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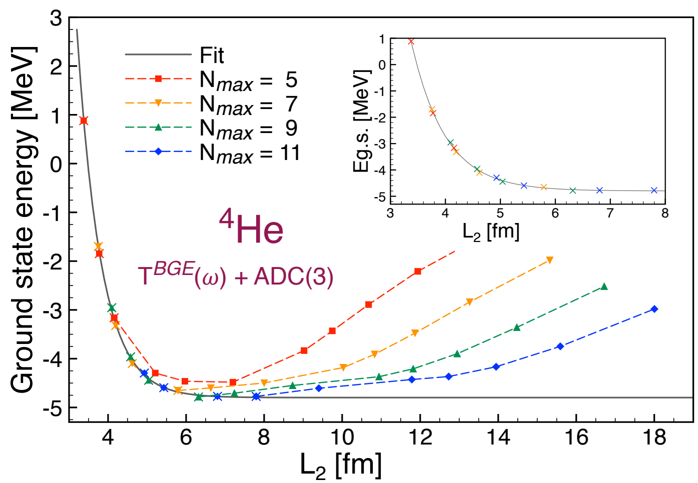
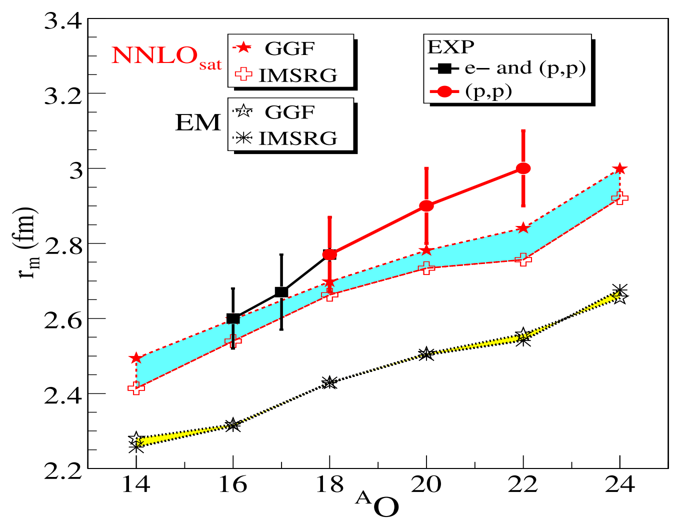
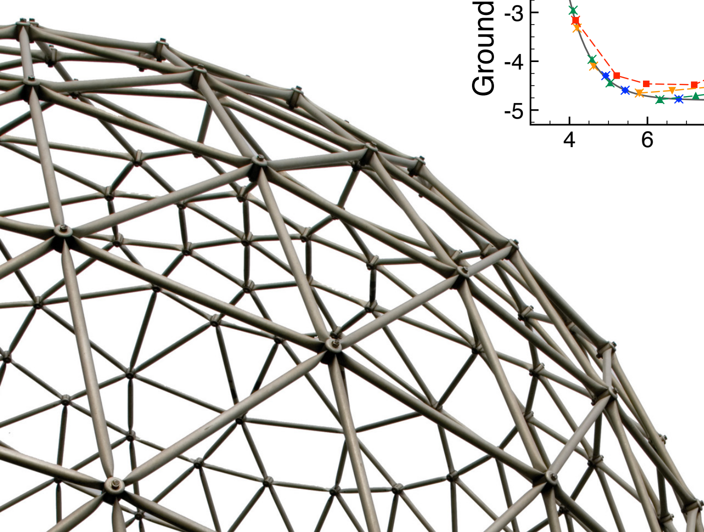
SCGF Computations of Nuclei

Carlo Barbieri — University of Surrey

16 May2017







Current Status of low-energy nuclear physics

Composite system of interacting fermions

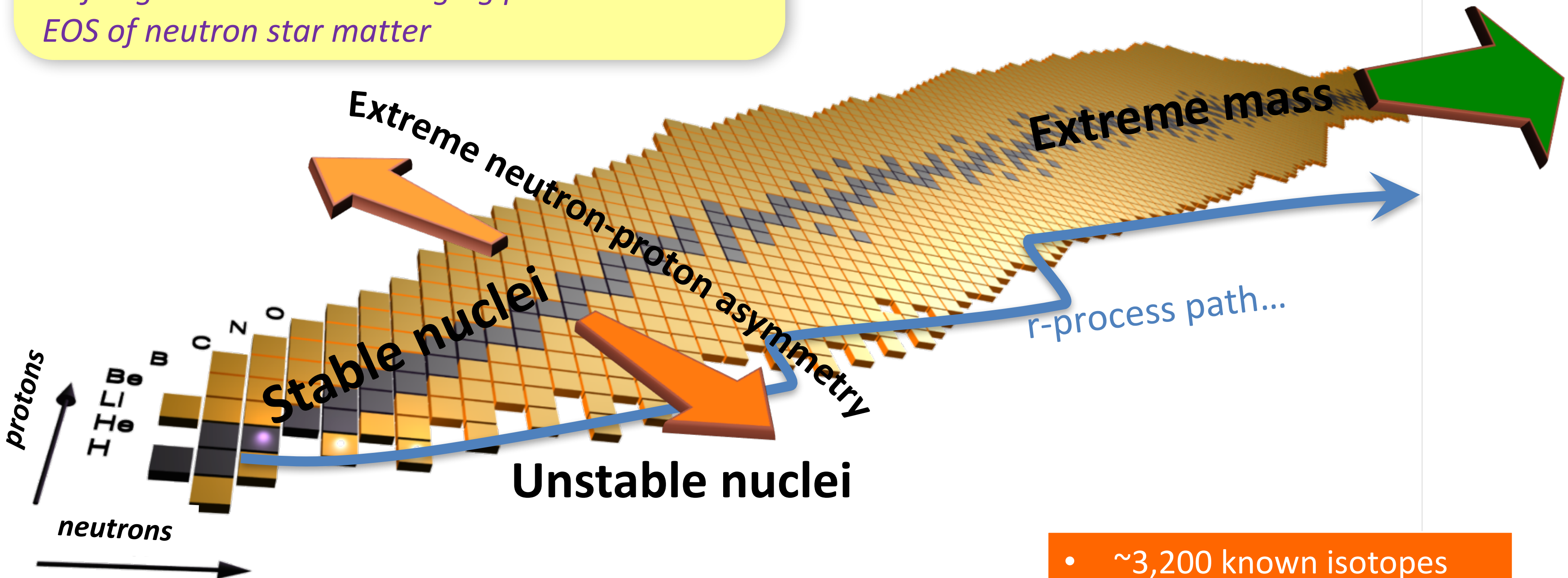
Binding and limits of stability

Coexistence of individual and collective behaviors

Self-organization and emerging phenomena

EOS of neutron star matter

Experimental programs RIKEN, FAIR, FRIB

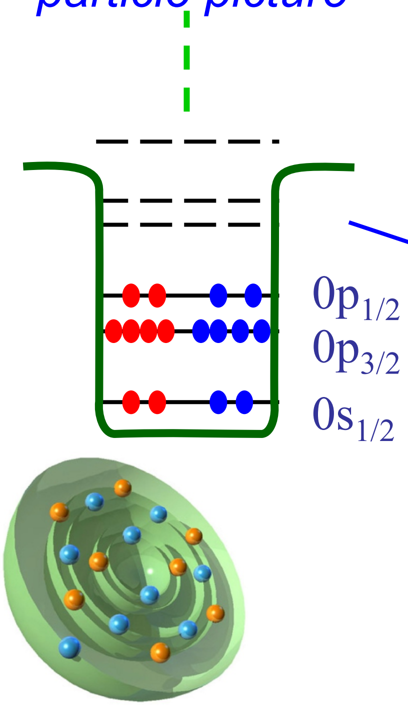


- ~3,200 known isotopes
- ~7,000 predicted to exist
- Correlation characterised in full for ~283 stable

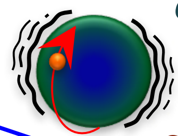
Nature **473**, 25 (2011); **486**, 509 (2012)

Concept of correlations

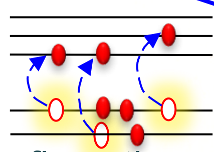
independent particle picture



Particle-vibration coupling (PV)



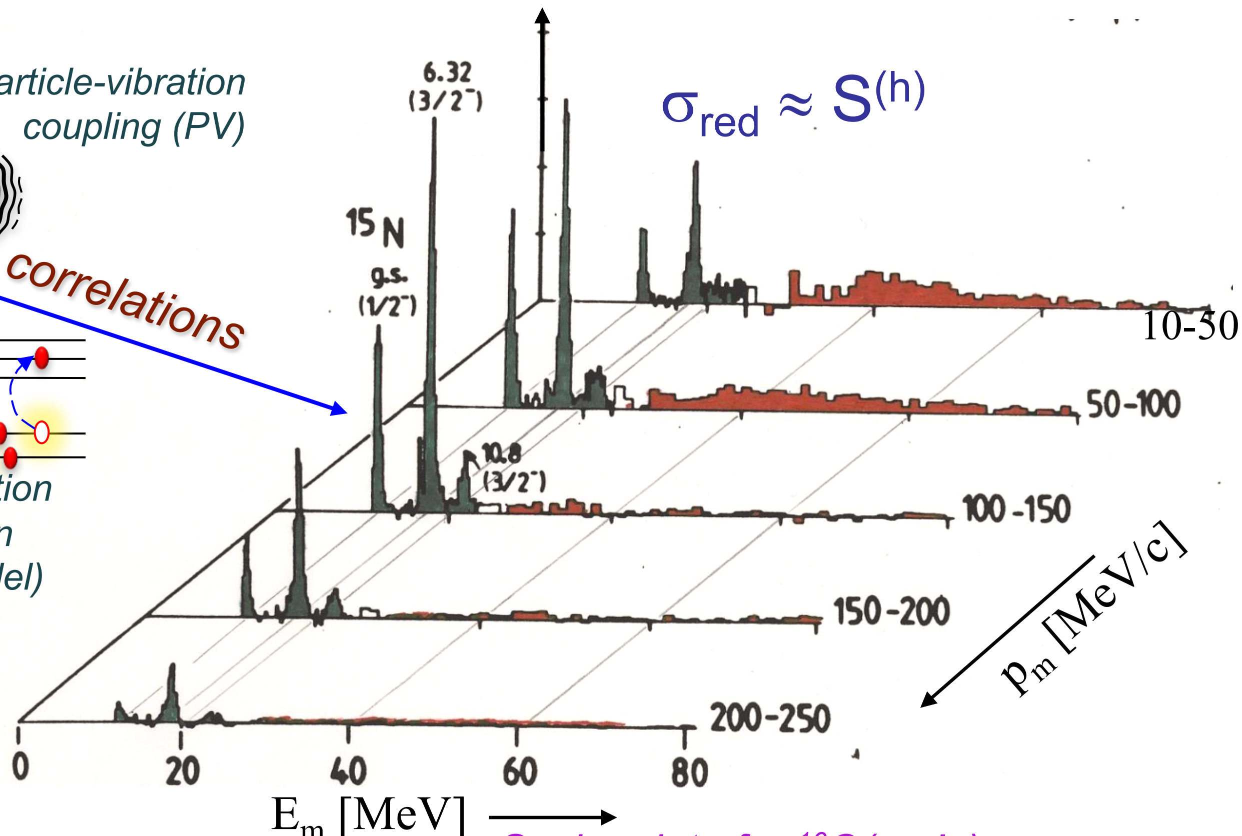
correlations



Configuration interaction (shell model)

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

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



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

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

Understood for a few stable closed shells:

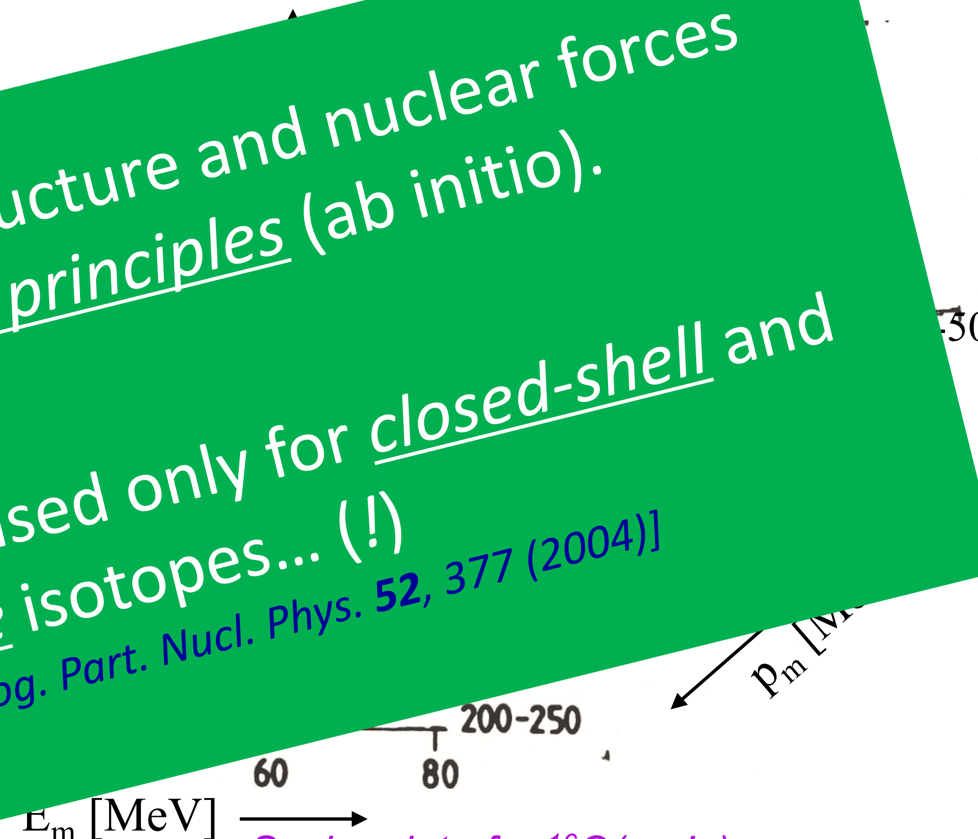
*[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys **52**, 377 (2004)]*

Concept of correlations

independent particle picture

Particle-vibration coupl

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



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)]*

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

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

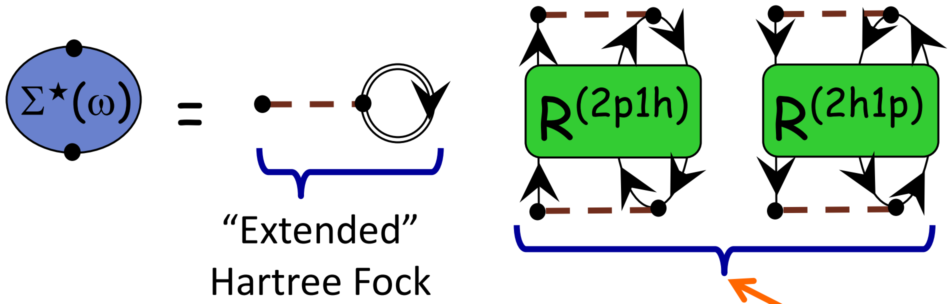
Unders... for a few stable closed shells:

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

The FRPA Method in Two Words

Particle vibration coupling is the main cause driving the distribution of particle strength—on both sides of the Fermi surface…

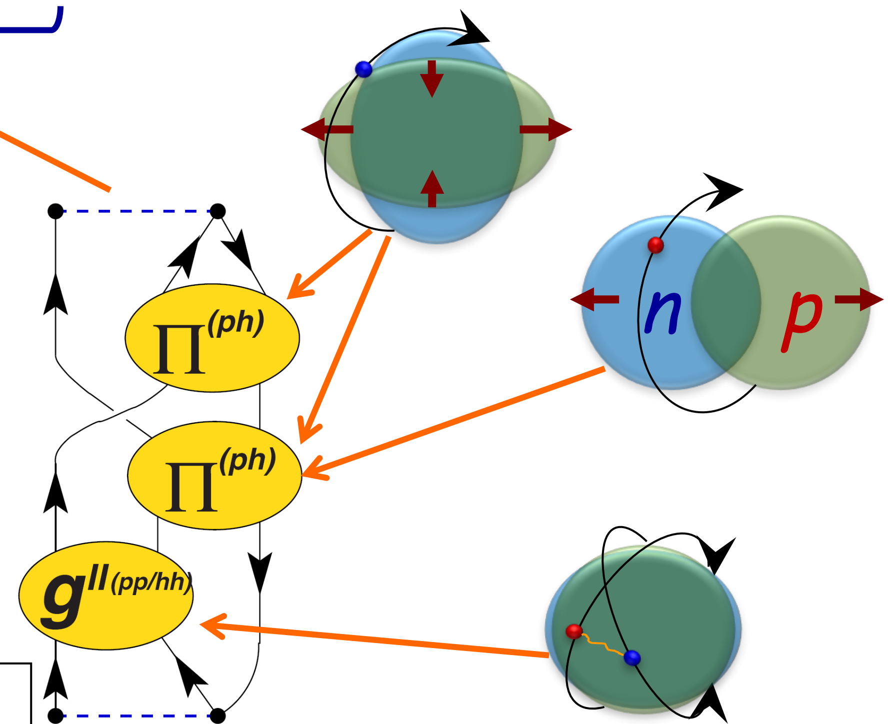
CB et al.,
Phys. Rev. C**63**, 034313 (2001)
Phys. Rev. A**76**, 052503 (2007)
Phys. Rev. C**79**, 064313 (2009)

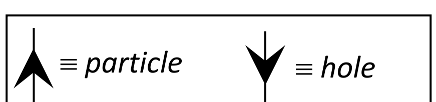


- A complete expansion requires <u>*all types*</u> of particle-vibration coupling

