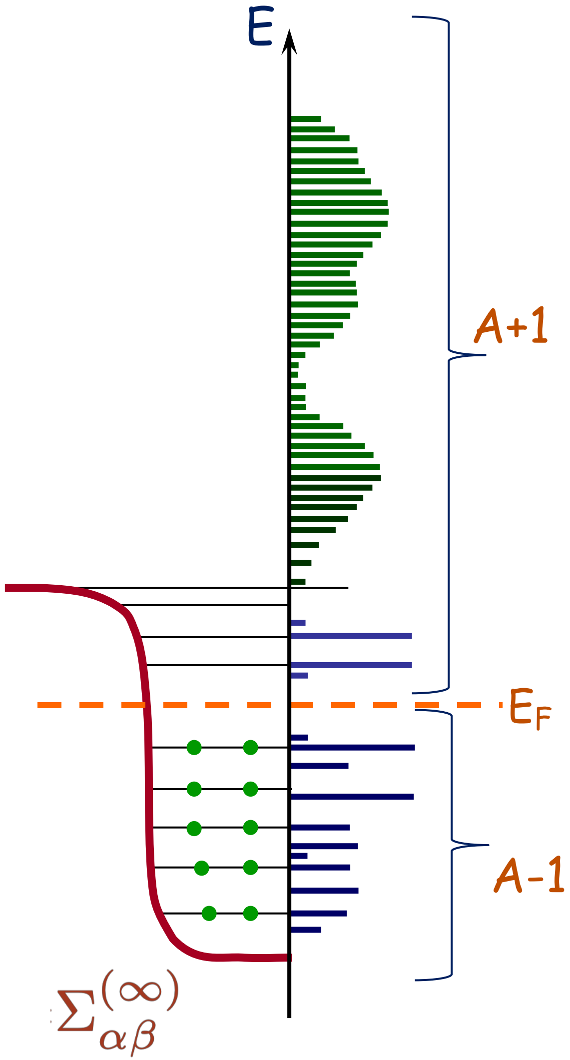
N. Rocco, CB and V. Somà, in preparation.

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, arXiv:1612.01478v1 [nucl-th] and in prep.

Microscopic optical potential



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

- contains *both* *particle* and *hole* props.
- it is proven to be a Feshbach opt. pot

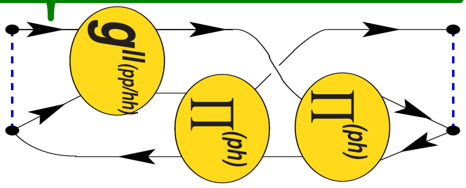
→ in general it is *non-local !*

$$\Sigma^\star_{\alpha\beta}(\omega) = \Sigma^{(\infty)}_{\alpha\beta} + \sum_{i,j} \mathbf{M}^\dagger_{\alpha,i} \left[\frac{1}{E - (\mathbf{K}^> + \mathbf{C}) + i\Gamma} \right]_{i,j} \mathbf{M}_{j,\beta}$$

$$+ \sum_{r,s} \mathbf{N}_{\alpha,r} \left[\frac{1}{E - (\mathbf{K}^< + \mathbf{D}) - i\Gamma} \right]_{r,s} \mathbf{N}^\dagger_{s,\beta}$$

mean-field

Particle-vibration couplings:



Solve scattering and overlap functions directly in momentum space:

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

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

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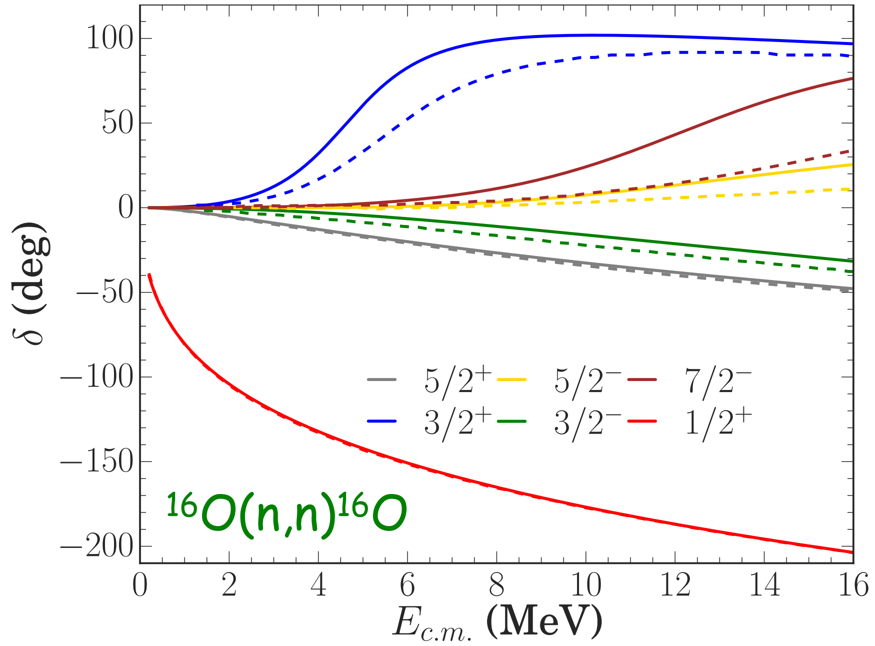
Low energy scattering – from SCGF

[A. Idini, CB, Navratil, arXiv:1903.xxzzww]

Benchmark with NCSM-based scattering.

