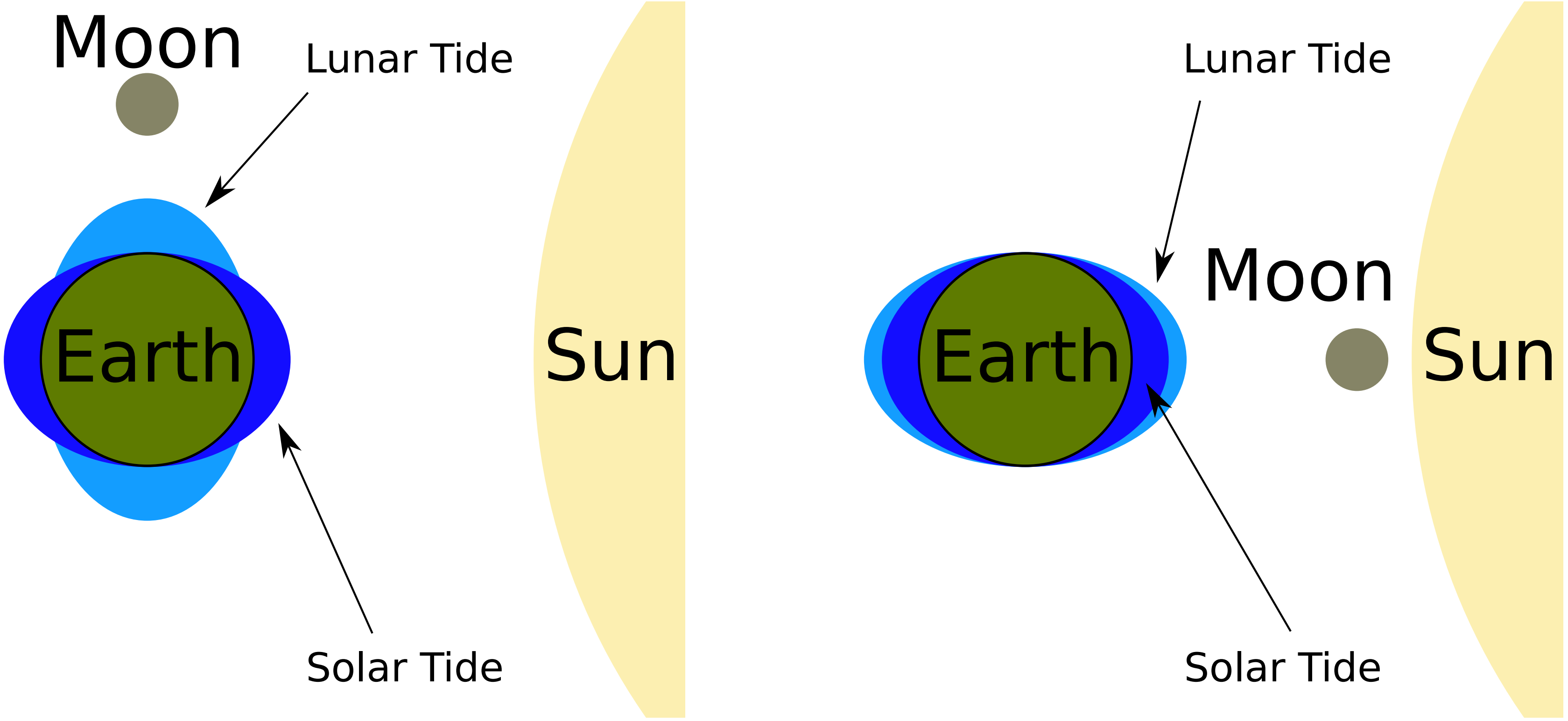
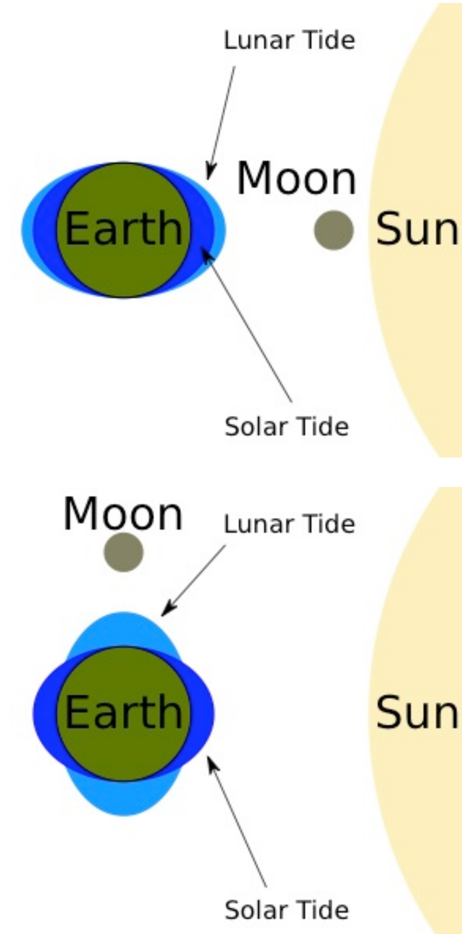
Why are there three-body forces?