…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





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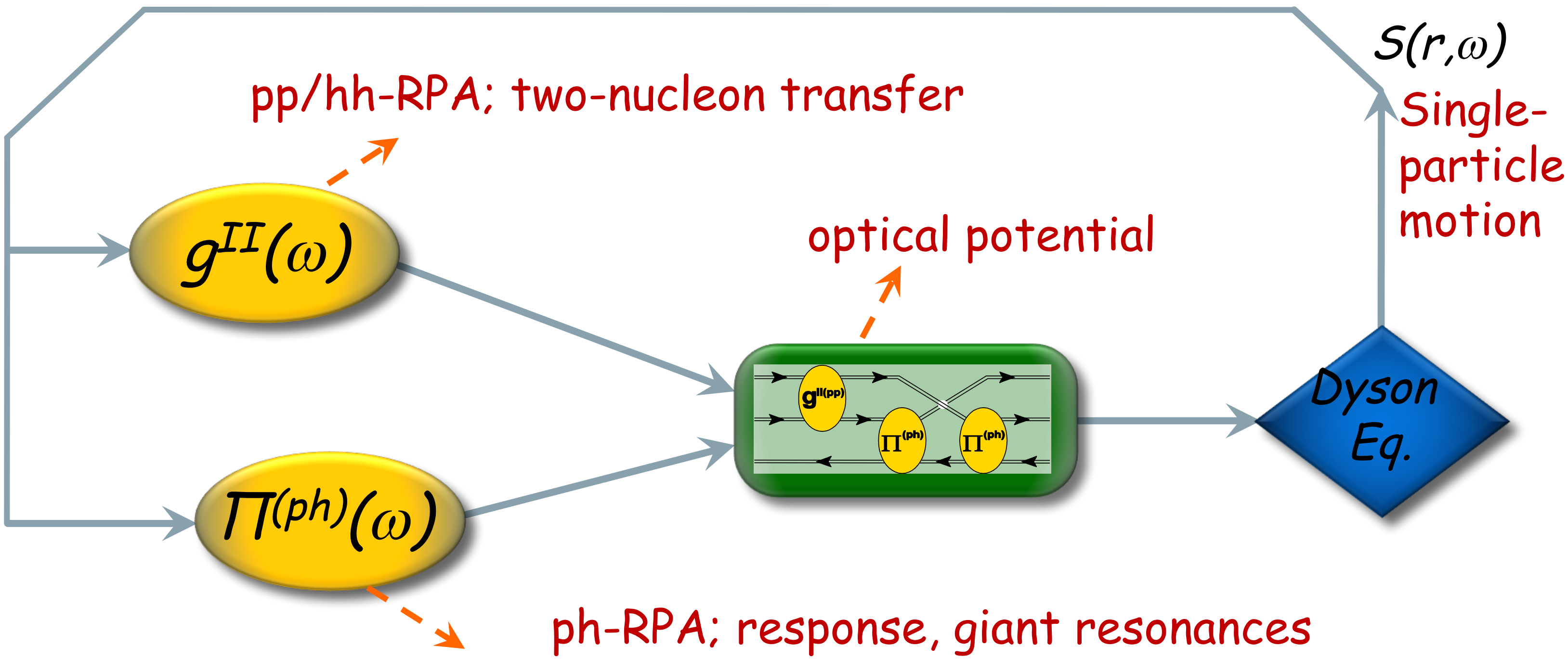
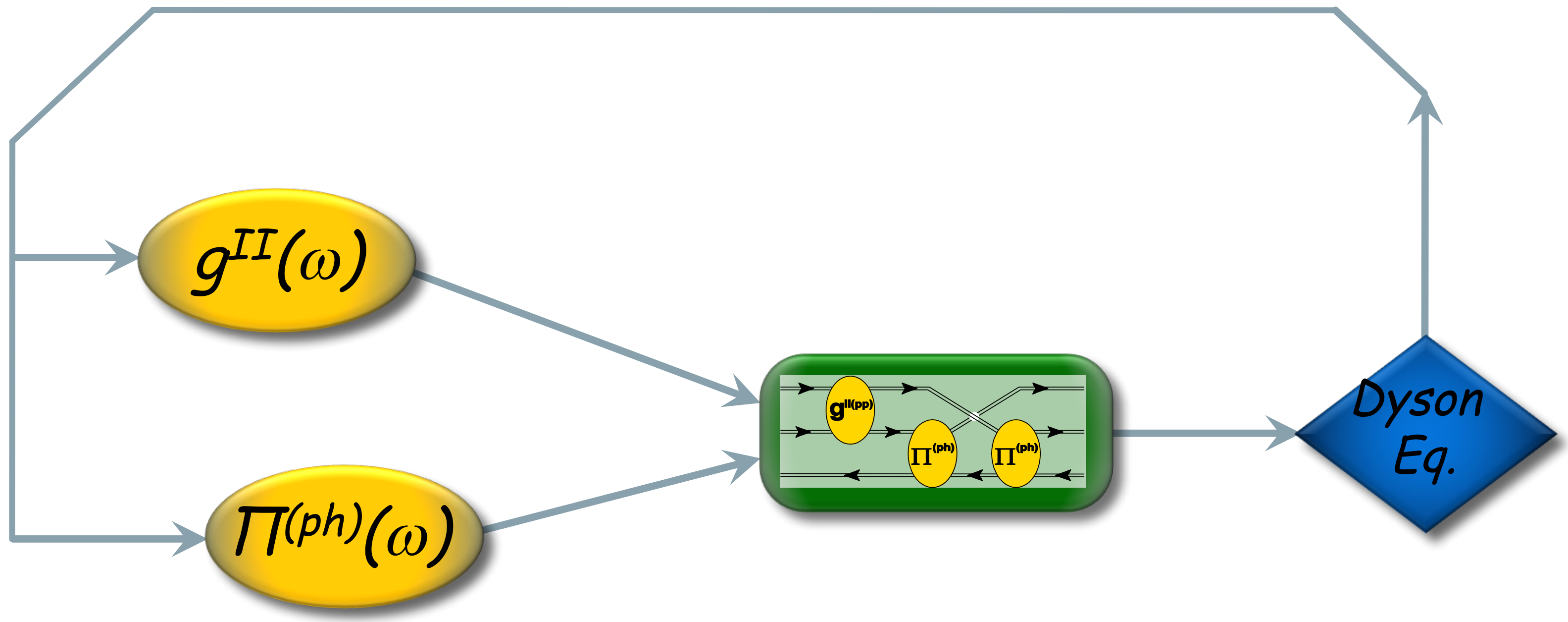
Self-Consistent Green's Function Approach

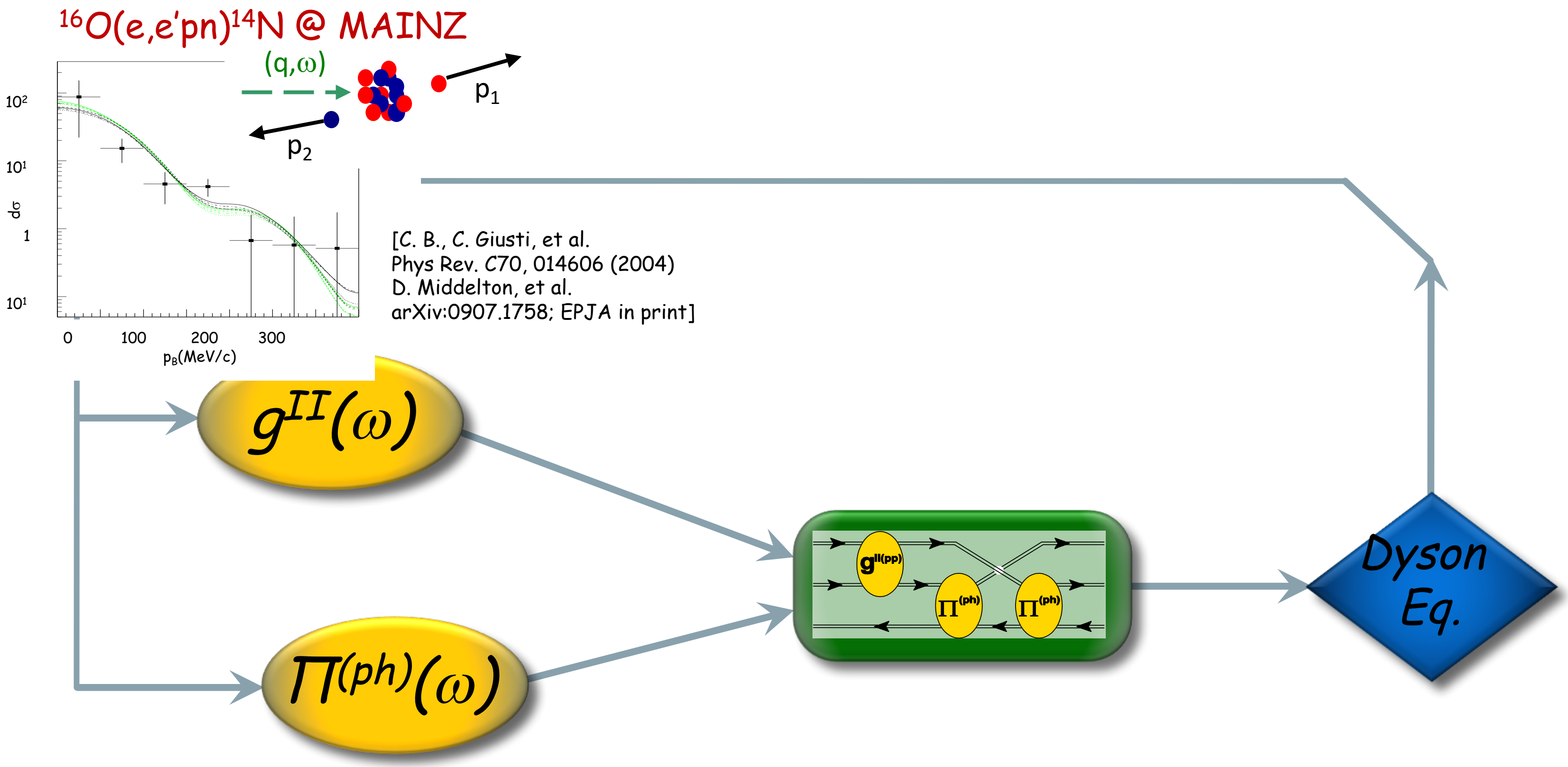


- Global picture of nuclear dynamics
- Reciprocal correlations among effective modes
- Guaranties *macroscopic conservation laws*

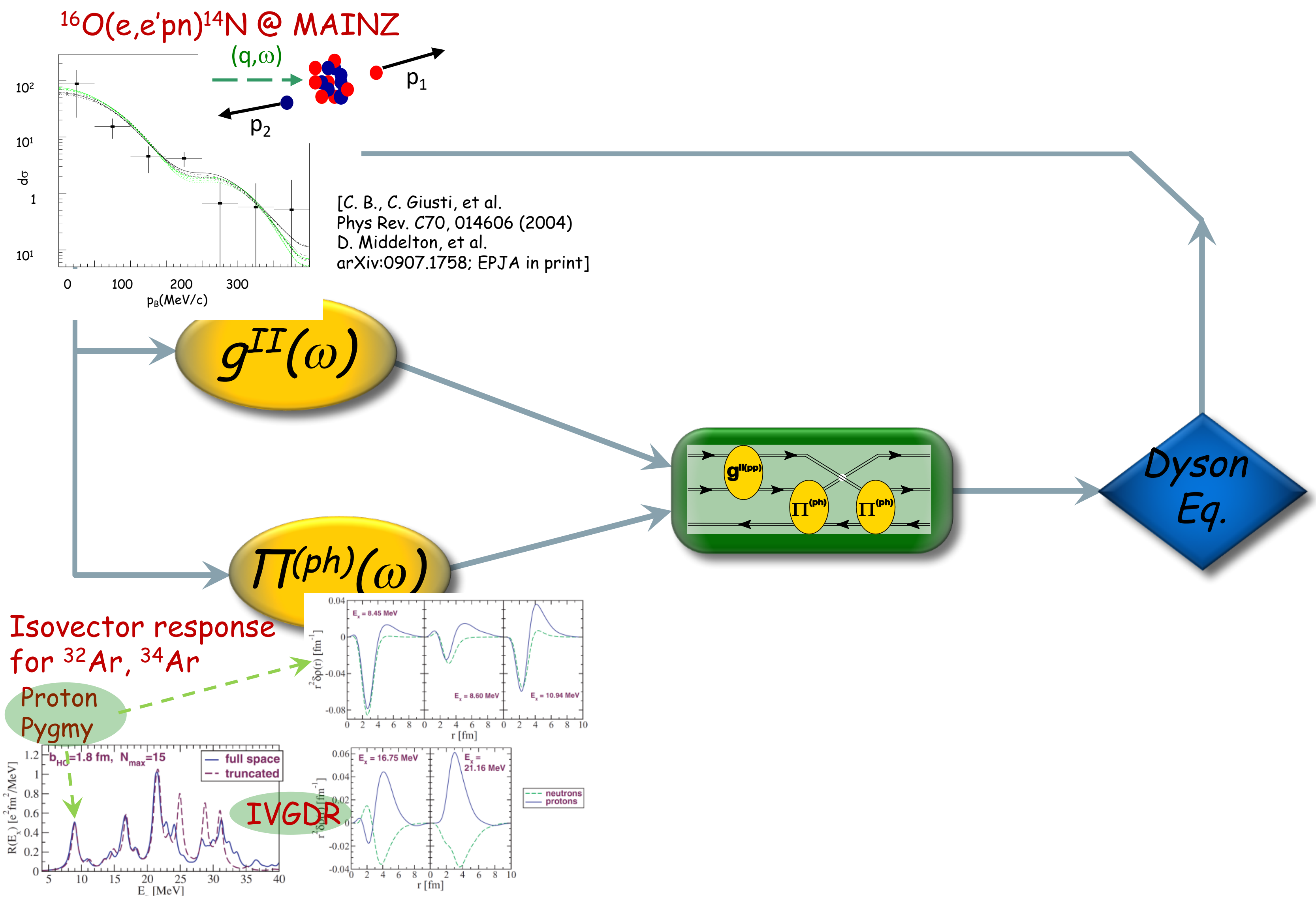
Self-Consistent Green's Function Approach



Self-Consistent Green's Function Approach



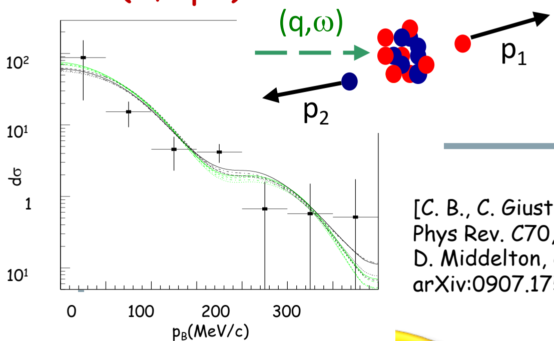
Self-Consistent Green's Function Approach



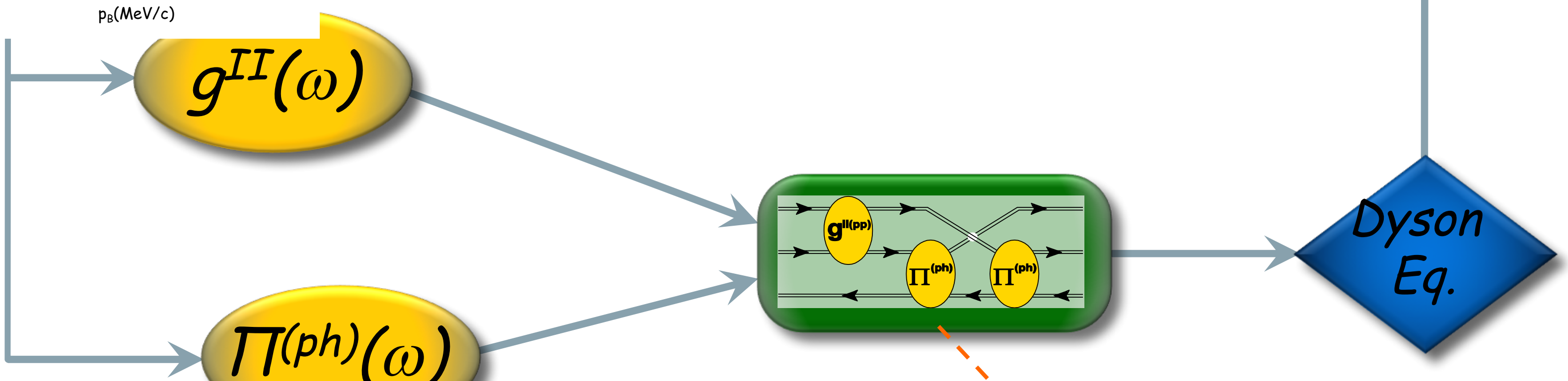
[C. B., K. Langanke, et al., Phys Rev. C77, 024304 (2008)]

Self-Consistent Green's Function Approach

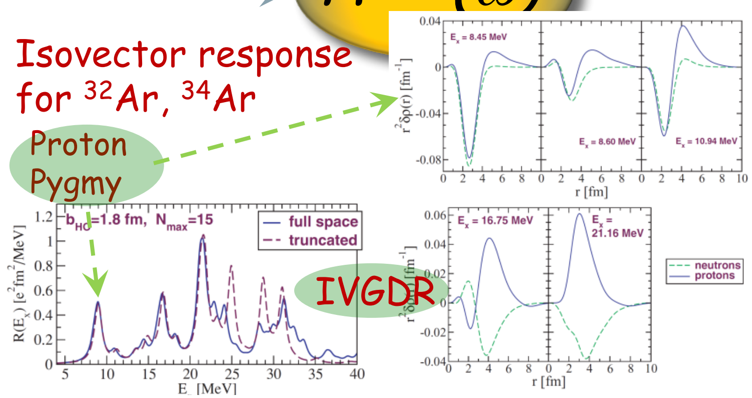
$^{16}O(e,e'pn)^{14}N$ @ MAINZ



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

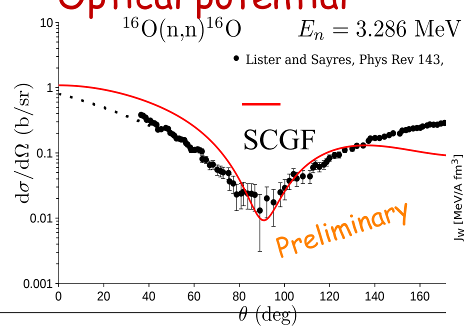


Isovector response for ^{32}Ar, ^{34}Ar

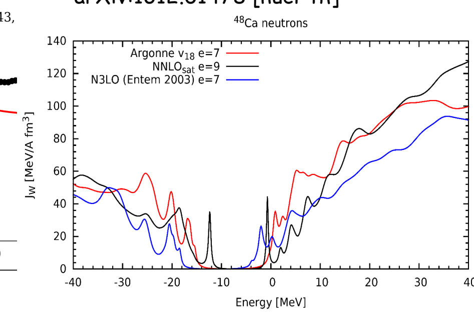


[C. B., K. Langanke, et al., Phys Rev. C77, 024304 (2008)]

Optical potential



See talk of A.Idini and arXiv:1612.01478 [nucl-th]



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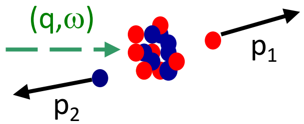
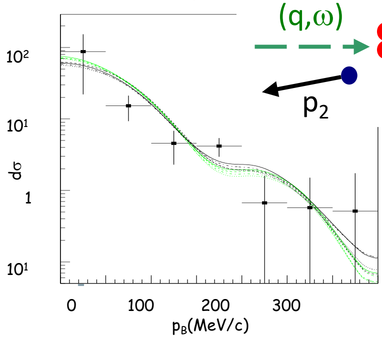
Self-Consistent Green's Function Approach