NN-only interaction at λ_{SRG}= 2.66 fm^{-1}

Scattering from mean-field only:



NCSM/RGM [no core excitations]
PRC**82**, 034609 (2010)

SCGF [$\Sigma^{(\infty)}$ only]

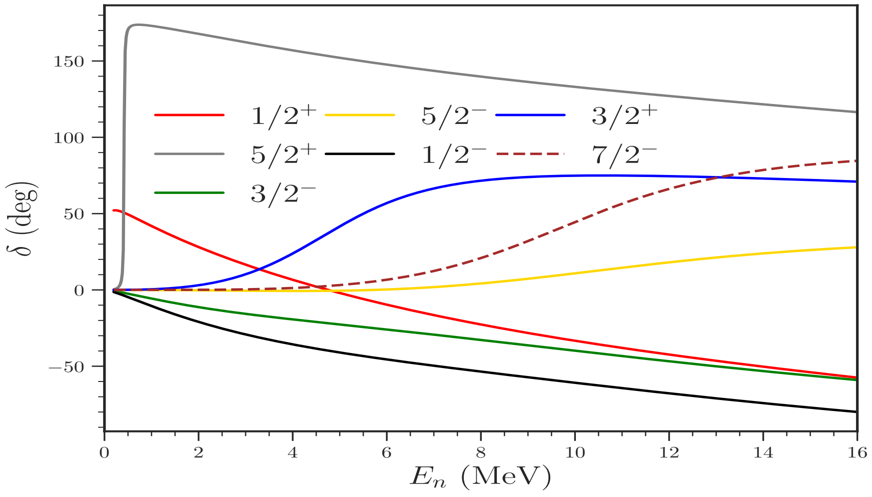
Low energy scattering – from SCGF

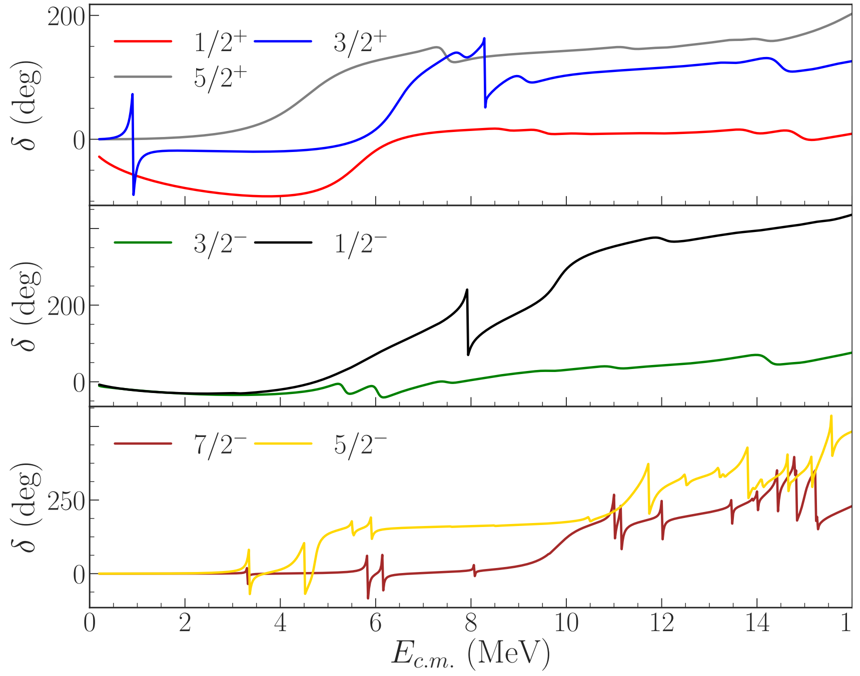
[A. Idini, CB, Navratil, arXiv:1903.xxzzww]

$$\Sigma^{(\infty)}(k,k';E)$$

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

$$\Sigma^{\star}(k,k';E)$$





Jπ	5/2+	1/2+	3/2+	1/2-	3/2-	5/2+	5/2-	7/2-
NNLO-sat [MeV]	-5.06	-3.58	0.91	-0.15	-2.24	4.57	3.36	3.37
Experiment [MeV]	-4.14	-3.27	0.94	-1.09	0.41	3.23	3.02	3.77

TABLE I. Excitation spectrum of ^{17}O with respect to the ^{16}O+n threshold, as obtained from Eq. (5) and the NNLO$_{\rm sat}$ interaction and compared to the experiment [38]. Broad resonances in the continuum (most notably, the $5/2^+$) are evaluated at midpoint.