tidal effects lead to 3-body forces in earth-sun-moon system

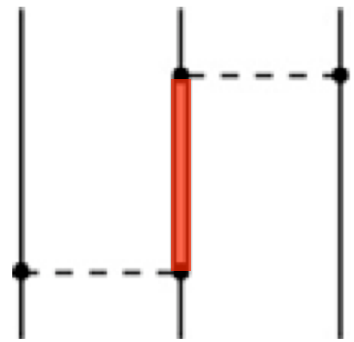


Why are there 3N forces?

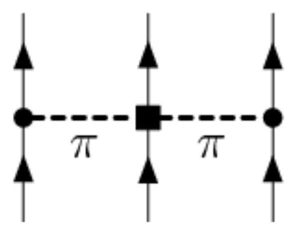
Nucleons are finite-mass composite particles,
can be excited to resonances



dominant contribution from Δ(1232 MeV)



+ many shorter-range parts

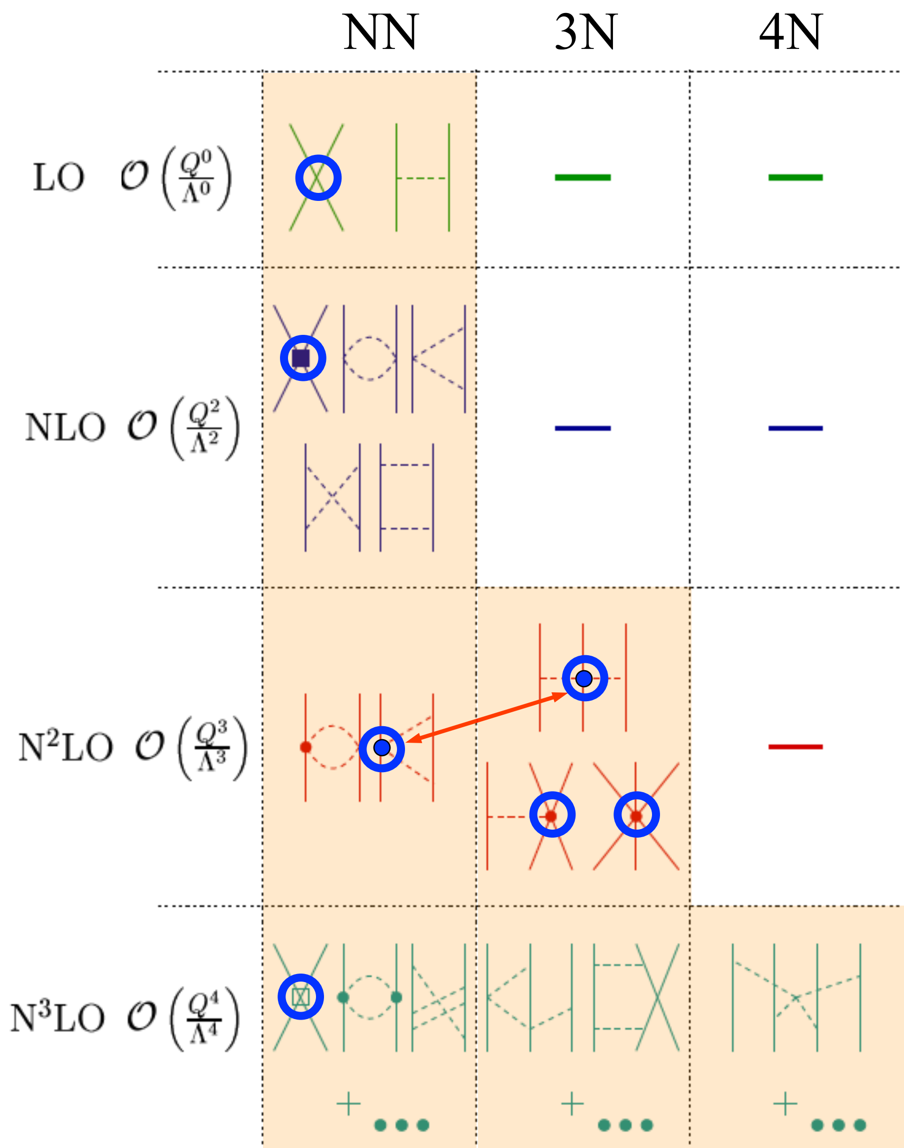
chiral effective field theory (EFT)
Delta-less (Δ is treated as heavy): 