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



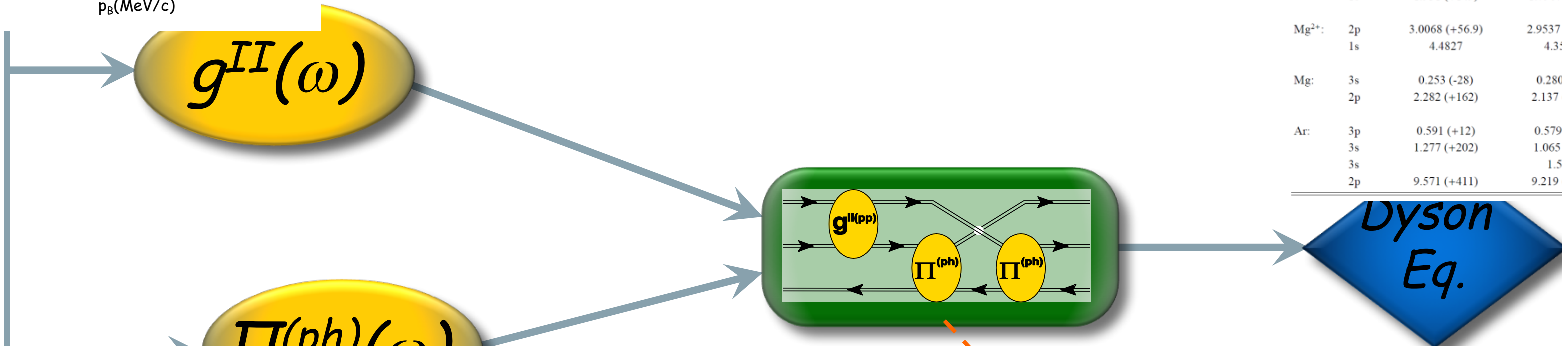


[C. B., C. Giusti, et al. Phys Rev. C70, 014606 (2004)
D. Middelton, et al. arXiv:0907.1758; EPJA in print]

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



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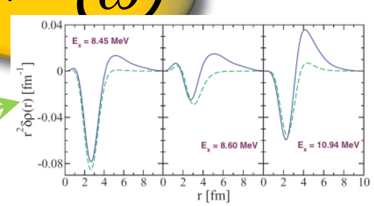

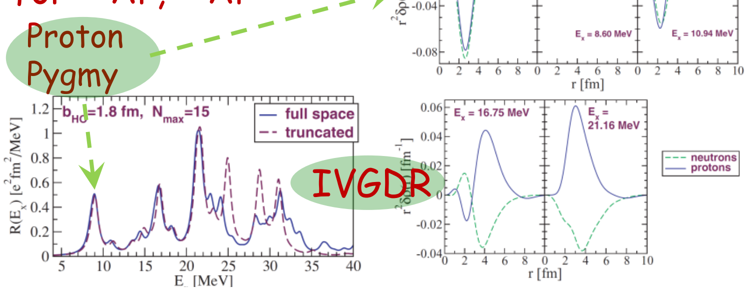

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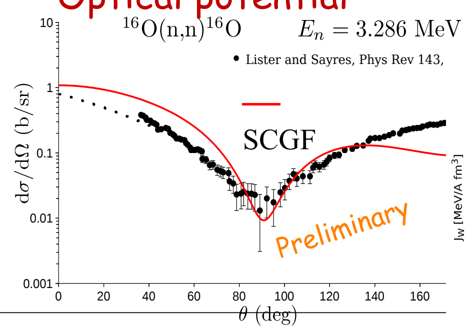

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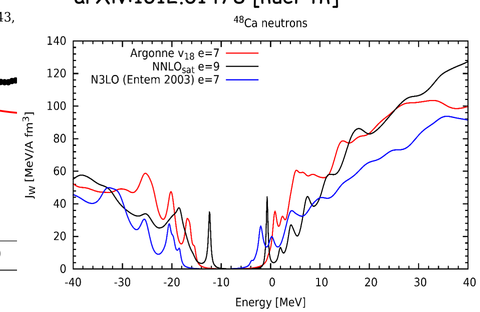

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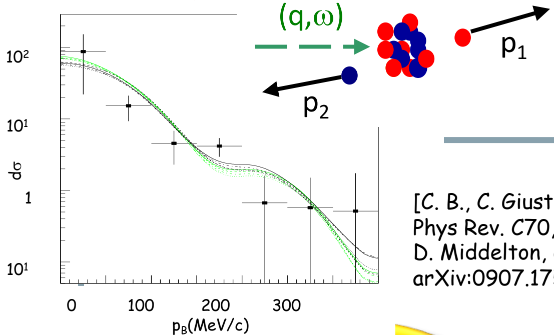

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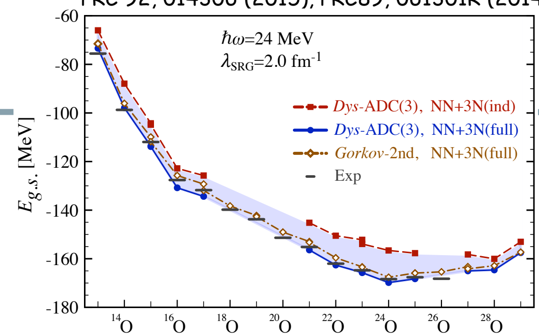
Binding energies

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



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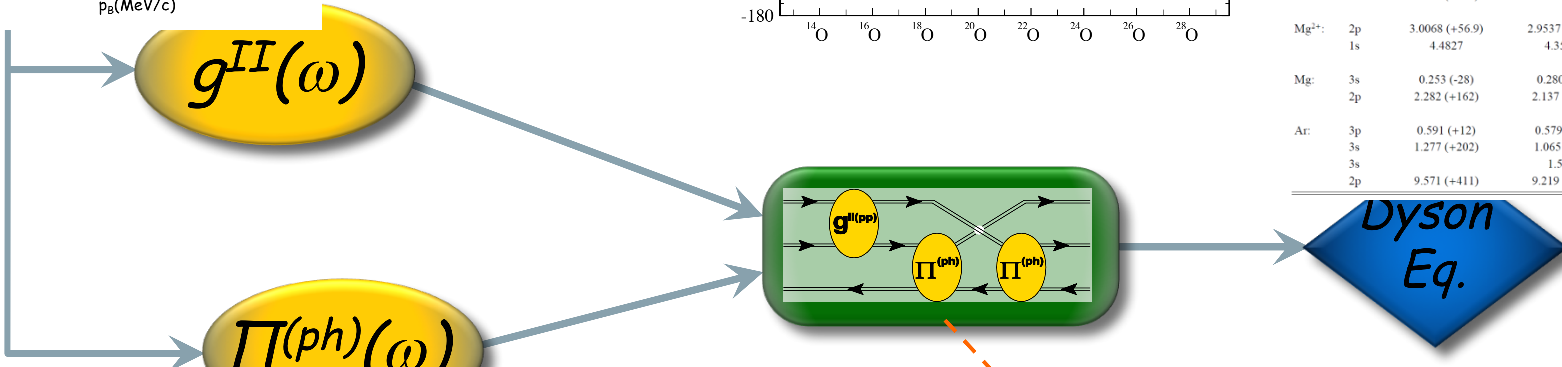

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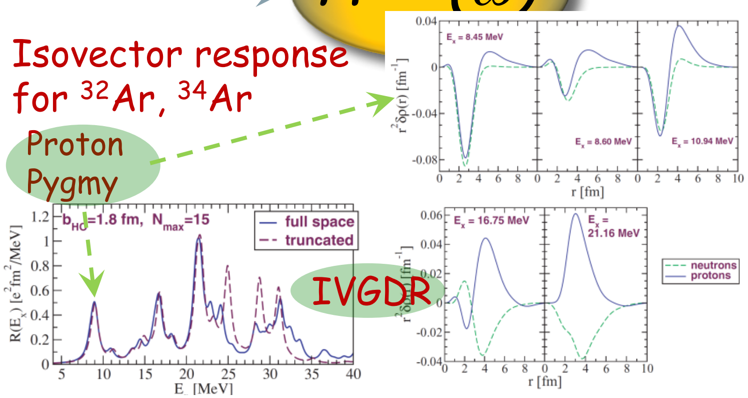

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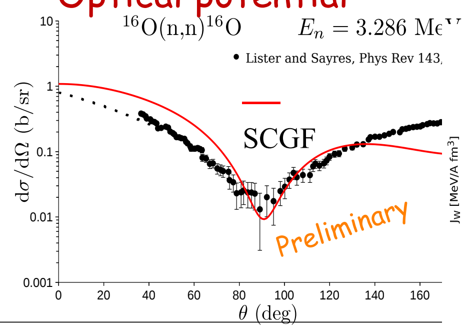
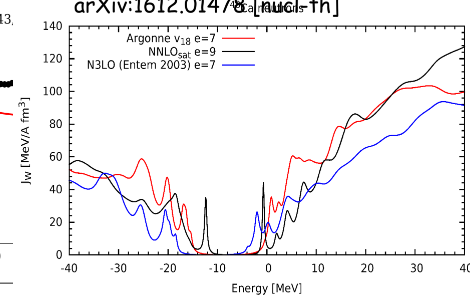
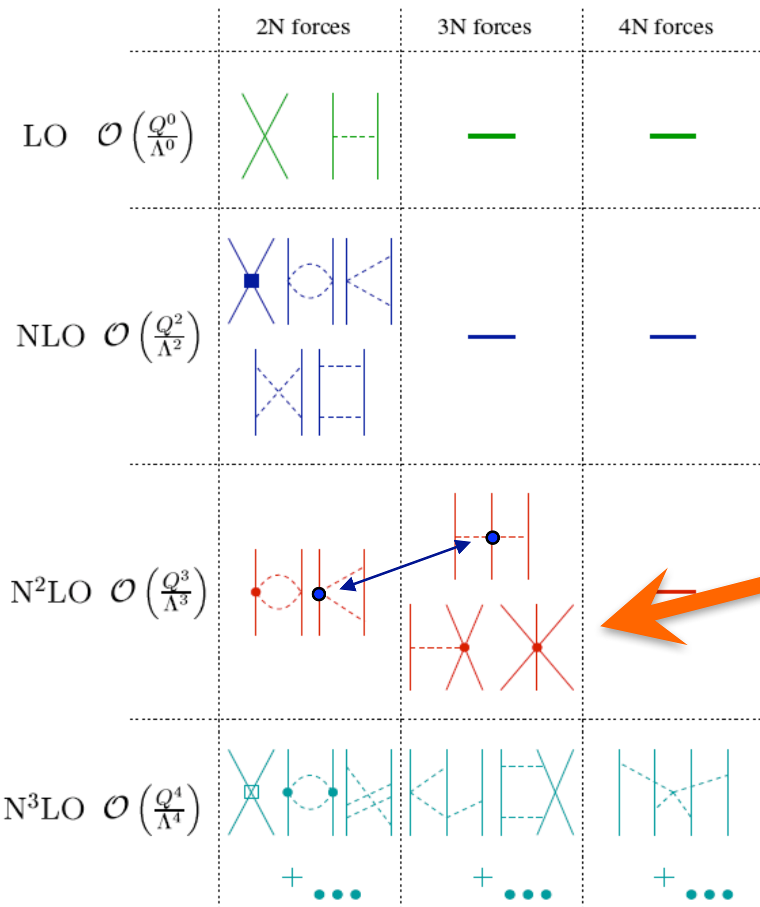


arXiv:1612.01478 [nucl-th]



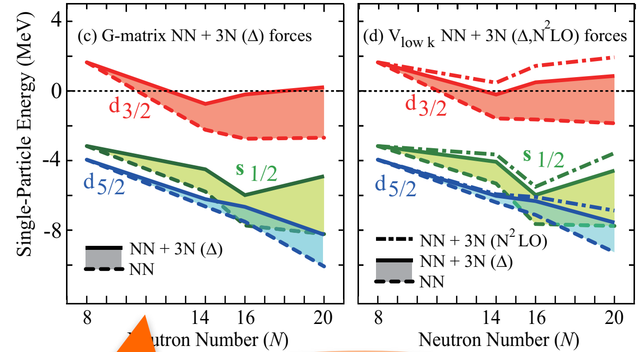
Modern realistic nuclear forces

Chiral EFT for nuclear forces:



(3NFs arise naturally at N2LO)

Single particle spectrum at E_{fermi}:

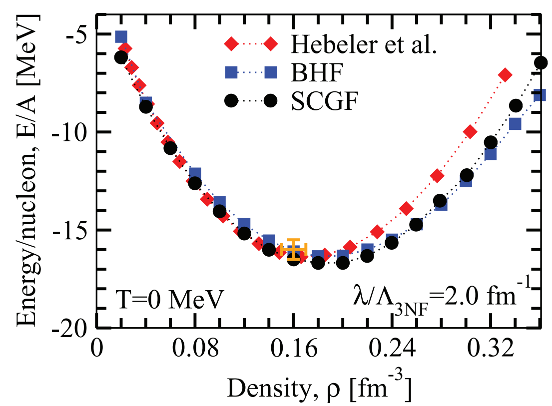


[T. Otsuka et al., Phys Rev. Lett **105**, 032501 (2010)]

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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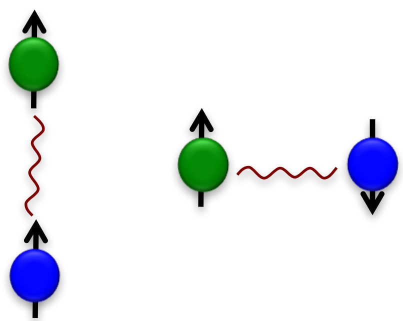
Nuclear forces in exotic nuclei

Nucleon interactions are very complex and difficult to handle…

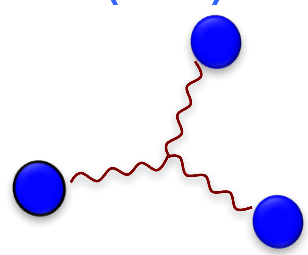
Symmetric matter:
N ≈ Z

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

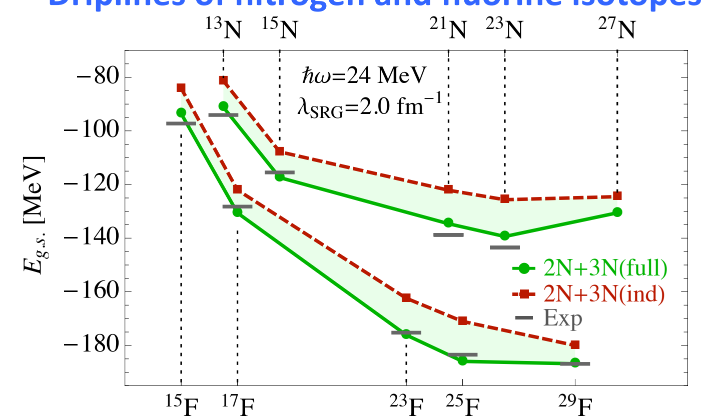
Tensor force (p-n)



Three-nucleon Force (3NF)



Driplines of nitrogen and fluorine isotopes



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

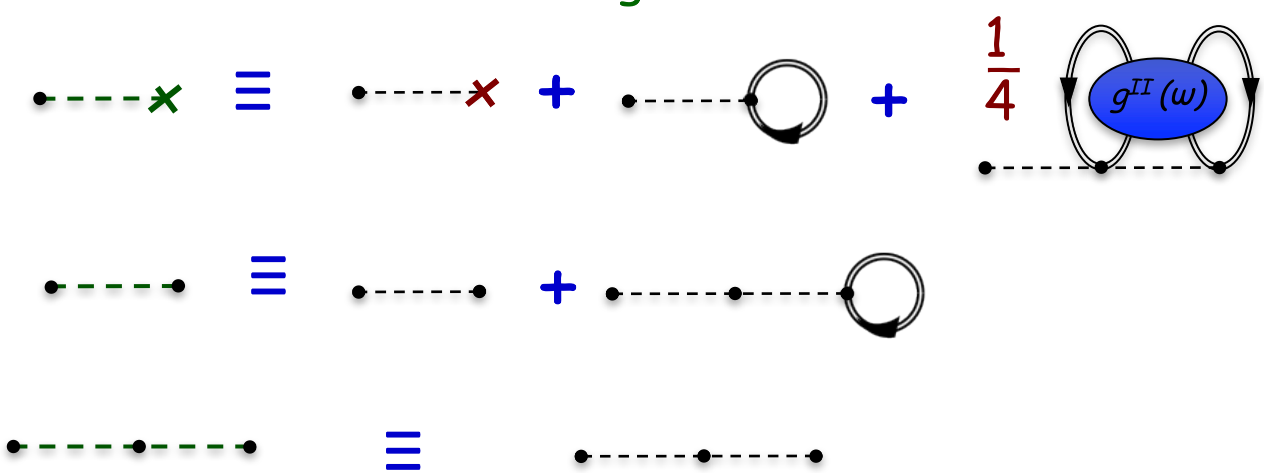
Change of regime from stable to dripline isotopes !