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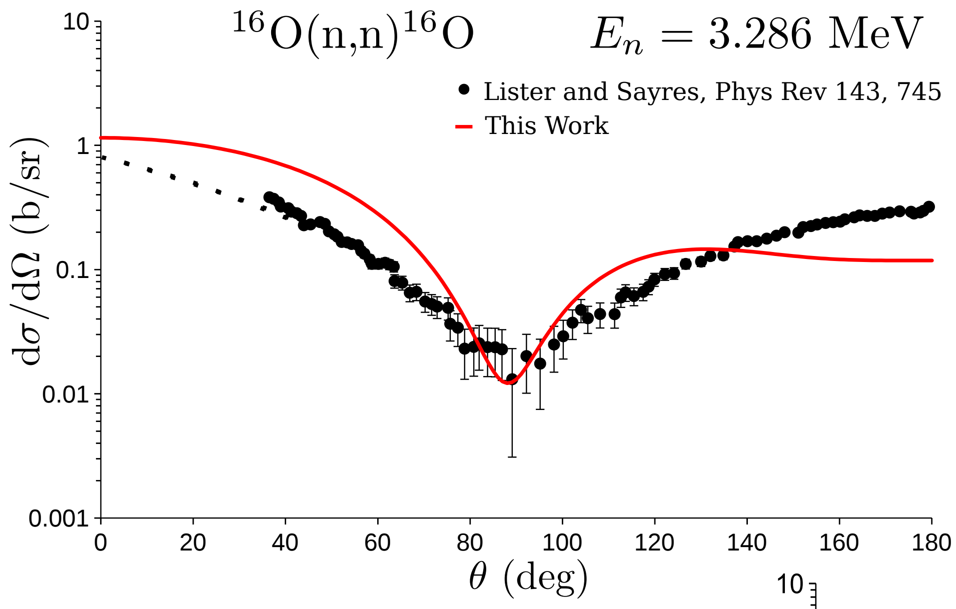
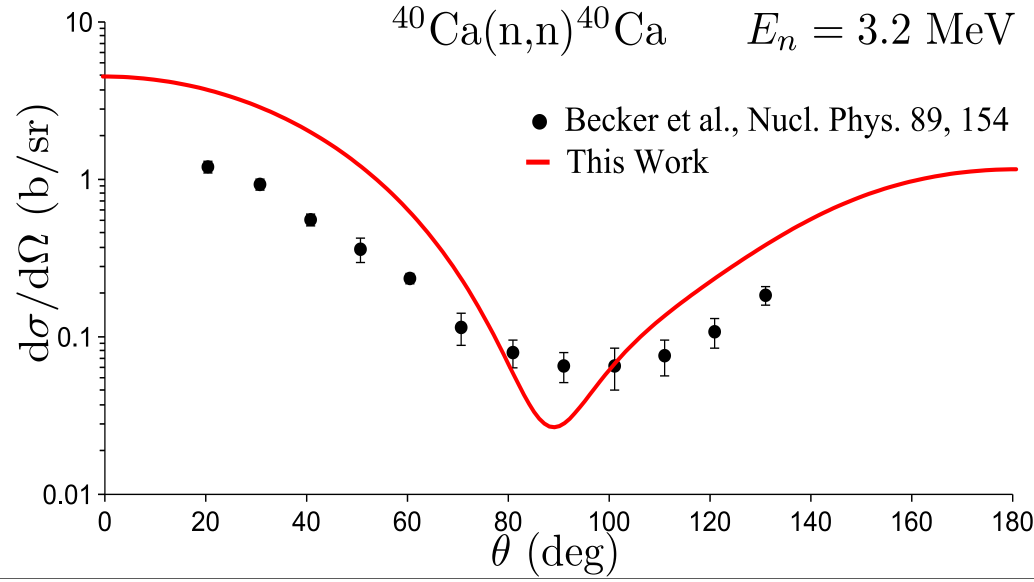
Low energy scattering - from SCGF

[A. Idini, CB, Navratil, in prep.]

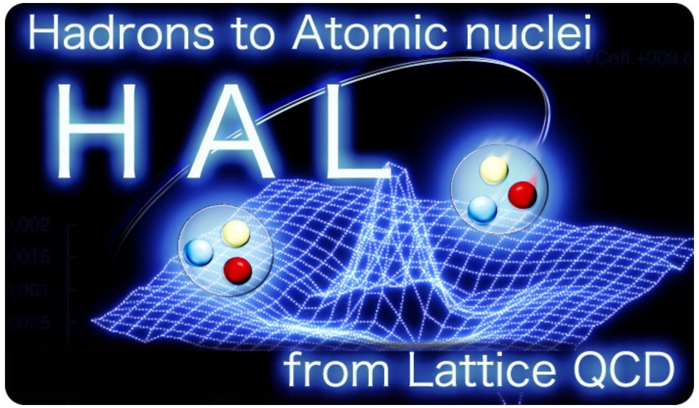




Study of nuclear interactions from Lattice QCD

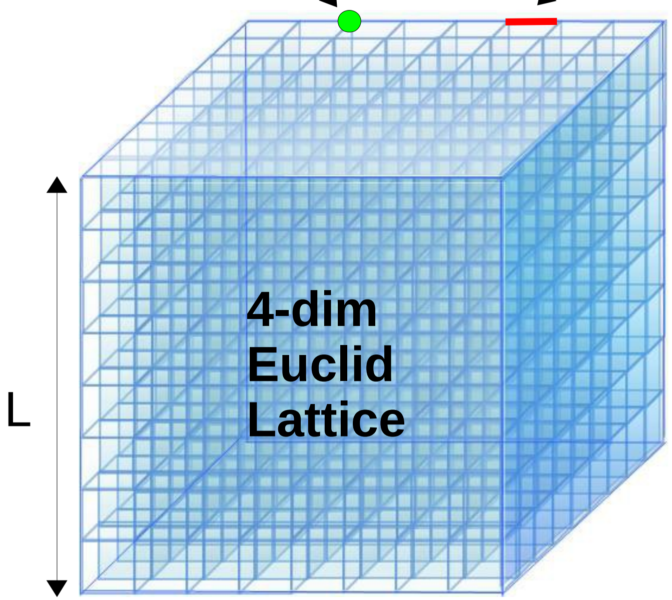
*C. McIlroy, CB et al. Phys. Rev. C**97**, 021303(R) (2018)*

In collaboration with:

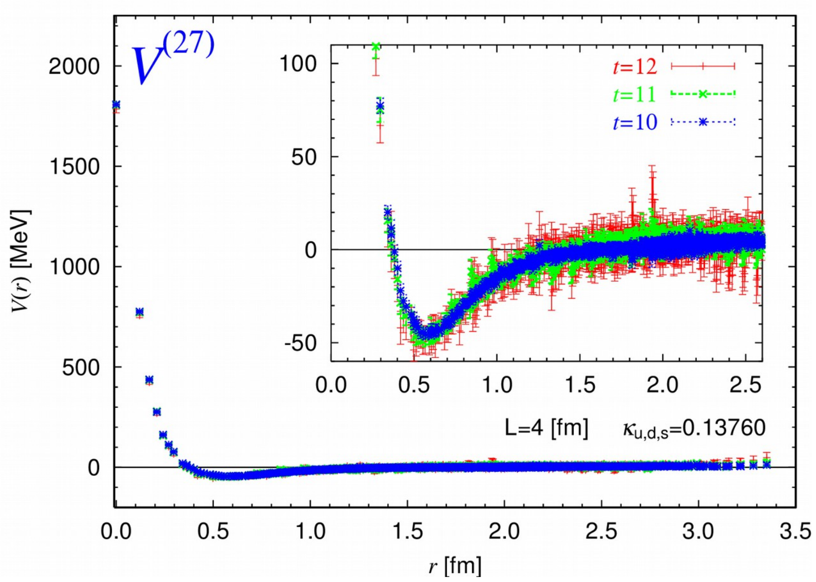


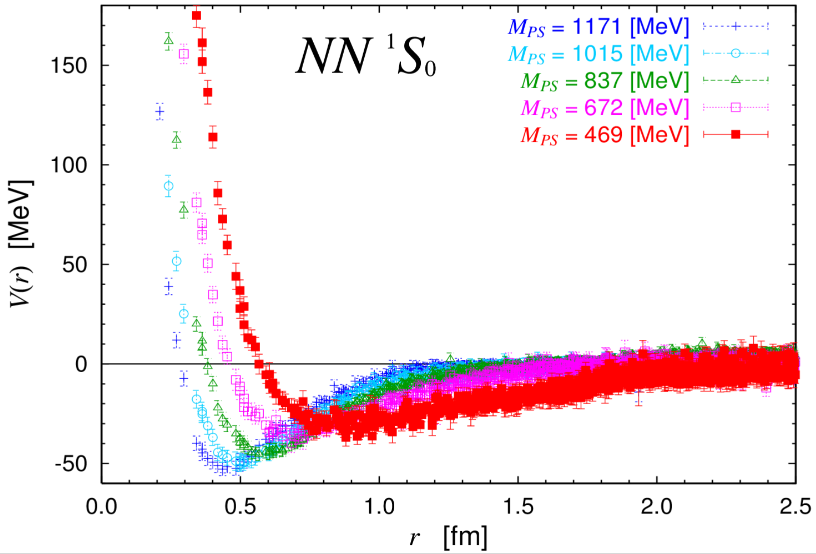
Two-Nucleon HAL potentials in flavour SU(3) symm.

HALQCD method; quarks q on the sites, gluons $U = e^{iaA_\mu}$ on the links ➔



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





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.