Inclusion of NNN forces

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

- NNN forces can enter diagrams in three different ways:

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

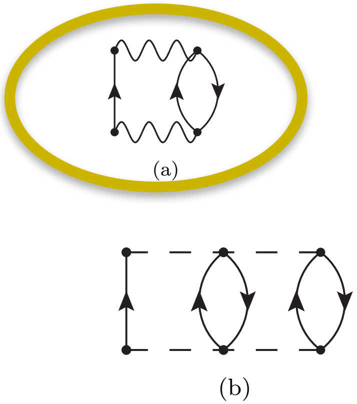


- Contractions are with <u>*fully correlated density matrices*</u>
(BEYOND a normal ordering…)

Inclusion of NNN forces

A. Carbone, CB, et al., Phys. Rev. C**88**, 054326 (2013)
and F. Raimondi, CB, arXiv:1709.04330 PRC (2017).

- *Second order* PT diagrams with 3BFs:



- *Third order* PT diagrams with 3BFs:

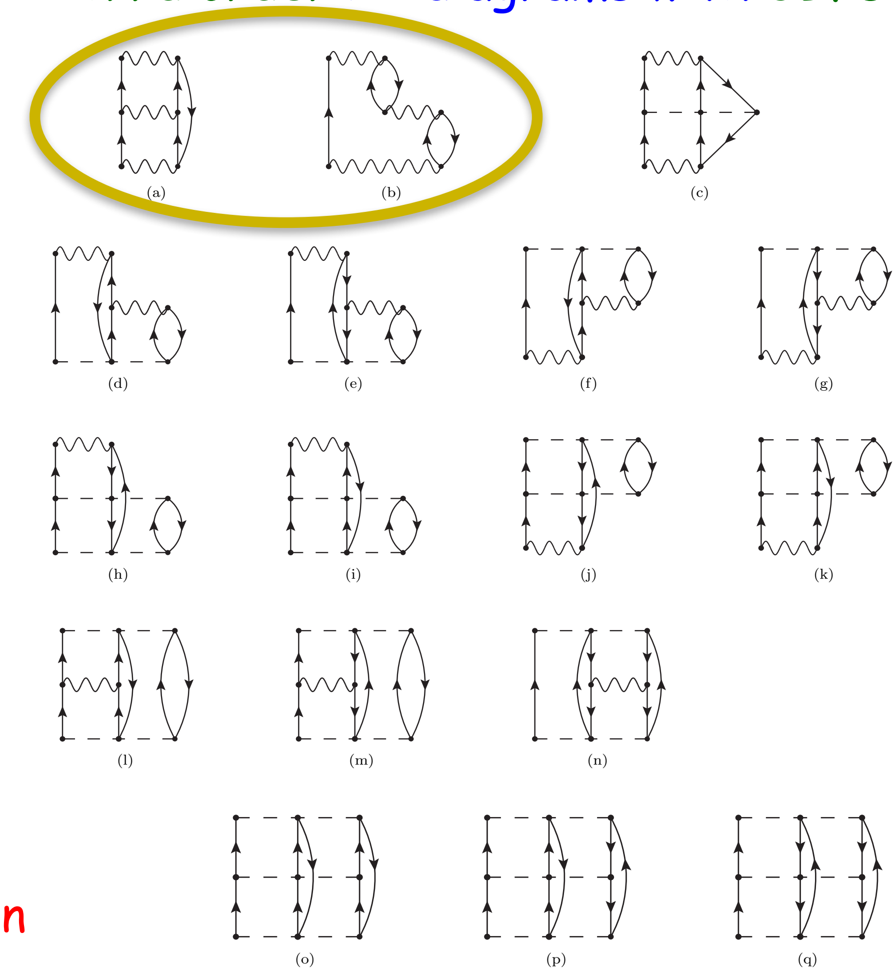


FIG. 5. 1PI, *skeleton* and *interaction irreducible* self-energy diagrams appearing at 3^{rd}-order in perturbative expansion (7), making use of the effective hamiltonian of Eq. (9).

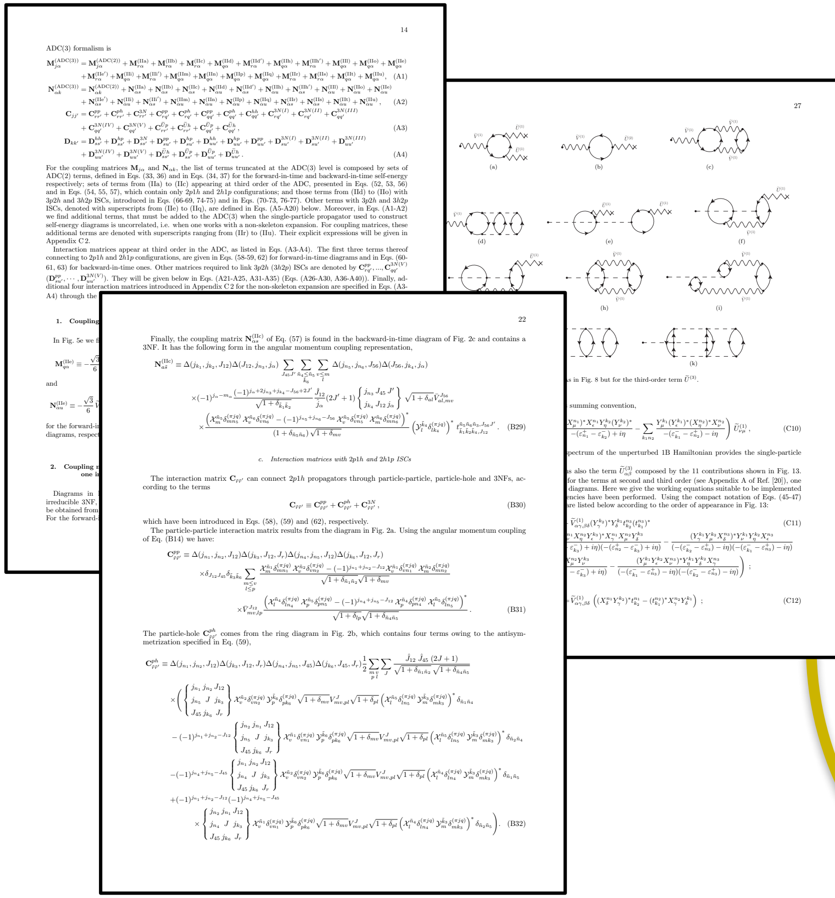
➔ Use of irreducible 2-body interactions

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

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

Inclusion of NNN forces

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



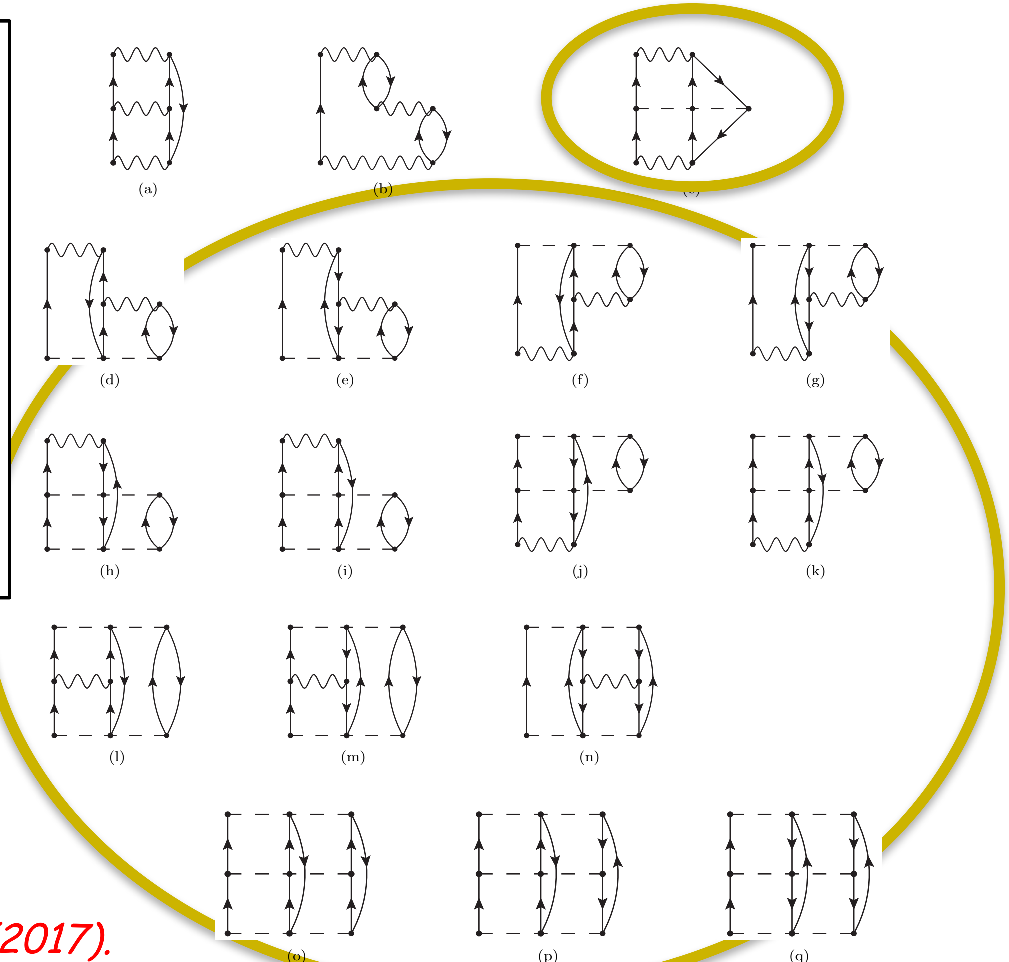


FIG. 5. 1PI, *skeleton* and *interaction irreducible* self-energy diagrams appearing at 3^{rd}-order in perturbative expansion (7), making use of the effective hamiltonian of Eq. (9).

Formalism already laid out:
F. Raimondi, CB, arXiv:1709.04330 PRC (2017).

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

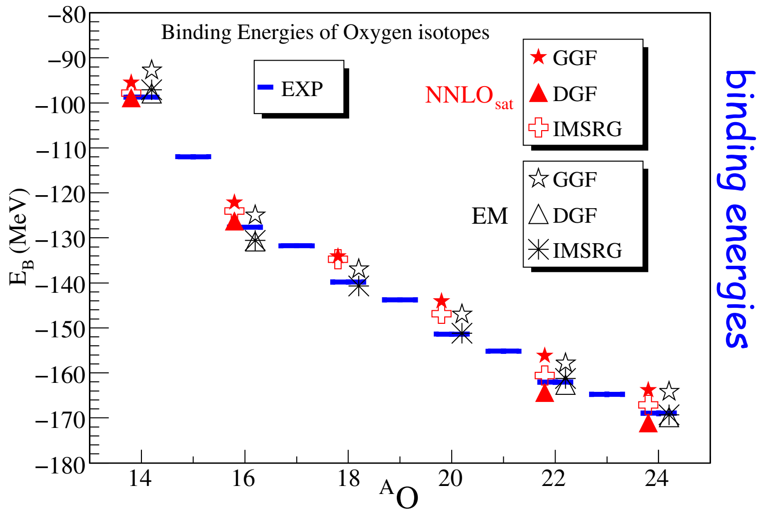
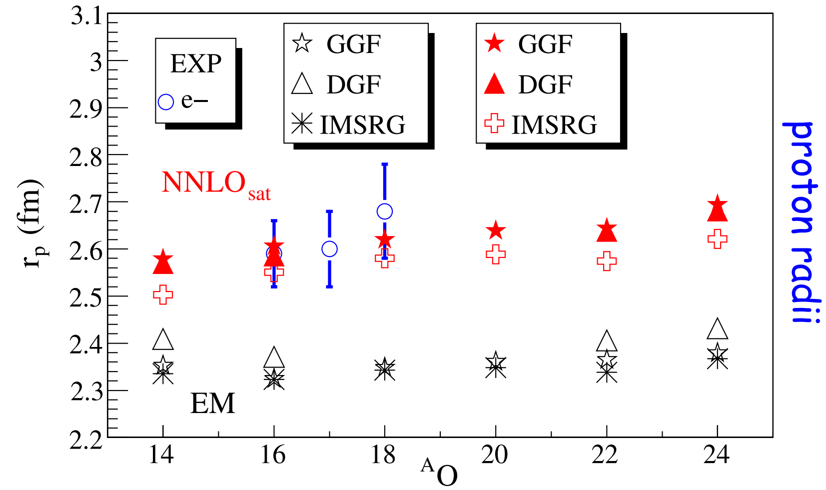
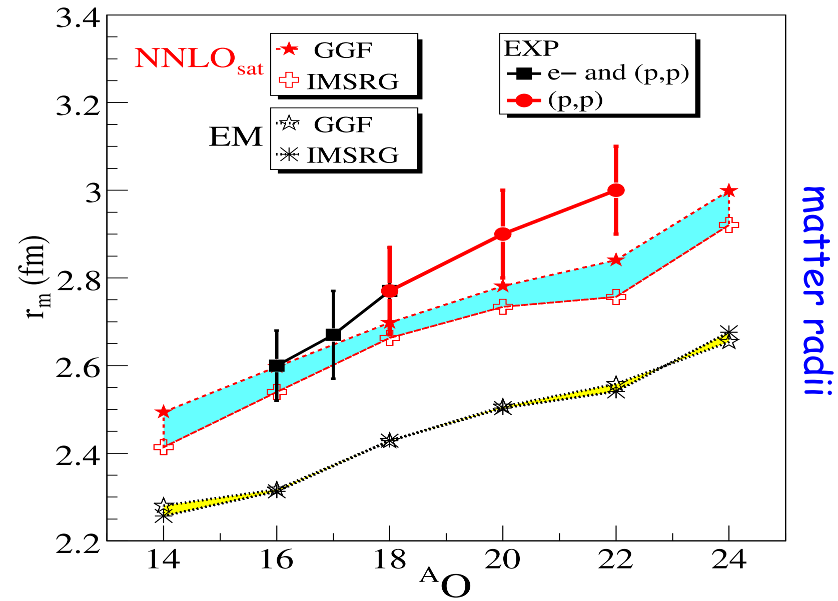


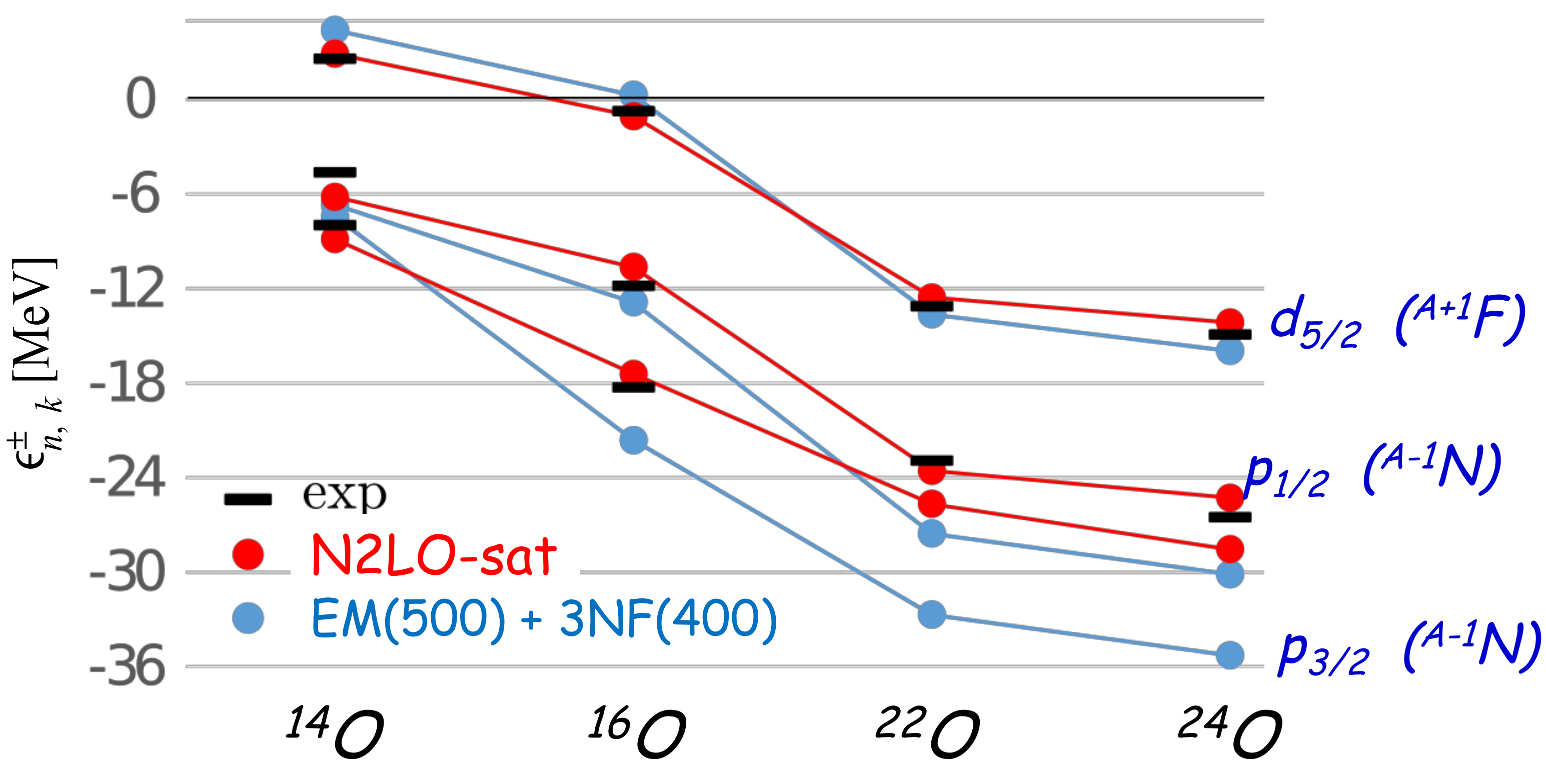
FIG. 1. Oxygen binding energies. Results from SCGF and IMSRG calculations performed with EM [20–22] and NNLO$_{sat}$ [26] interactions are displayed along with available experimental data.





Single particle spectra in Oxygen

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



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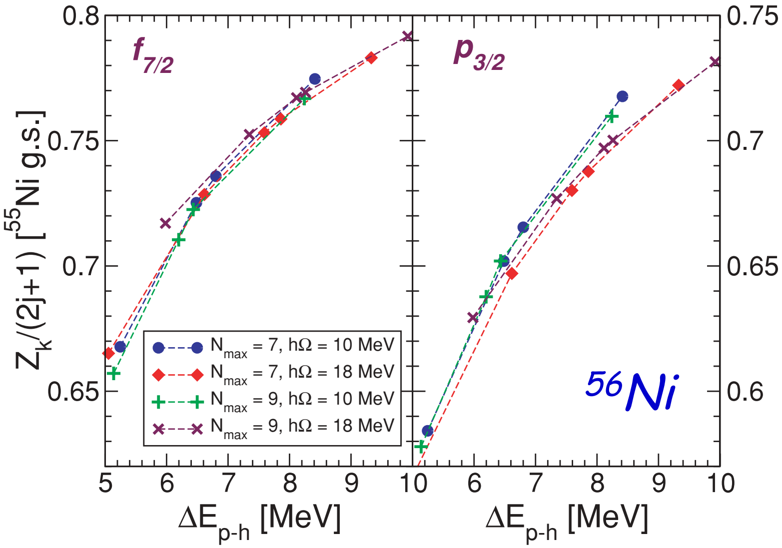
Z/N asymmetry dependence of SFs - Theory

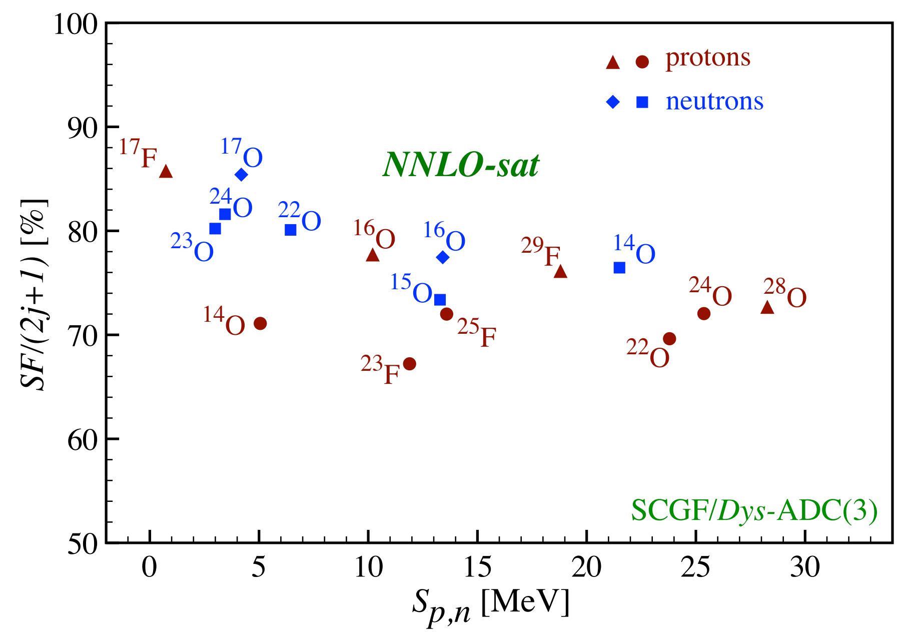
Ab-initio calculations explain (a very weak) the Z/N dependence but the effect is much lower than suggested by direct knockout

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

Spectroscopic factor are strongly correlated to p-h gaps:



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



A. Cipollone, CB, P Navrátil,Phys. Rev. C**92**, 014306 (2015)
and CB, unpublished (2016)

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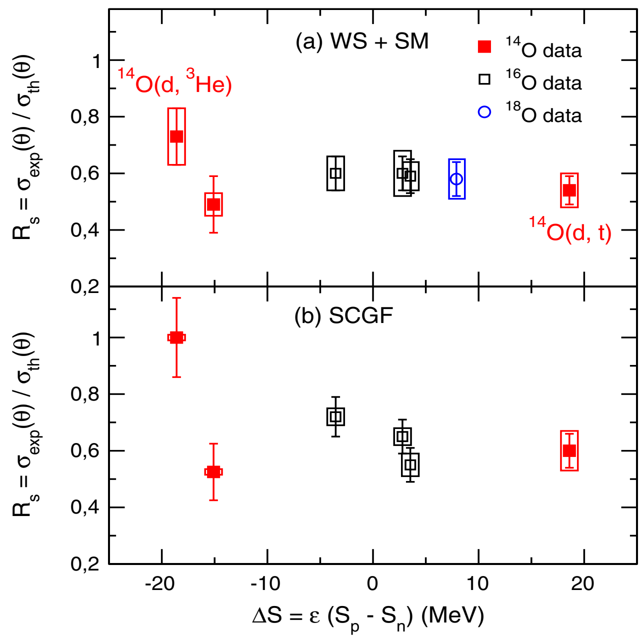
Z/N asymmetry dependence of SFs

Calculated spectroscopic factors are found to be:

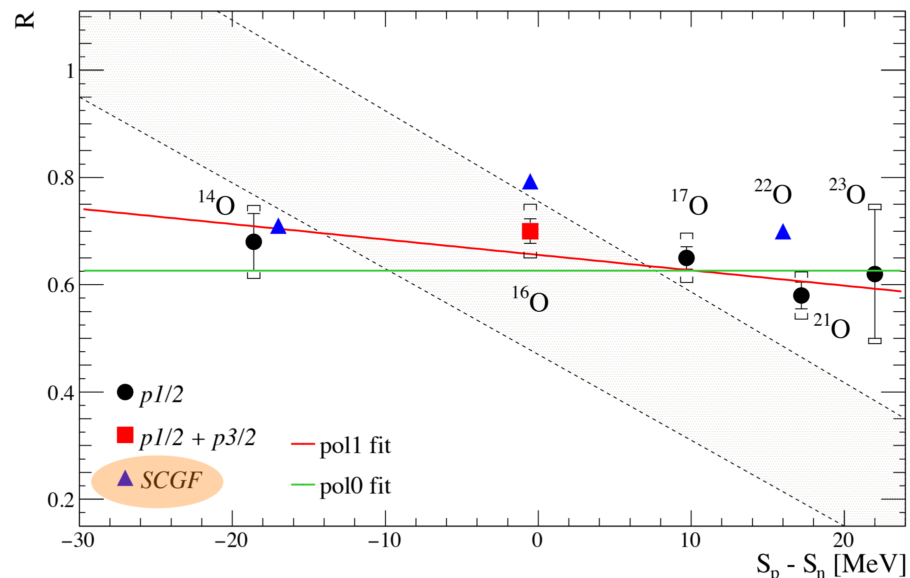
- correlated to p-h gaps
- independent of asymmetry
- consistent with experimental data

$^{14}O(d,t)^{13}O$ and $^{14}O(d,^{3}He)^{13}N$ transfer reactions @ SPIRAL



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

$^{A}O(p,2p)^{A-1}N$ at GSI (R^3B-LAND)



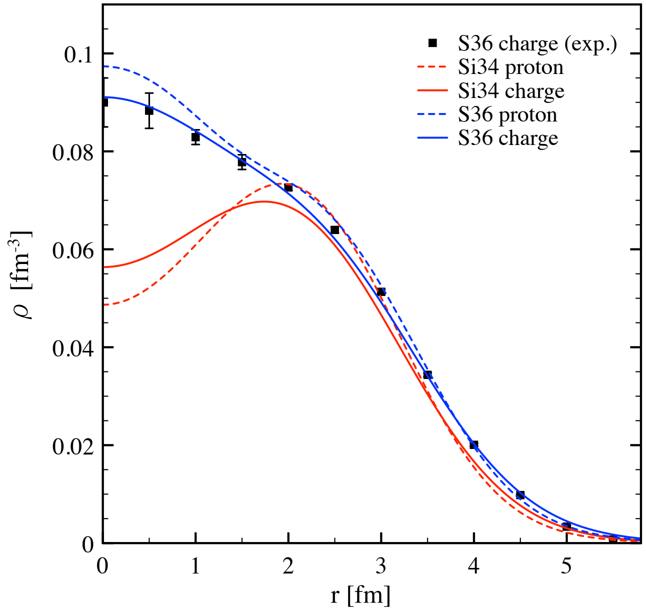
Proton SF for $^{16}O \rightarrow ^{15}N$:

$p_{1/2}$: 0.78 (SCGF) 0.80 (exp.)

$p_{3/2}$: 0.80 (SCGF) 0.65 (exp. – up to cont.)

L. Atar, et al., in preparation (2017) – see talk by T. Aumann

Bubble nuclei... ^{34}Si prediction



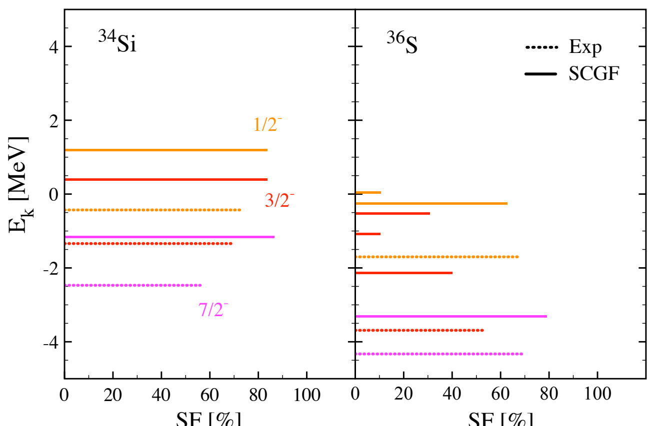
Duguet, Somà, Lecuse, CB, Navrátil,
Phys.Rev. C**95**, 034319 (2017)

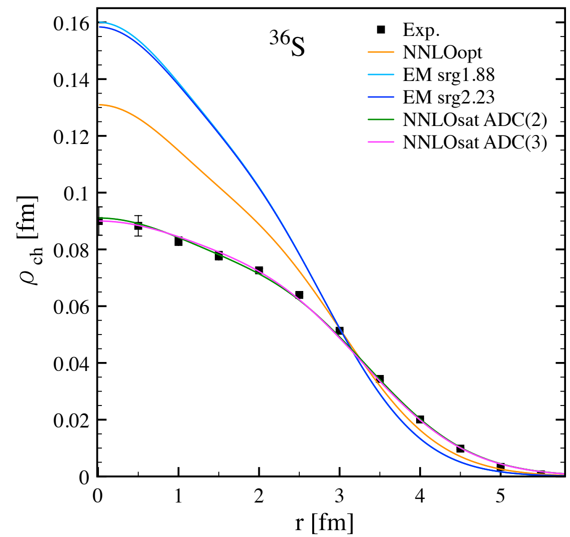
- ^{34}Si is unstable, charge distribution is still unknown

- Suggested central depletion from mean-field simulations

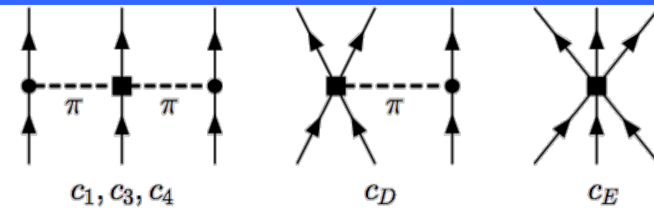
- *Ab-initio* theory confirms predictions

Validated by charge distributions and neutron quasiparticle spectra:





Local vs. non-local chiral N^2LO NNN interaction — by P. Navrátil



- Local: chiral N^3LO NN+ N^2LO 3N500
  - c_D=-0.2 c_E=-0.205 (^{3}H E_{gs}=-8.48 MeV)
  - ^{4}He

<H>=-28.4939 <V3b_2pi>= -5.8819 <V3b_D>= -0.2206 <V3b_E>= 1.2665

- Non-local: chiral N^2LO_{sat} NN+3N
  - c_D=+0.8168 c_E=-0.0396 (^{3}H E_{gs}=-8.53 MeV)
  - ^{4}He

<H>=-28.4596 <V3b_2pi>= -4.7260 <V3b_D>= 1.3897 <V3b_E>= 0.4174

- Local/Non-local: chiral N^3LO NN+ N^2LO

$$F(\tfrac{1}{2}(\pi_1^2+\pi_2^2);\Lambda_{\text{nonloc}})\,W_1^Q(\Lambda_{\text{loc}})\,F(\tfrac{1}{2}(\pi_1^2+\pi_2^2);\Lambda_{\text{nonloc}})$$

Use completeness in HO basis to calculate products of *F W F*

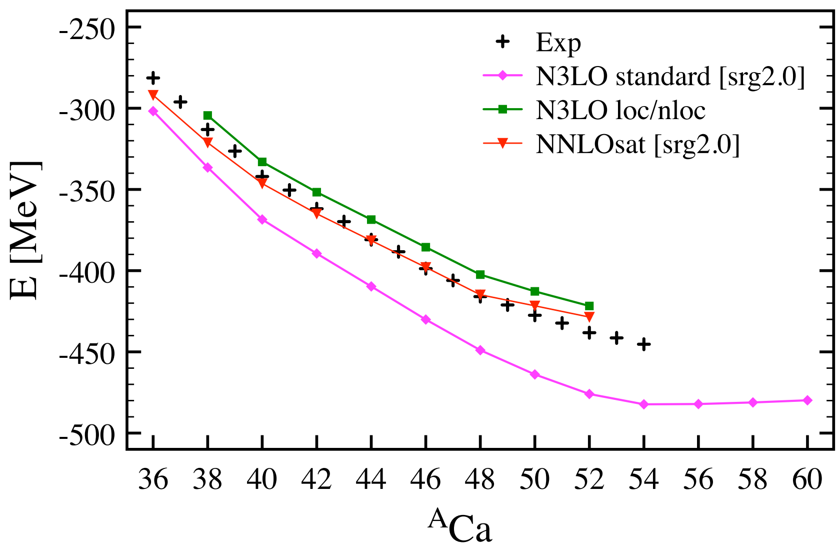
  - c_D=+0.7 c_E=-0.06 (^{3}H E_{gs}=-8.44 MeV)
  - ^{4}He

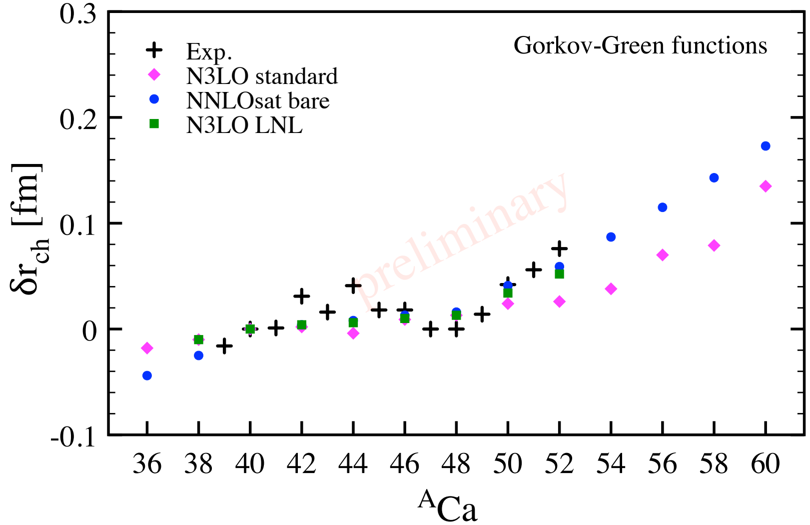
<H>=-28.2530 <V3b_2pi>= -4.8124 <V3b_D>= 0.7414 <V3b_E>= 0.4255

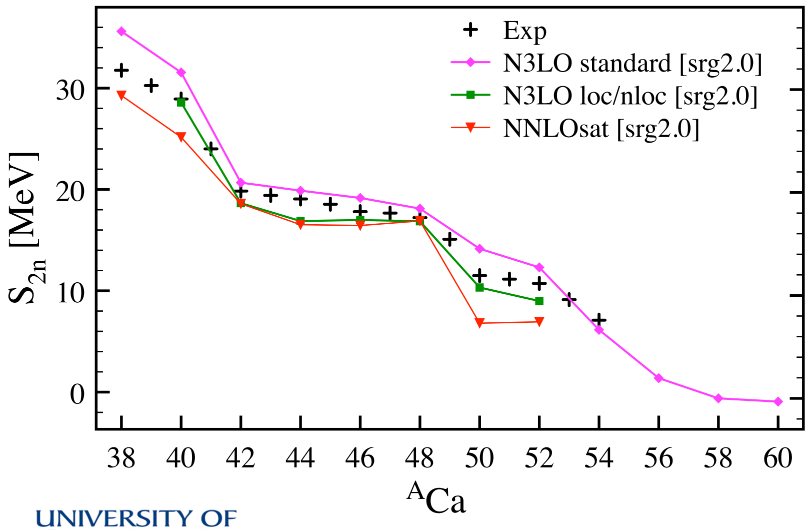
N3LO(500) + nln 3NF

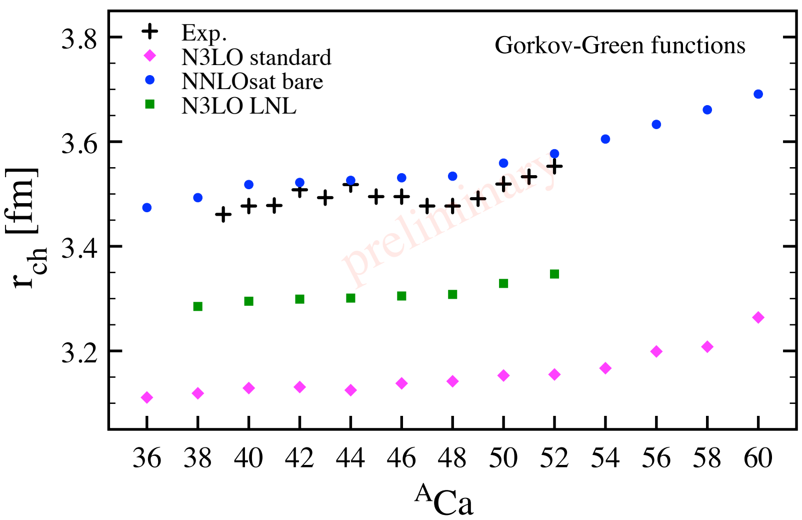
SCGF – Gorkov-ADC(2)

PRELIMINARY









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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)