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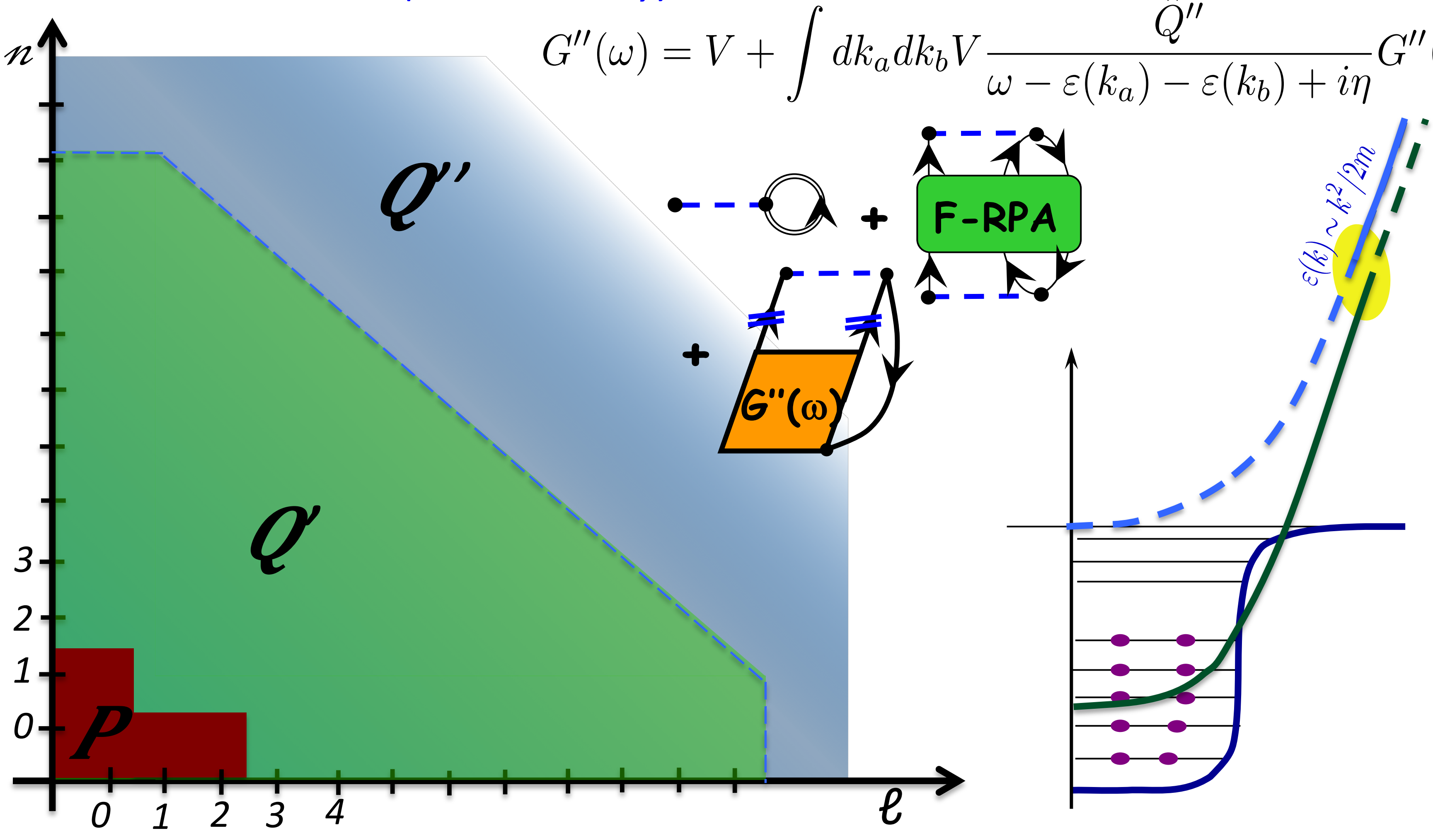
Prog. Theor. Exp. Phys. 01A105 (2012)