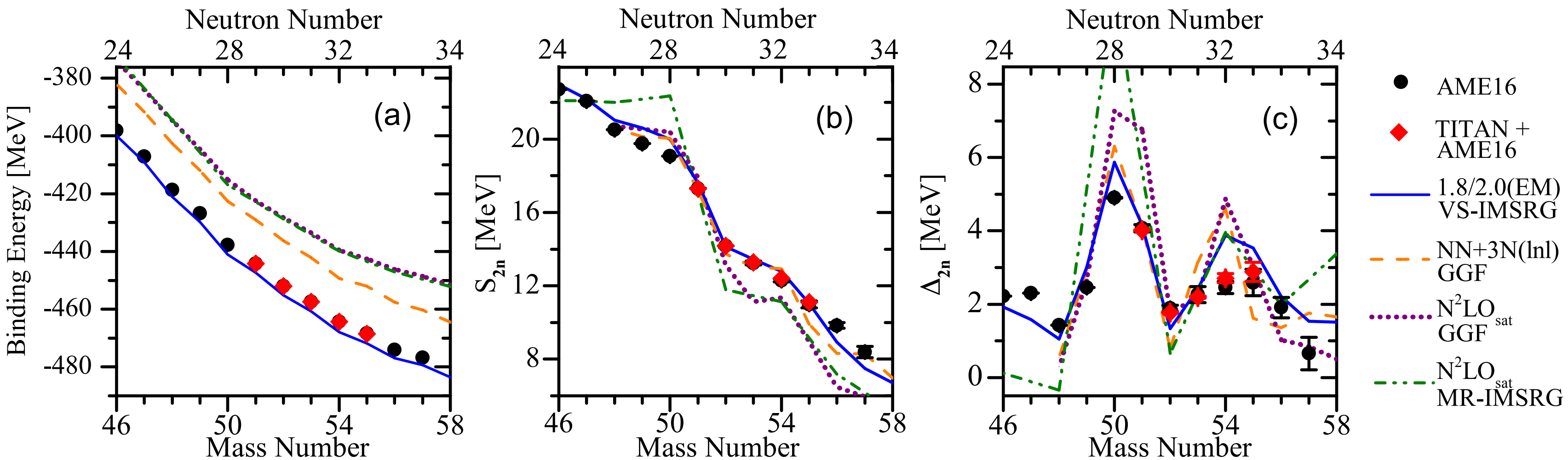
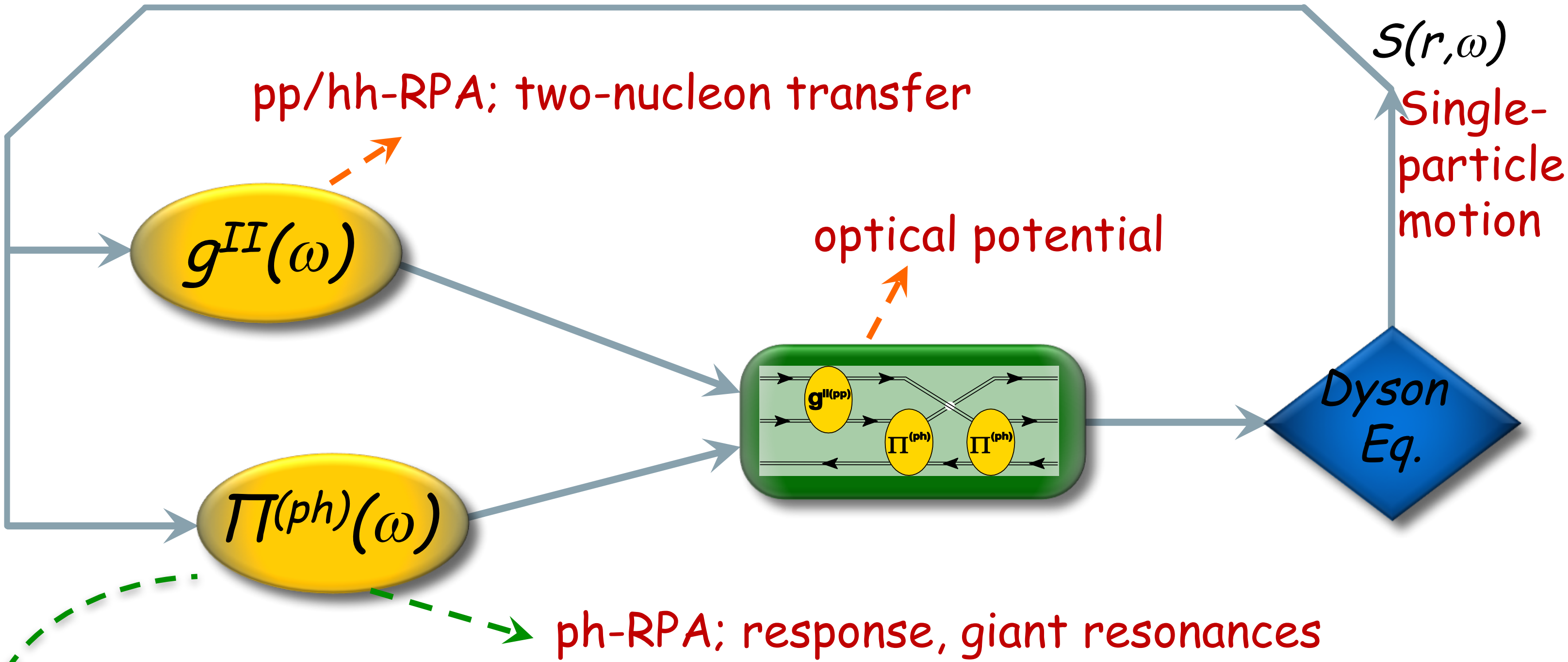


FIG. 4. The mass landscape of titanium isotopes is shown from three perspectives: (a) absolute masses (shown in binding energy format), (b) its first "derivative" as two-neutron separation energies (S_{2n}), and (c) its second "derivative" as empirical neutron-shell gaps (Δ_{2n}). Both theoretical *ab-initio*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

E. Leistenschneider *et al.*, arXiv:1710.08537 (2017) – ***TITAN*** coll. @ TRIUMF

Electromagnetic response in SCGF

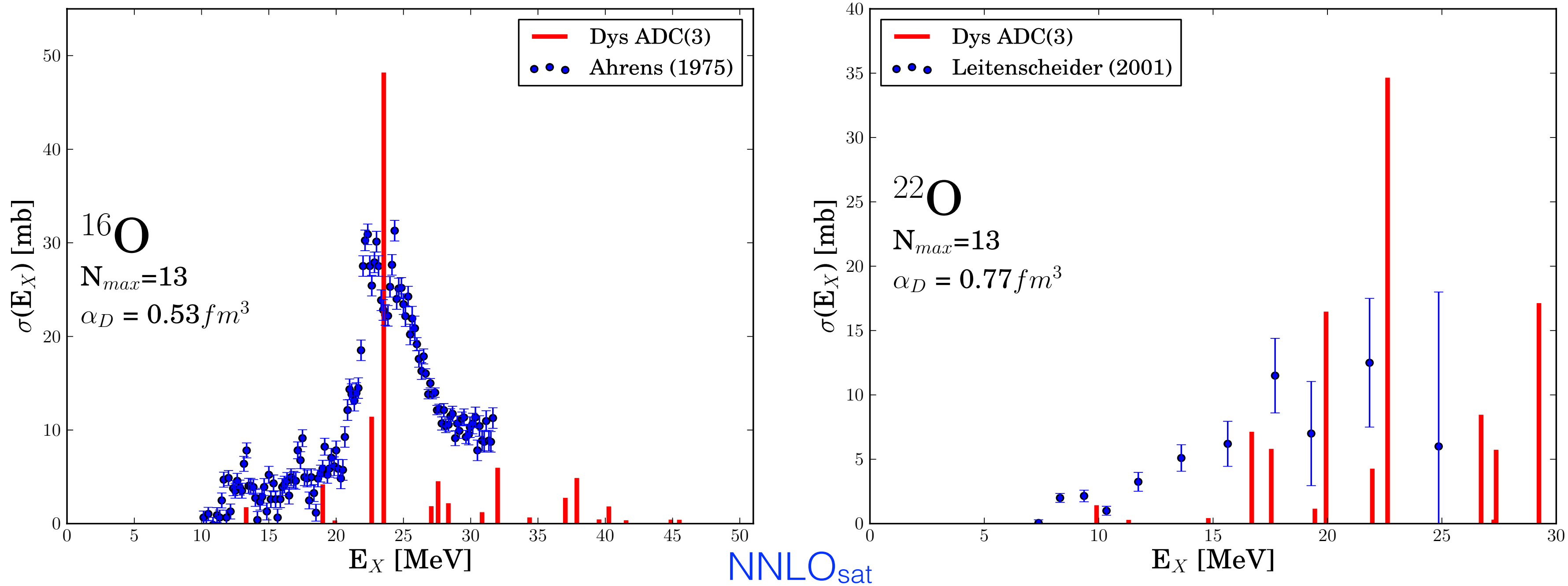


$$\sigma_\gamma(E) = 4\pi^2 \alpha E\, R(E)$$ **photo-absorption cross section**

$$\alpha_D = 2\alpha \int_0^\infty dE\, \frac{R(E)}{E}$$ **electric dipole polarizability**

Results for Oxygen isotopes

σ from RPA response (discretized spectrum) vs σ from photoabsorption and Coulomb excitation



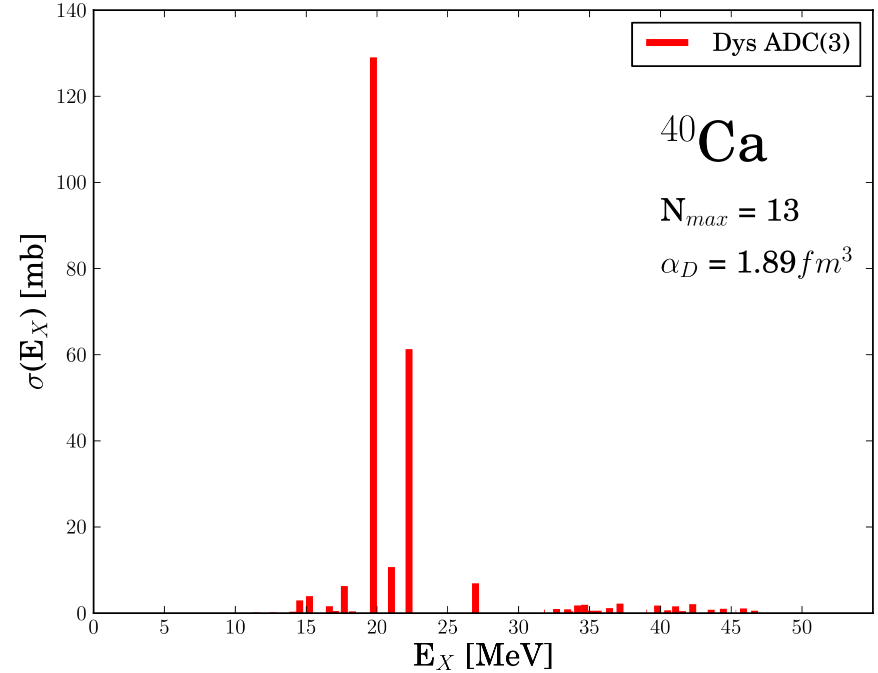
- GDR position of ^{16}O reproduced
- Hint of a soft dipole mode on the neutron-rich isotope

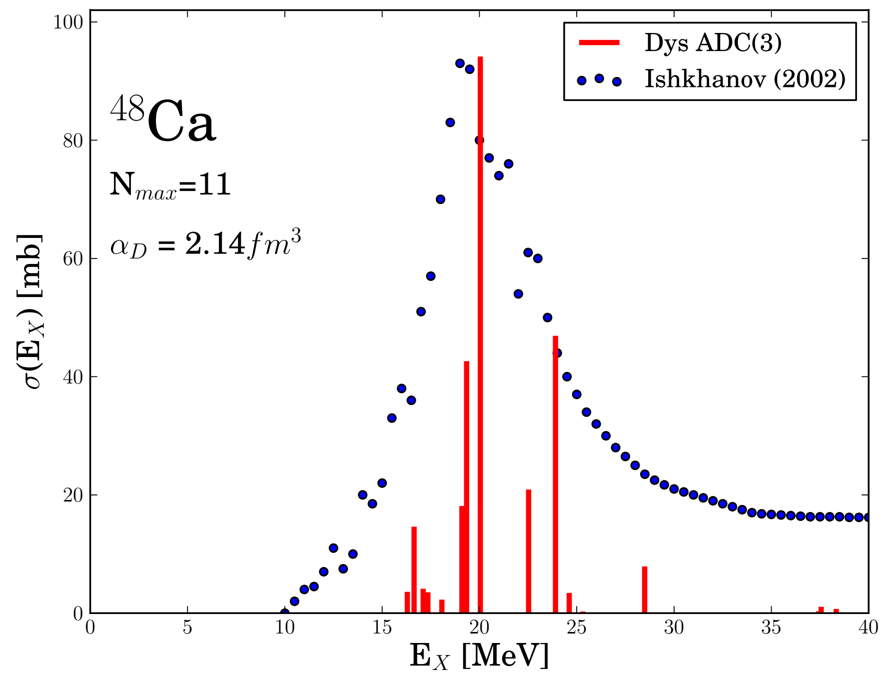
Dipole polarizability α_D (fm^3)			
Nucleus	SCGF	CC/LIT	Exp
^{16}O	0.53	0.57(1)	0.585(9)
^{22}O	0.77	0.86(4)	0.43(4)

Slides courtesy of F. Raimondi – TRIUMF wks, Mar 2017

Results for Calcium isotopes

σ from RPA response (discretized spectrum) vs σ from photoabsorption and Coulomb excitation





NNLO$_{sat}$

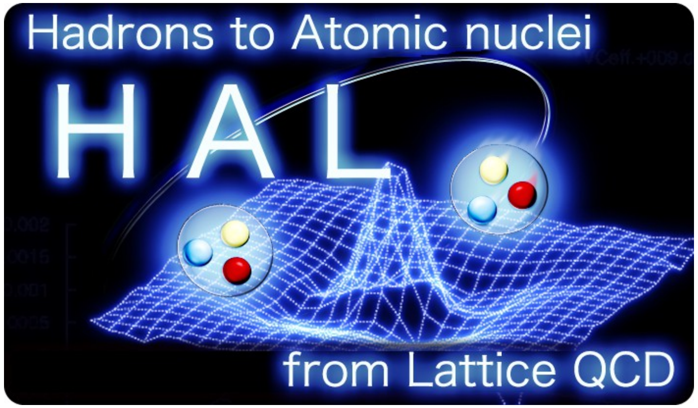
- GDR positions reproduced

Dipole polarizability α_D (fm^3)			
Nucleus	SCGF	CC/LIT	Exp
^{40}Ca	1.89	1.47 $(1.87)_{thresh}$	1.87(3)
^{48}Ca	2.14	2.45	2.07(22)

Slides courtesy of F. Raimondi – TRIUMF wks, Mar 2017

Study of nuclear interactions from Lattice QCD

In collaboration with:

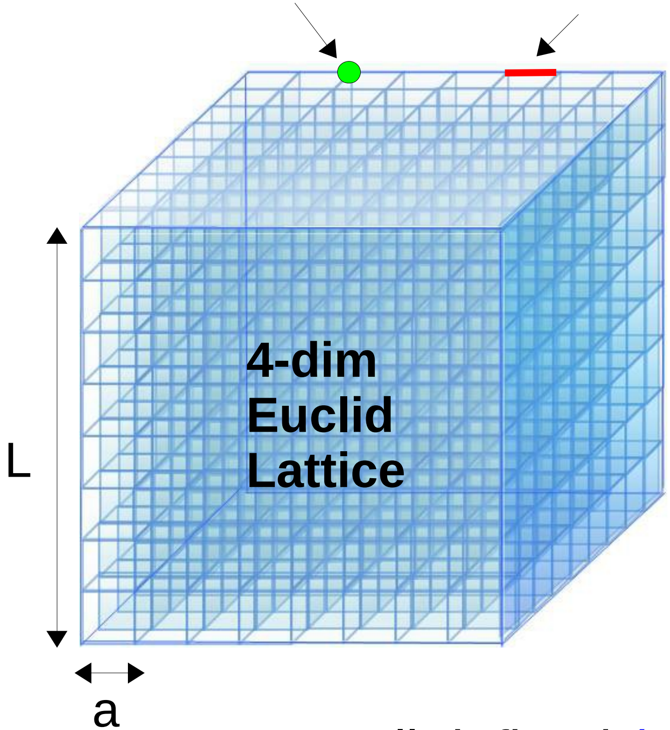


Lattice QCD

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

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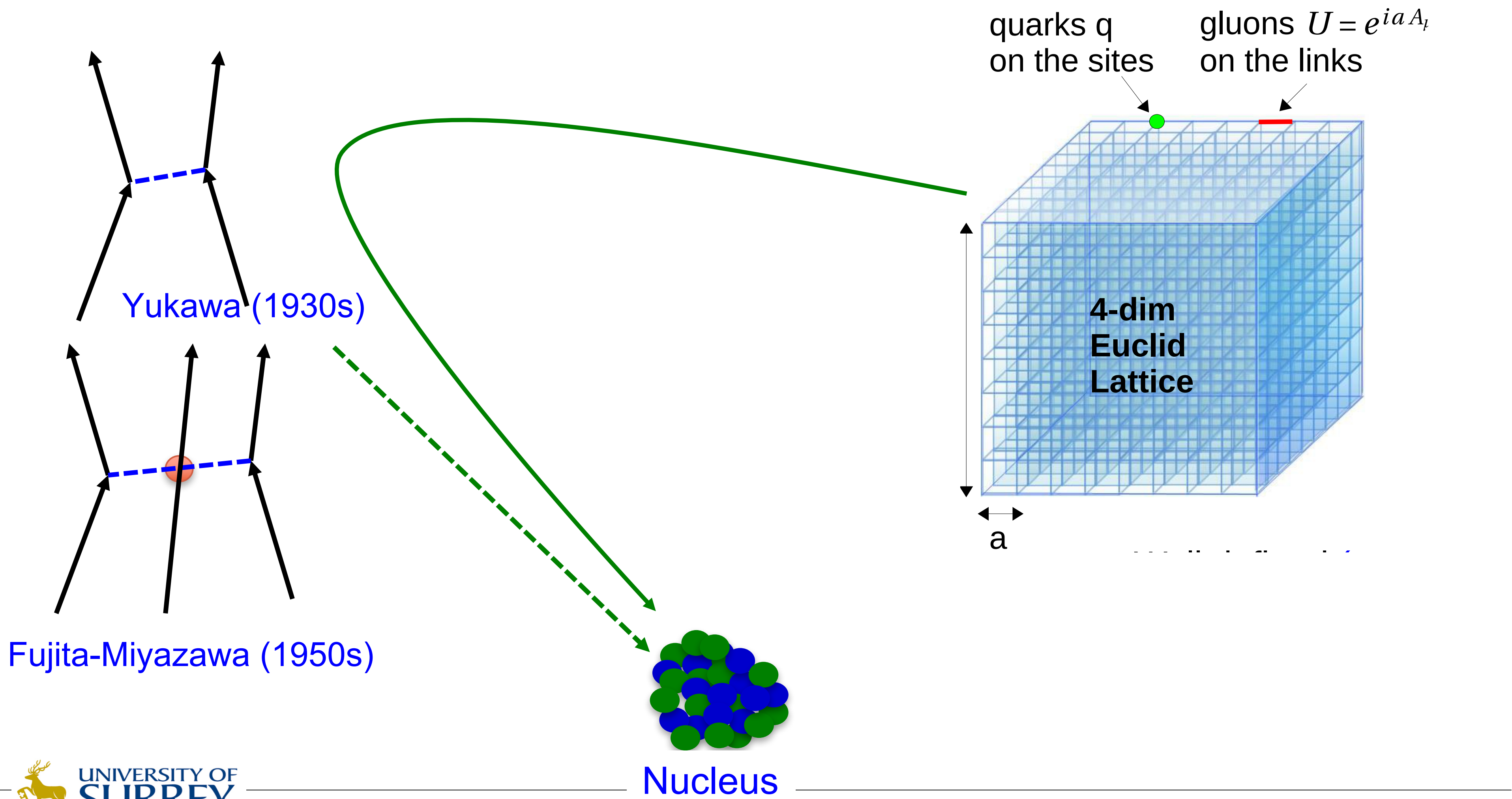
Slide, courtesy of T. Inoue (YITP talk, Oct. 8th 2015)

Approaches to nuclei from LQCD

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



Why nuclear interactions on the Lattice??

- *Extend LQCD beyond few-bodies*

- *Reproduces exactly scattering and NN, 3N, observables that would be computed with Lattice QCD.*

- *Not based on a specific EFT momentum scale*
  ➔ *exploitable to high densities (e.g. Neutron stars)*

- *No LECs to worry about* *...AND:*

- *Variation in potentials from variation in sink operators (➔ estimation of theoretical uncertainties, missing N-body terms, etc...)*

- *Direct derivation of hyperon-nucleon interactions*

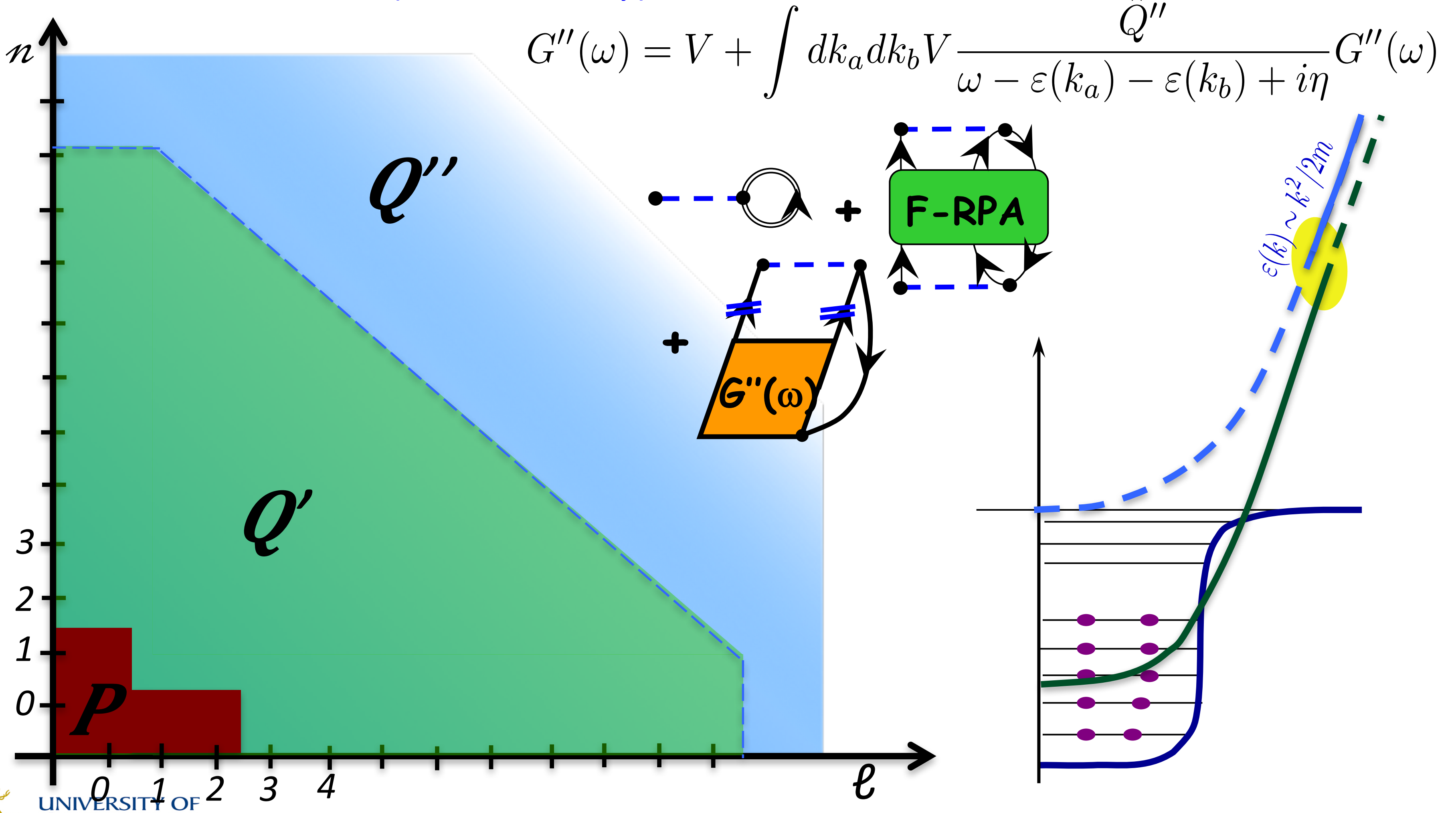
- *3NF can be derived consistently with NN interactions*

➔ *Need to develop appropriate many-body methods*

Mixed SCGF–Brueckner approach

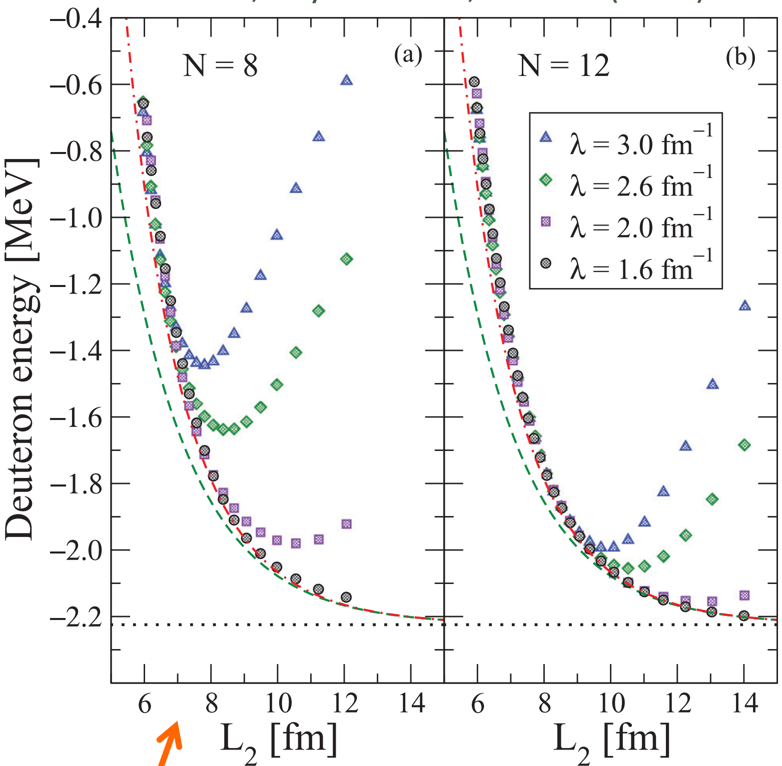
Solve full many-body dynamics in model space (P+Q') and the Goldstone's ladders outside it (i.e. in Q'' only):

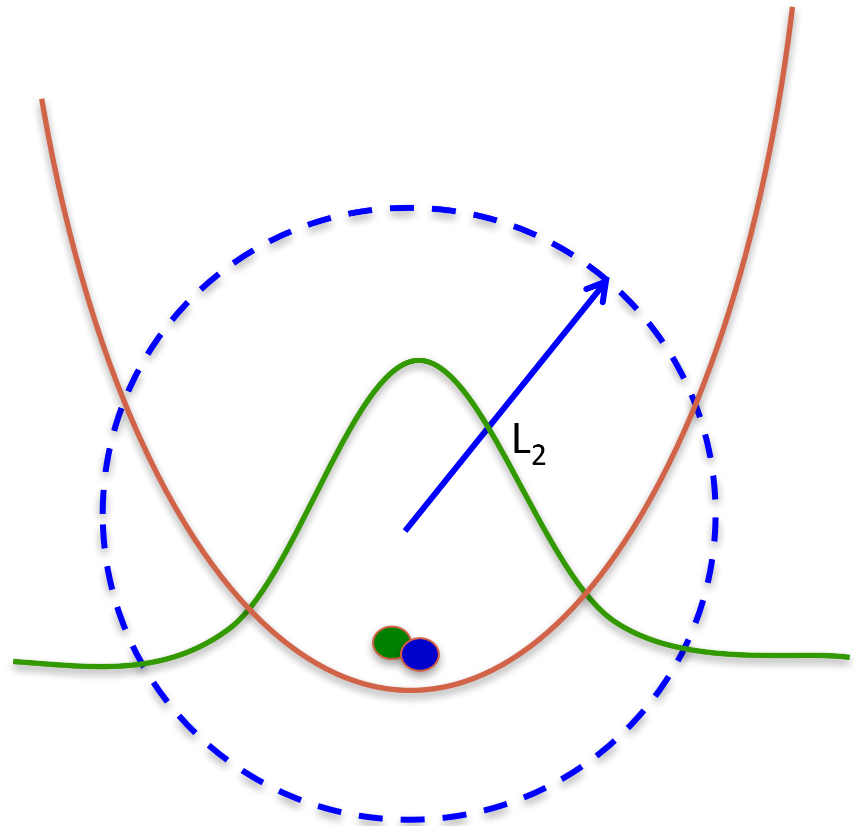
$$G''(\omega) = V + \int dk_a dk_b V \frac{\hat{Q}''}{\omega - \varepsilon(k_a) - \varepsilon(k_b) + i\eta} G''(\omega)$$



Infrared convergence

Moore et al., Phy. Rev. C**87**, 044326 (2013)



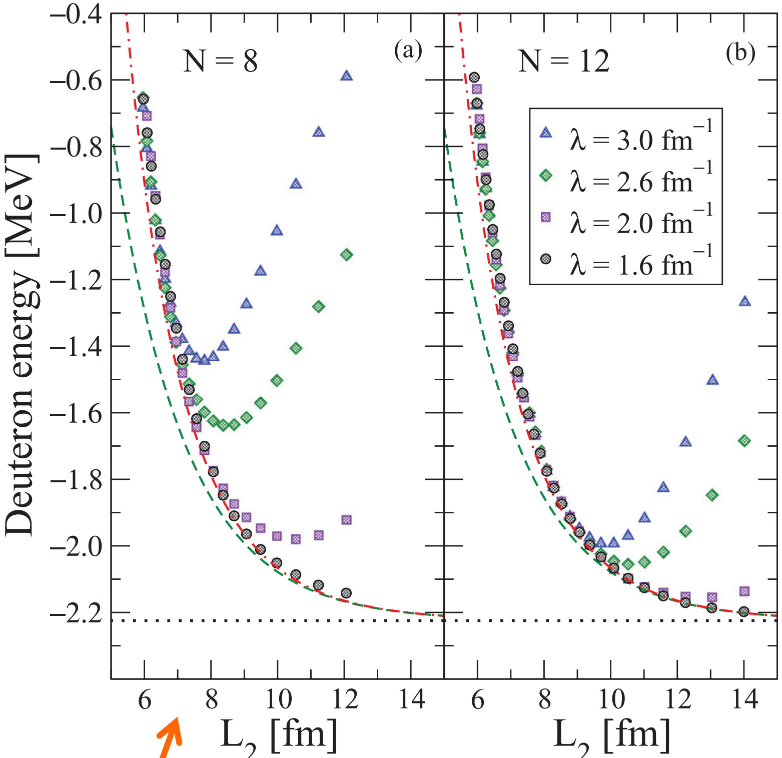


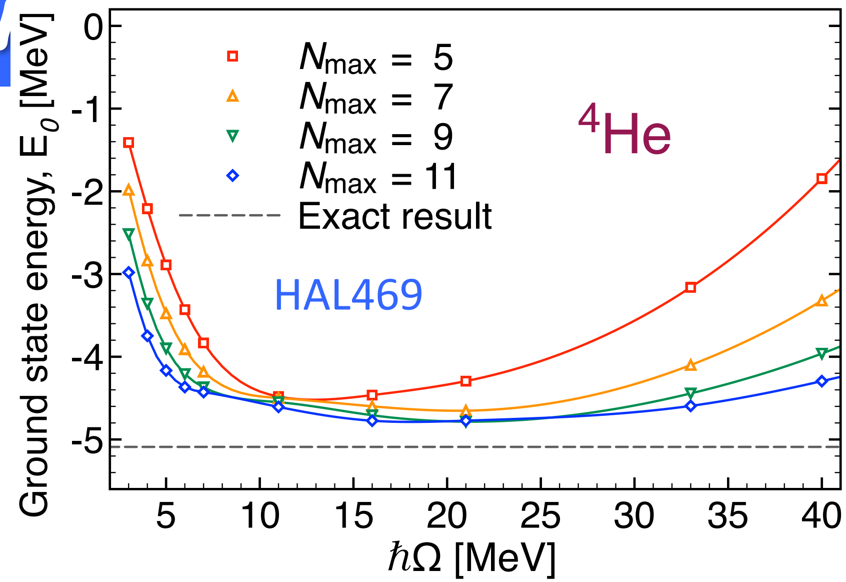
Deuteron g.s. Energy
EM(500) – N3LO two-nucleon force

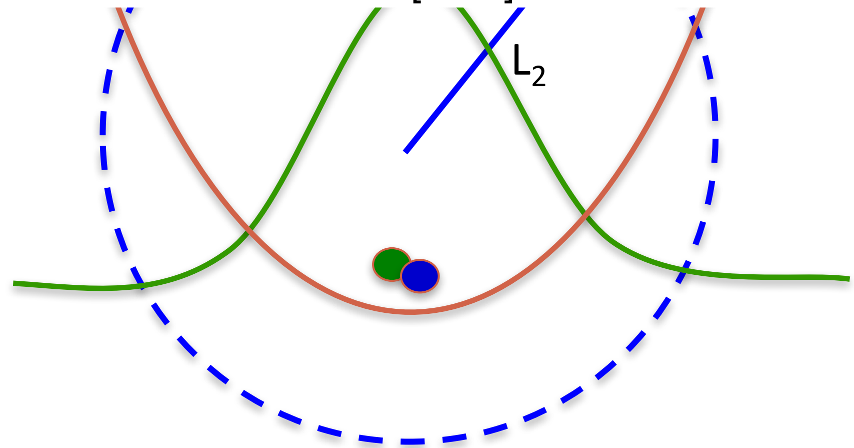
$$L_2 = \sqrt{2(N + 3/2 + 2)}b$$

Infrared converge

Moore et al., Phy. Rev. C**87**, 044326 (2013)







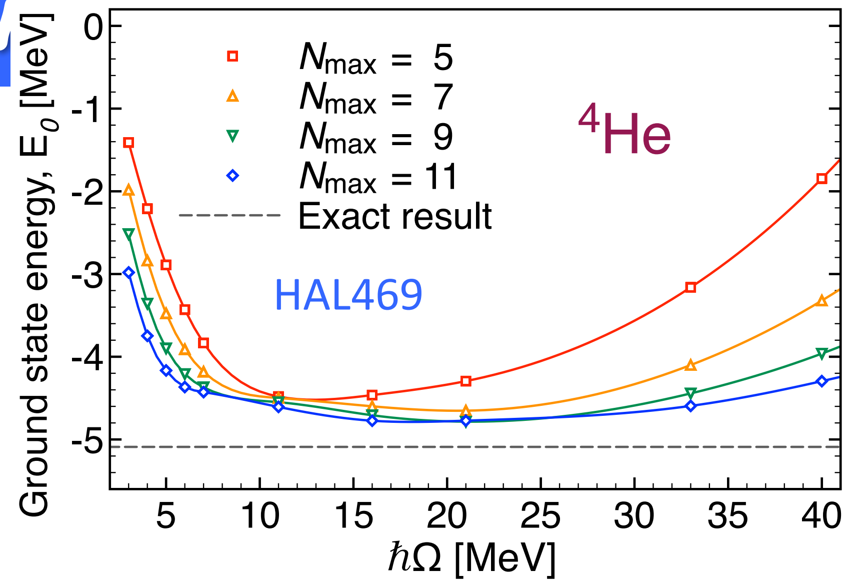
Deuteron g.s. Energy
EM(500) – N3LO two-nucleon force