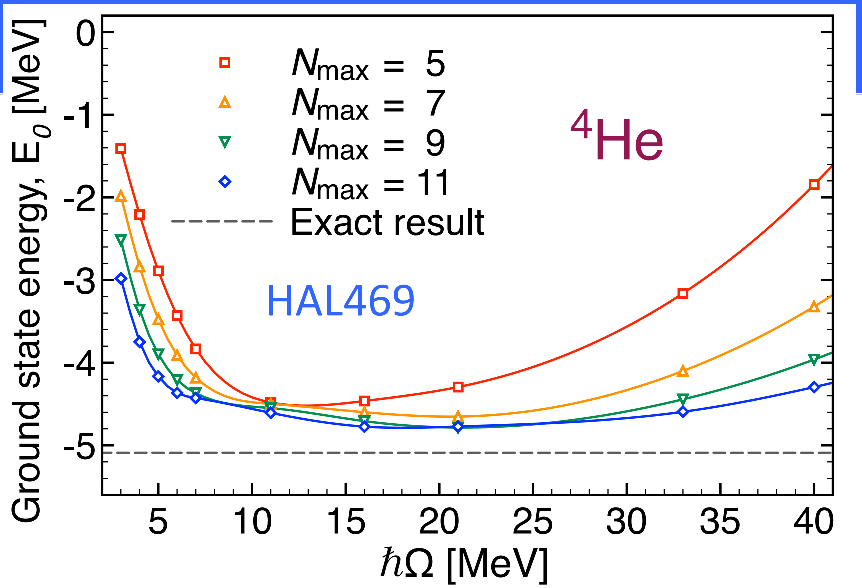
Mixed SCGF-Brueckner approach

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

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

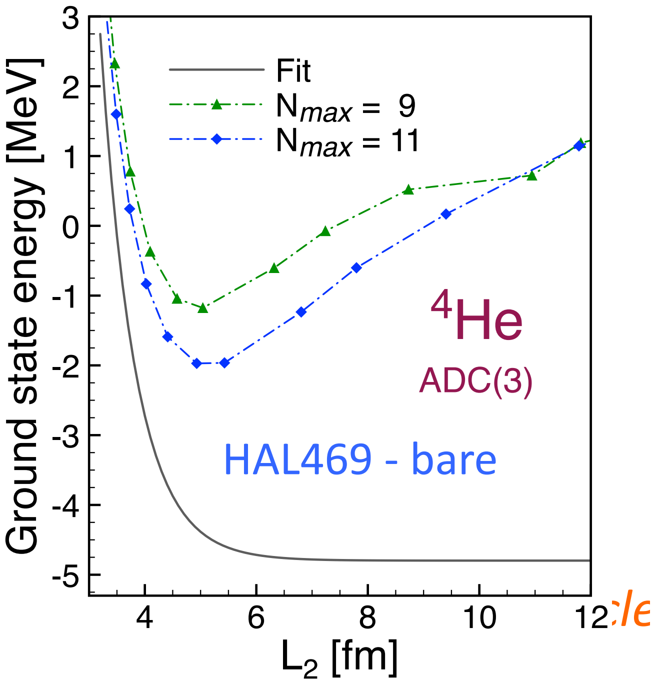


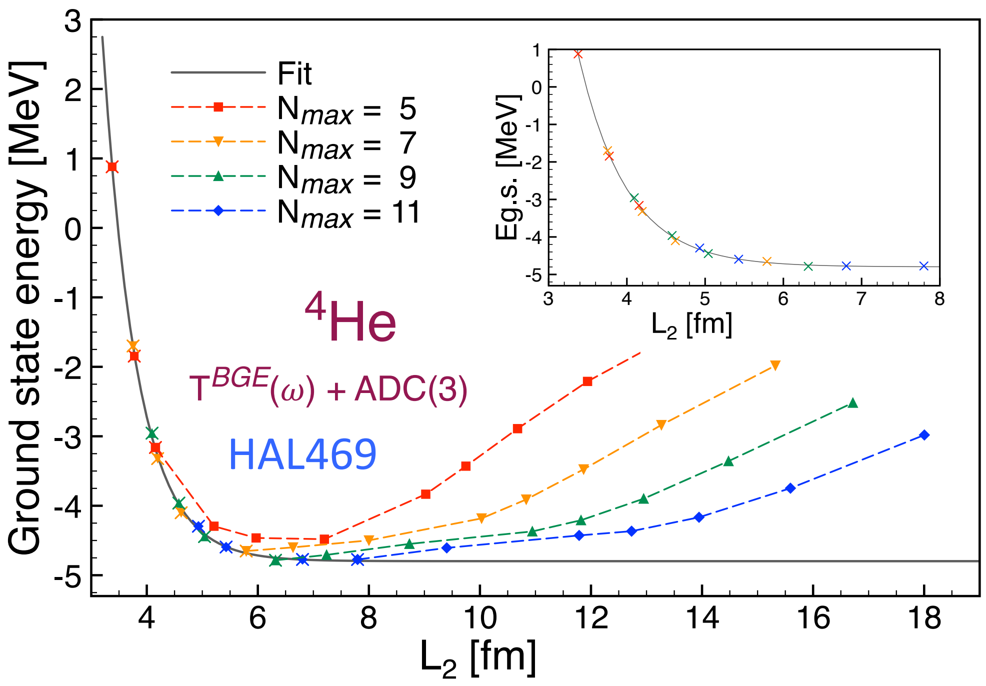
Infrared convergence



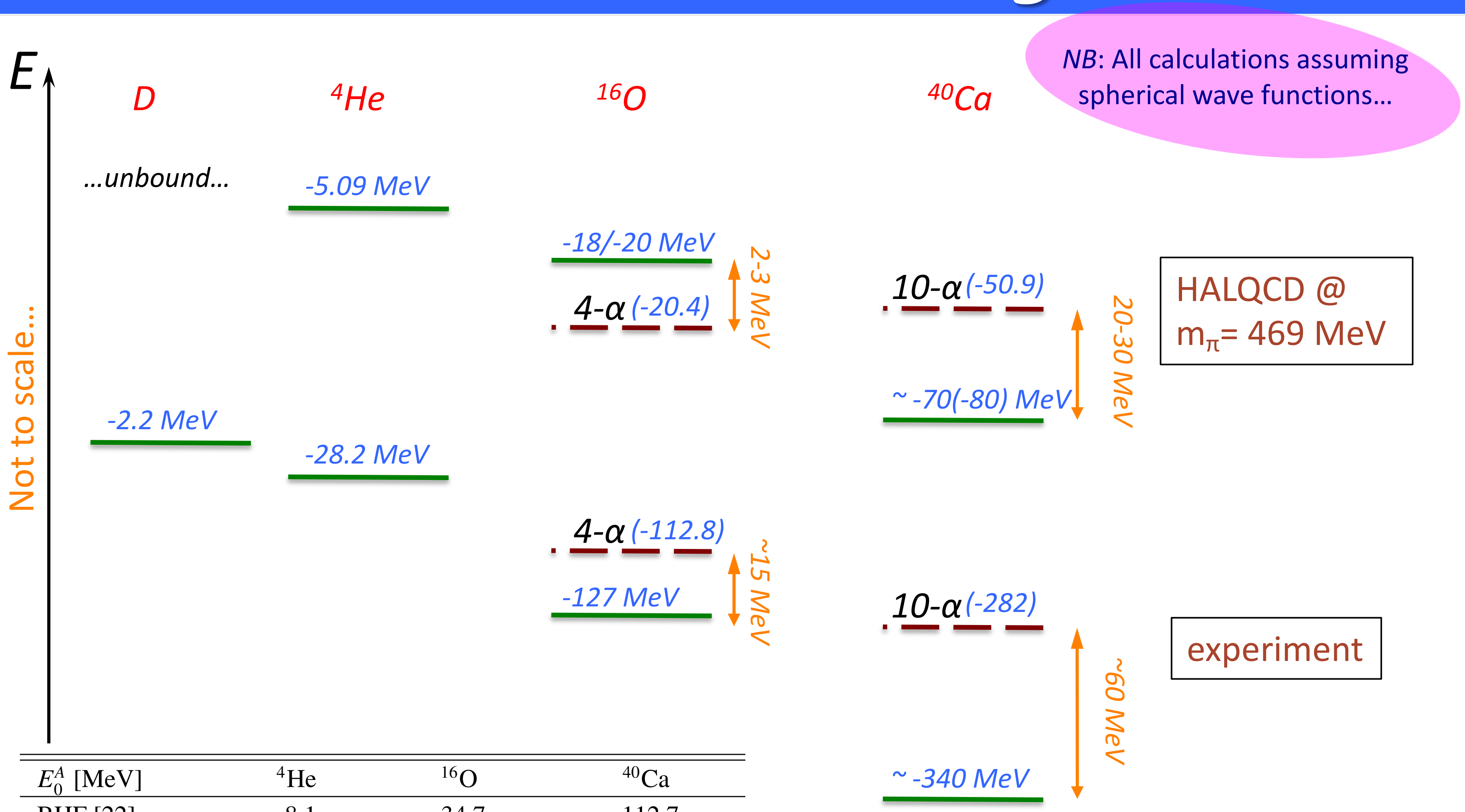
Short-range repulsion in the HALQCD-type potentials can be tamed correctly even for large nuclei.

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





Results for binding



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)

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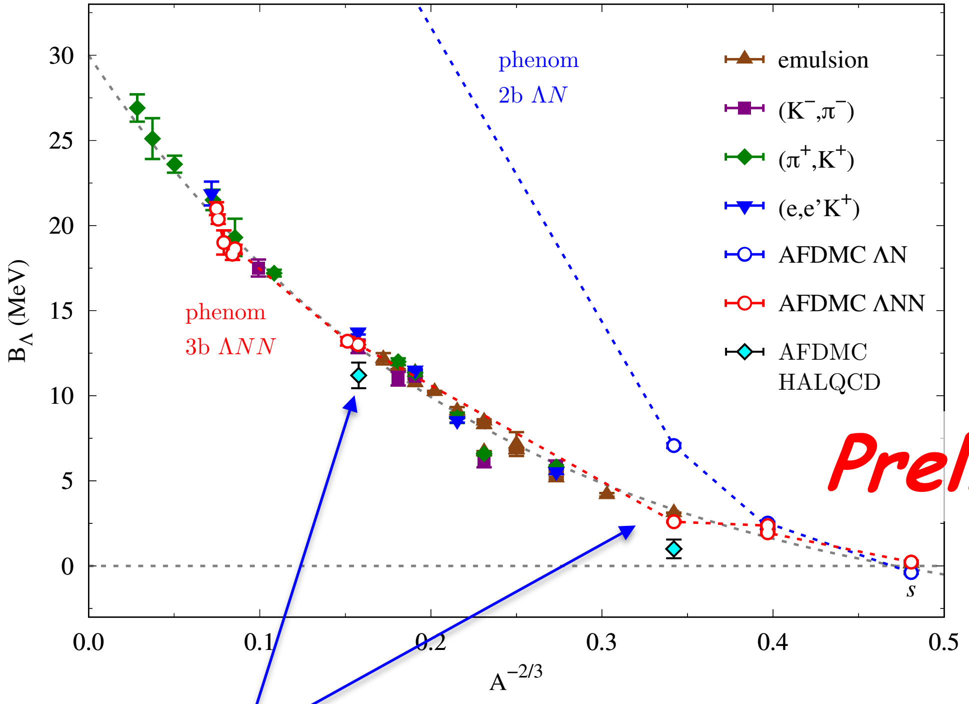
C. McIlroy, CB, et al., Phys. Rev. C**97**, 021303(R) (2018)

Future application for Ys in nuclei now possible

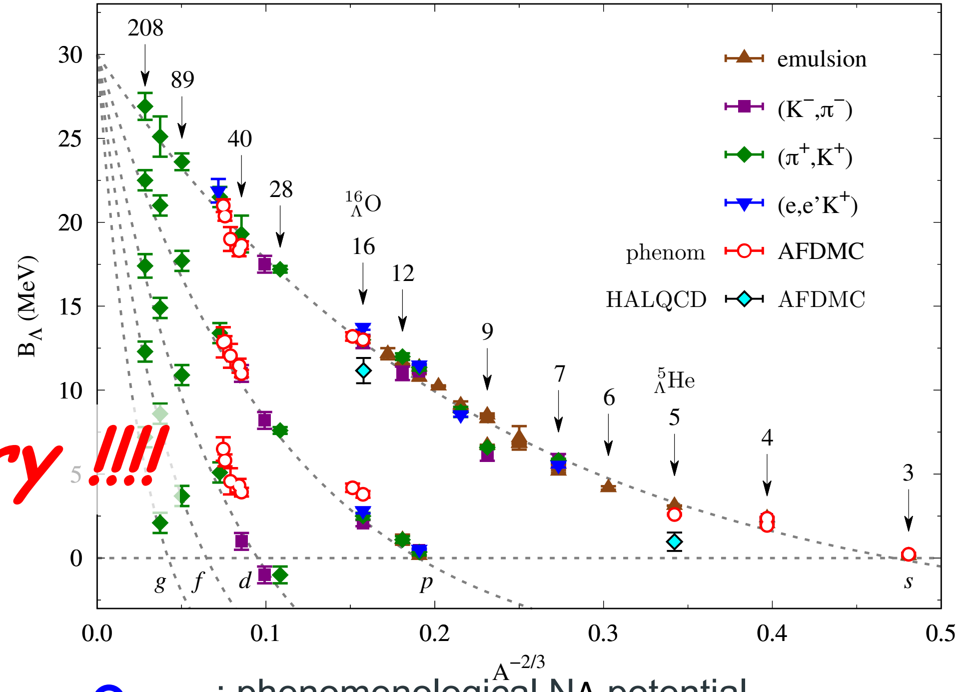
- AV4’ + UIX requires very large with phenomenological hypernuclear forces requires large ΛNN 3-baryon force
- Physical mass now under reach ($m_\pi \approx$ 145 MeV) for hyperons
- HALQCD ΛN 3-baryon force is already very close to experiment