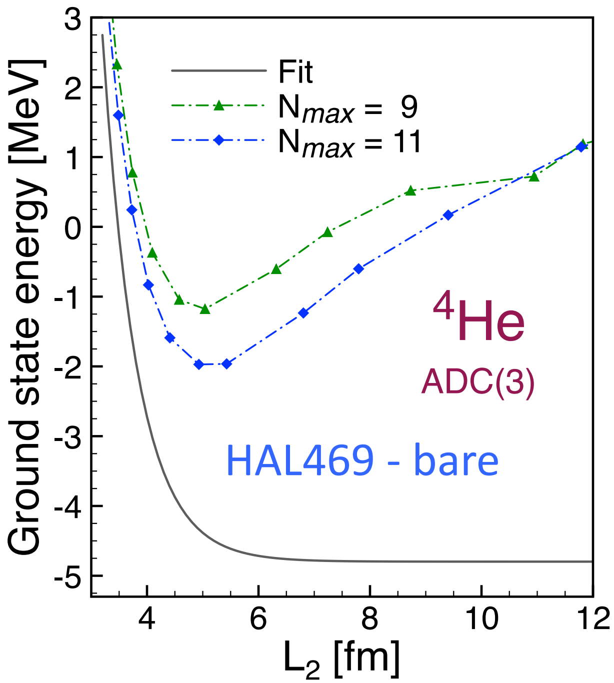
$$L_2 = \sqrt{2(N + 3/2 + 2)}b$$

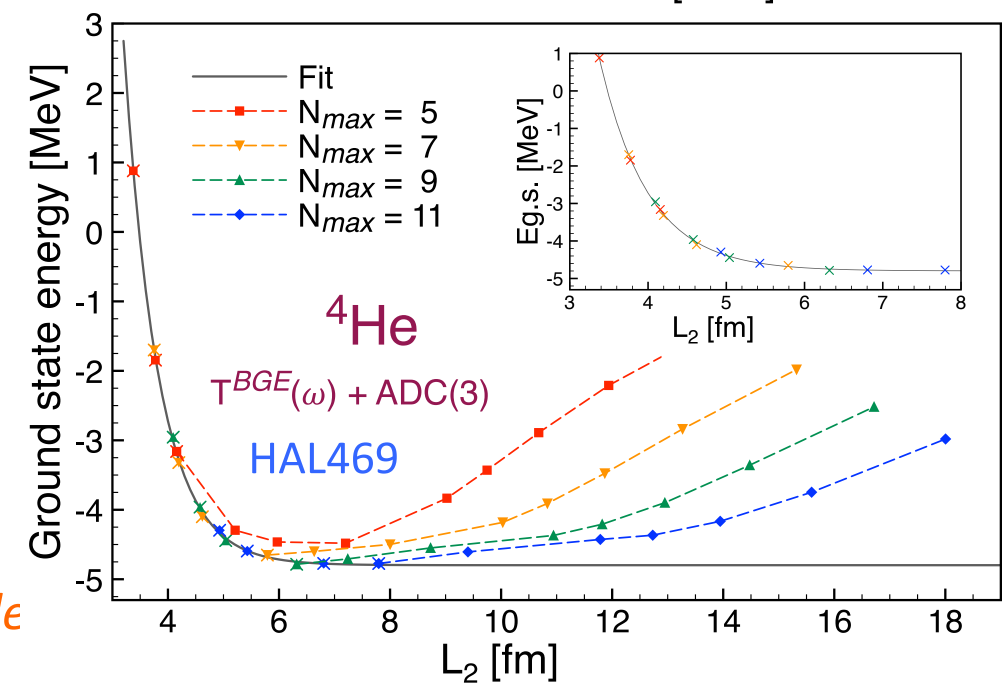
Infrared converge

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

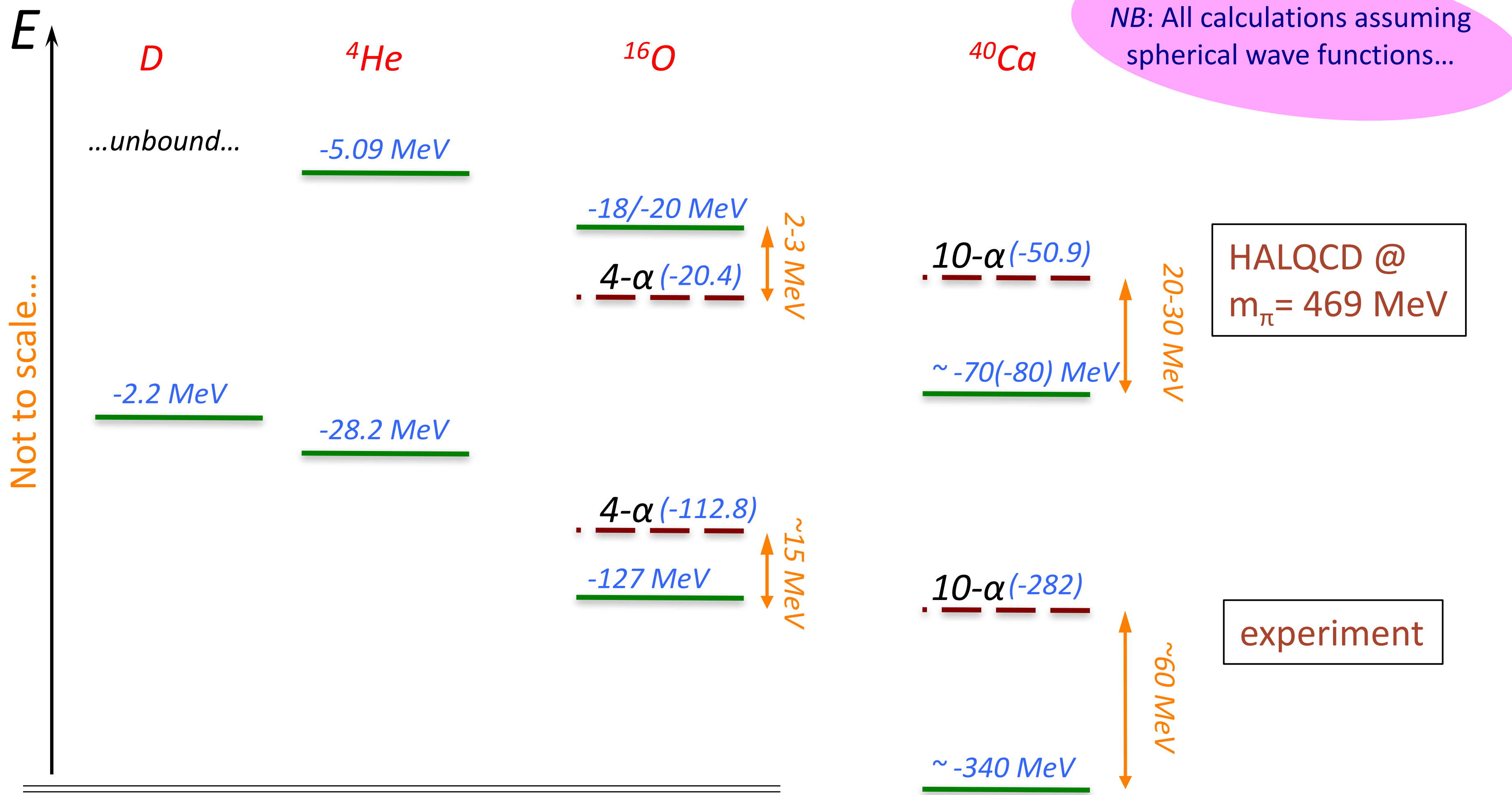
C. McIlroy, CB, et al., arXiv:1701.02607 [nucl-th]







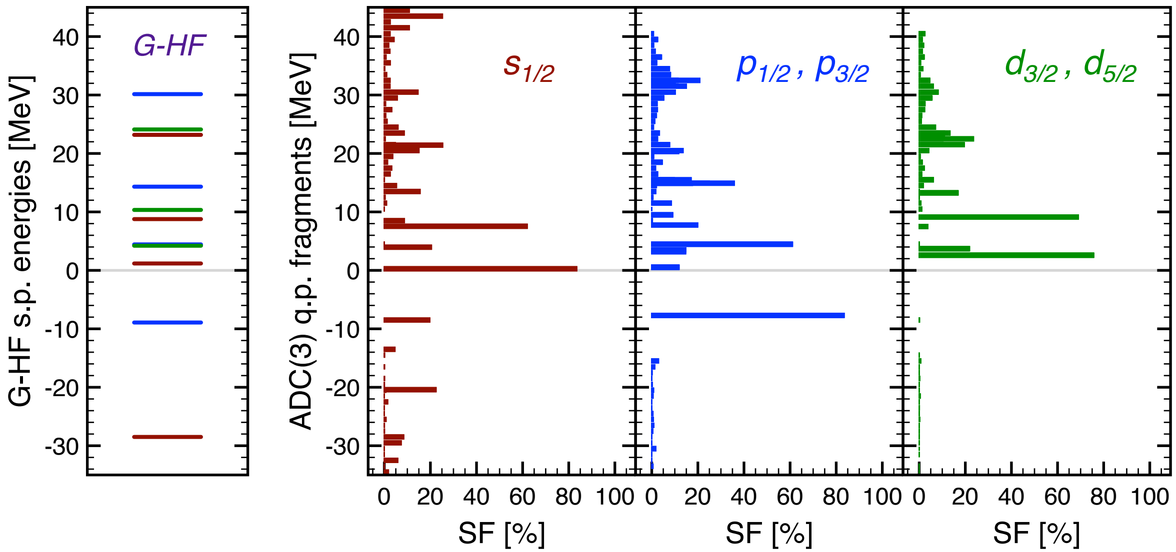
Results for binding



E_0^A [MeV]	^{4}He	^{16}O	^{40}Ca
BHF [22]	-8.1	-34.7	-112.7
$G(\omega)$ + 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)

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

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

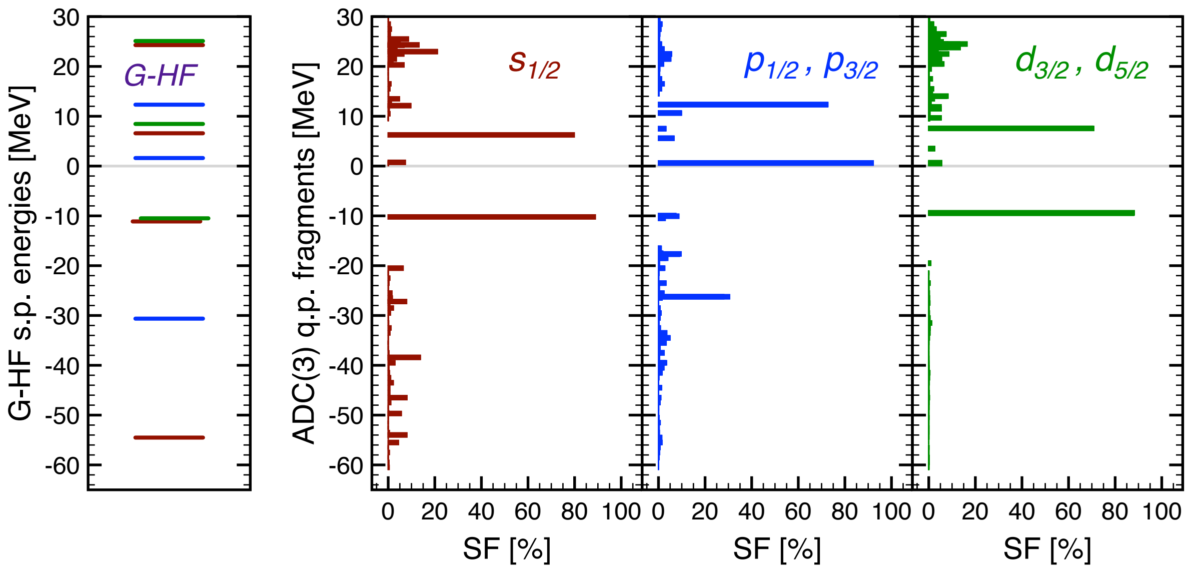


Particle-hole gaps:

^{16}O

m_π= 469 MeV: ~8 MeV

Expt (phys m_π): 11.5 MeV



^{40}Ca

m_π= 469 MeV: ~10 MeV

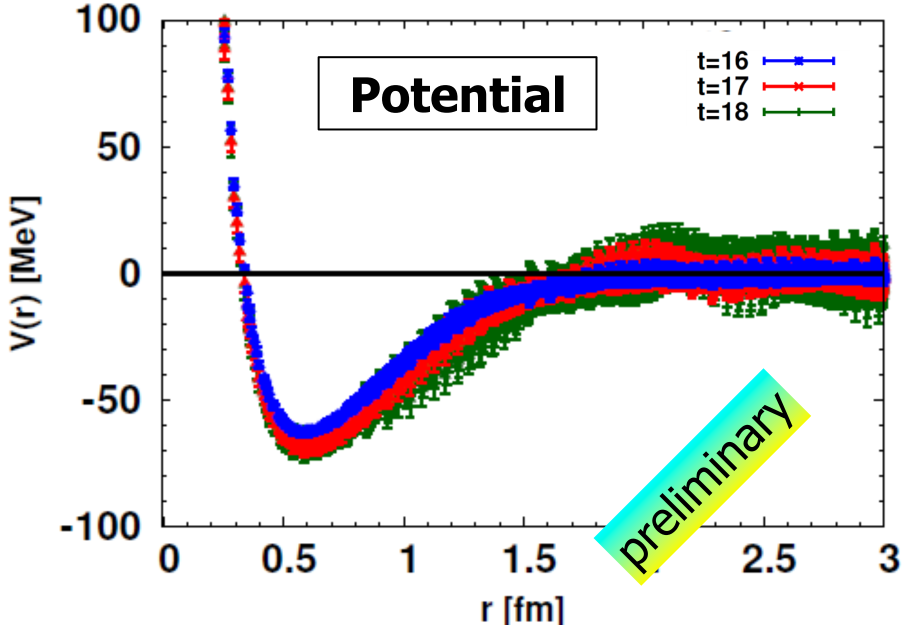
Expt (phys m_π): 7.5 MeV

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

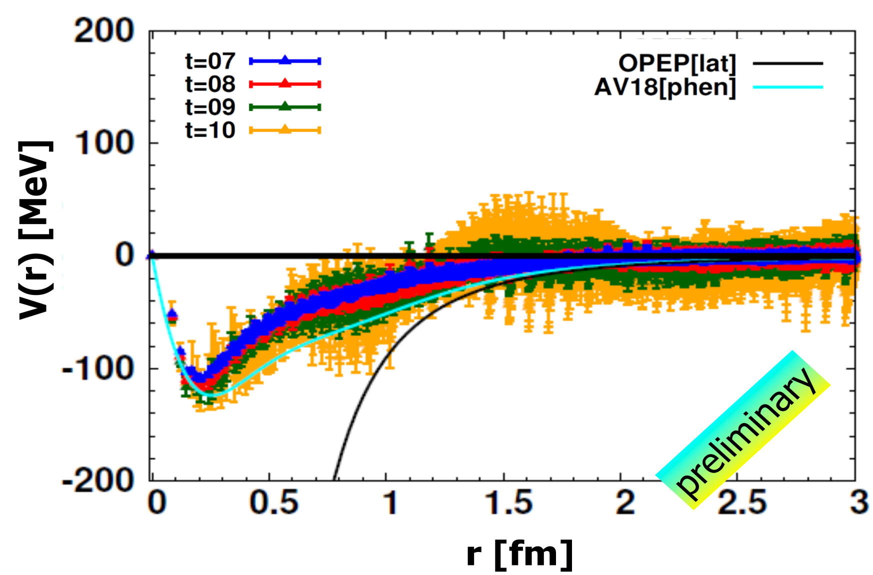
Future application for Ys in nuclei now possible

- 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

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…)

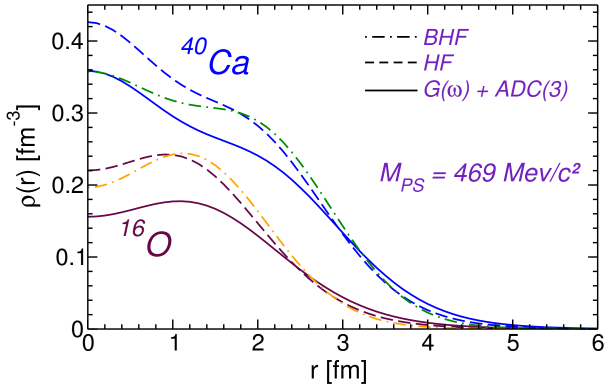
→ New fits of chiral interaction are promising for low-energy observables and for scattering – mass/radii/spectroscopy are improved but there remain issues (symm energy, neutron rich) and dependency on LEC/cutoffs.

→ Ab intio optical potentials (nucleon-nucleus) within reach.

→ Dipole responses and polarizabilities, are reproduced well at (LO) RPA .

→ Effective charges can be computed for SM applications

HALQCD Nuclear forces:



→ Strong short range behavior calls for new ideas in ab-initio many-body methods. Diagram resummation through G-matrix is good 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.

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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…)

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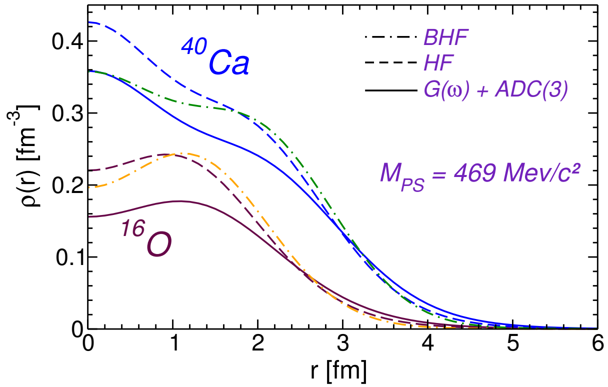
HALQCD Nuclear forces:



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Thanks to all collaborators!!

A. Cipollone, *C. McIlroy*
A. Rios, ***A. Idini***, ***F. Raimondi*** — University of Surrey

V. Somà, T. Duguet — CEA (energie atomique • energies alternatives)

A. Carbone — ECT* European Centre for Theoretical Studies in Nuclear Physics and Related Areas

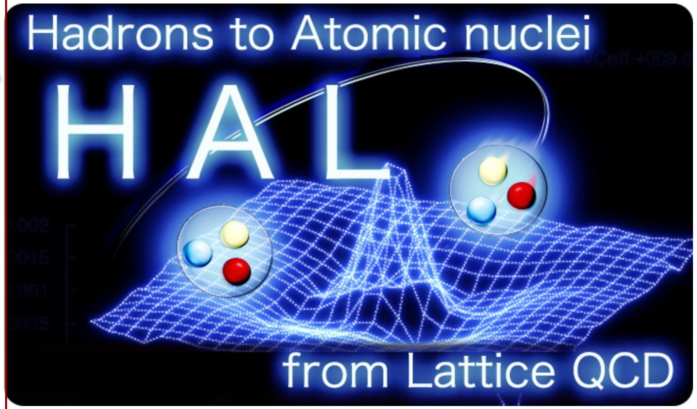
P. Navratil — TRIUMF

A. Polls — Universitat de Barcelona

W.H. Dickhoff, S. Waldecker — Washington University in St.Louis

D. Van Neck — Center for Molecular Modeling

M. Hjorth-Jensen

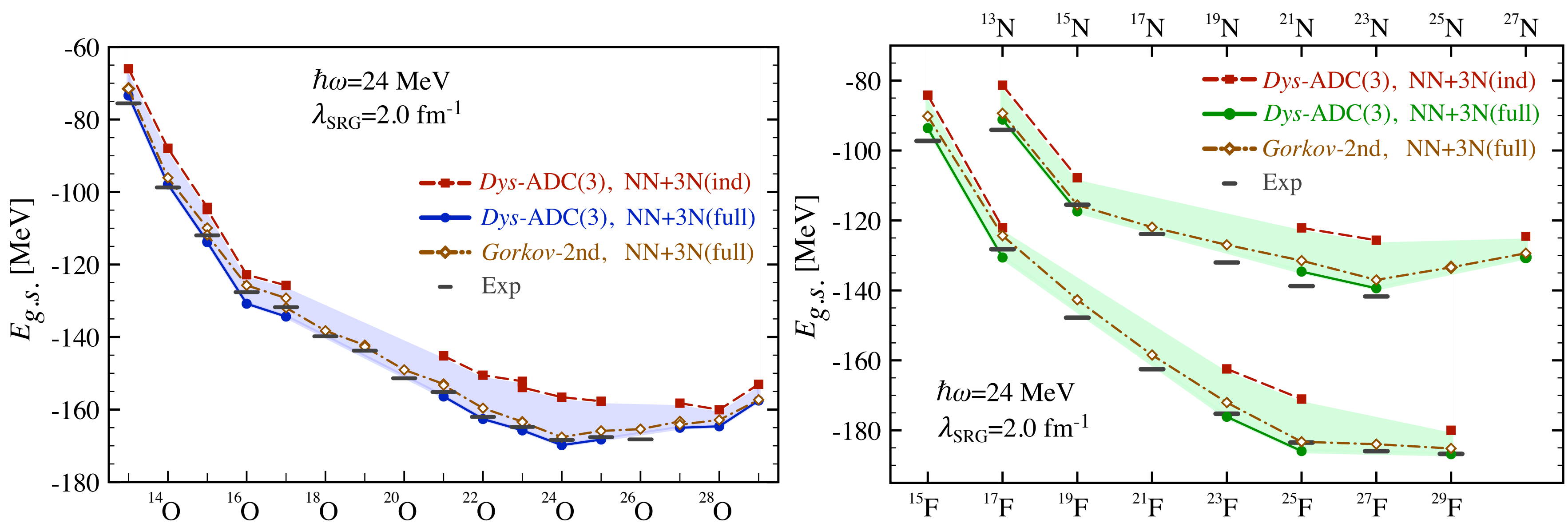


S. Aoki,	YITP Kyoto Univ.
T. Doi, **T. Hatsuda**, Y. Ikeda,	RIKEN Nishina
T. Inoue,	Nihon Univ.
N. Ishii, K. Murano,	RCNP Osaka Univ
H. Nemura, K. Sasaki	Univ. Tsukuba
F. Etminan	Univ. Birjand
T. Miyamoto,	Univ. Tsukuba
T. Iritani	Stony Brook Univ.
S. Gongyo	YITP Kyoto Univ.

…and thank you for your attention!!!

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})