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



HALQCD simulations
D. Lonardoni, A. Lovato, CB
(*work in progress*)

Preliminary !!!!



: phenomenological NΛ potential

: phenomenological NΛ + NNΛ potential

: HALQCD NΛ potential

This meeting will focus on the theme of **what next in ab initio theory?** We anticipate discussions on:

- Technical challenges: the precision frontier, the limits of mass number and nuclear properties;
- Computational and statistical techniques to guide the quantification of theoretical uncertainties, and
- Physics opportunities: neutrino oscillations, physics beyond the standard model, hypernuclear physics.

https://sites.google.com/view/ab-initio-surrey-workshop-2019/

Summary

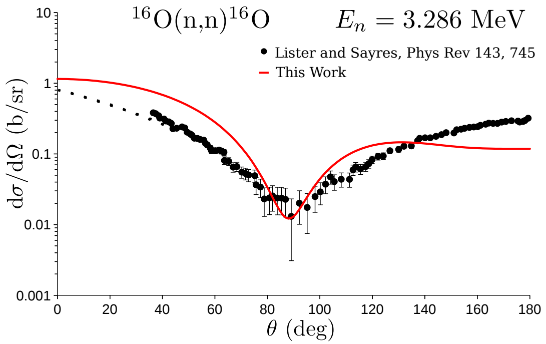
Thank you for your attention!!!

Future challenges in SCGF (and ab-initio theories in general) in mid-mass nuclei:

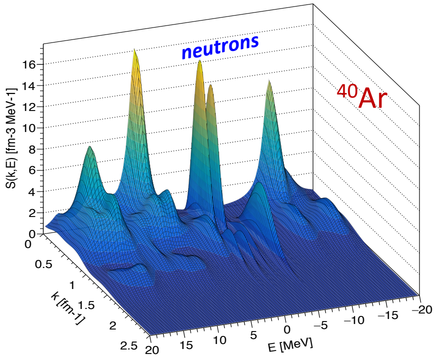
→ *Description of nuclear g.s. in the pf shell is improved-especially in the trends w.r.t. iso-sopin asymmetry.*

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

→ *The implementation will call top-end supercomputing facilities.*

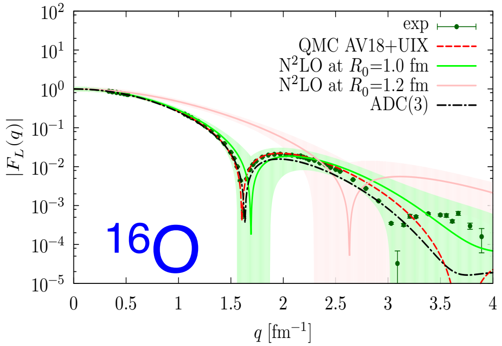


Applications to electron and neutrino scattering:



→ *Spectral functions are extracted naturally from the SCGF formalism.*

→ *Inclusion of electroweak currents (1b and 2b) and SCGF spectral functions to be applied in event reconstruction for neutrino oscillation experiments.*



HALQCD Nuclear forces:

→ *At m_π=469MeV, closed shell 4He and 40Ca are bound. But oxygen is unstable toward 4-α break up.*

→ *Preliminary forces for Lambda-nucleon at near the physical pion mass (m_π = 145 MeV/c^2) very promising!*

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Collaborators

Thank you for your attention!!!

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A. Carbone

cea
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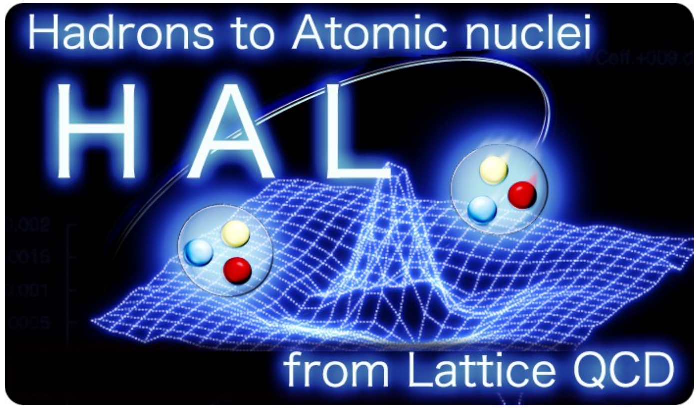
V. Somà, T. Duguet, ***F. Raimondi***

TRIUMF

P. Navratil



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