+ shorter-range parts

EFT provides a systematic and powerful approach for 3N forces

Chiral effective field theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



include long-range pion physics

few short-range couplings,
fit to experiment once

systematic: can work to desired accuracy and obtain **error estimates**

consistent **electroweak interactions** and **matching to lattice QCD**

Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

3N forces in different EFTs

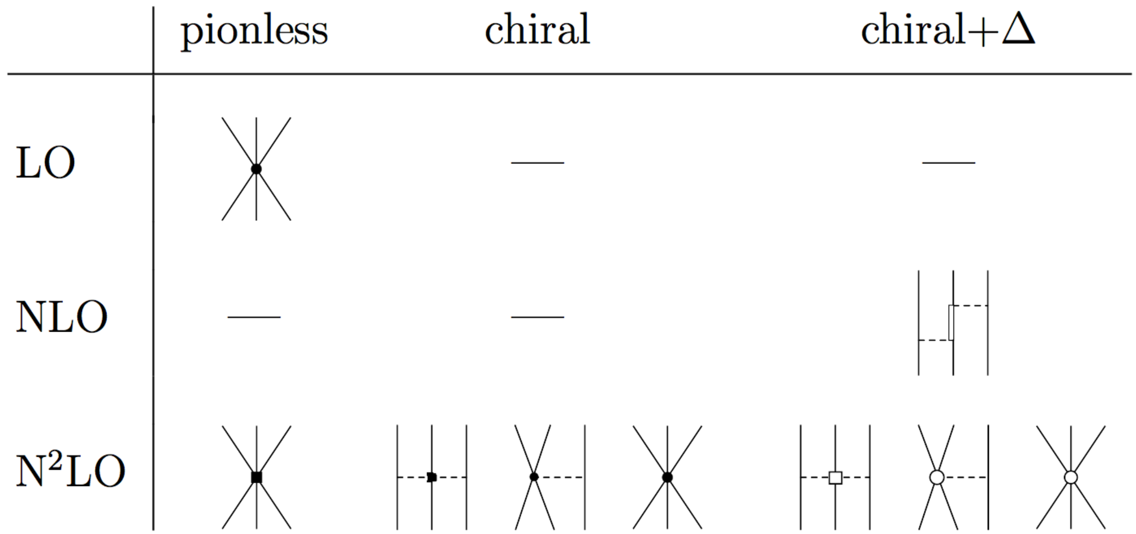
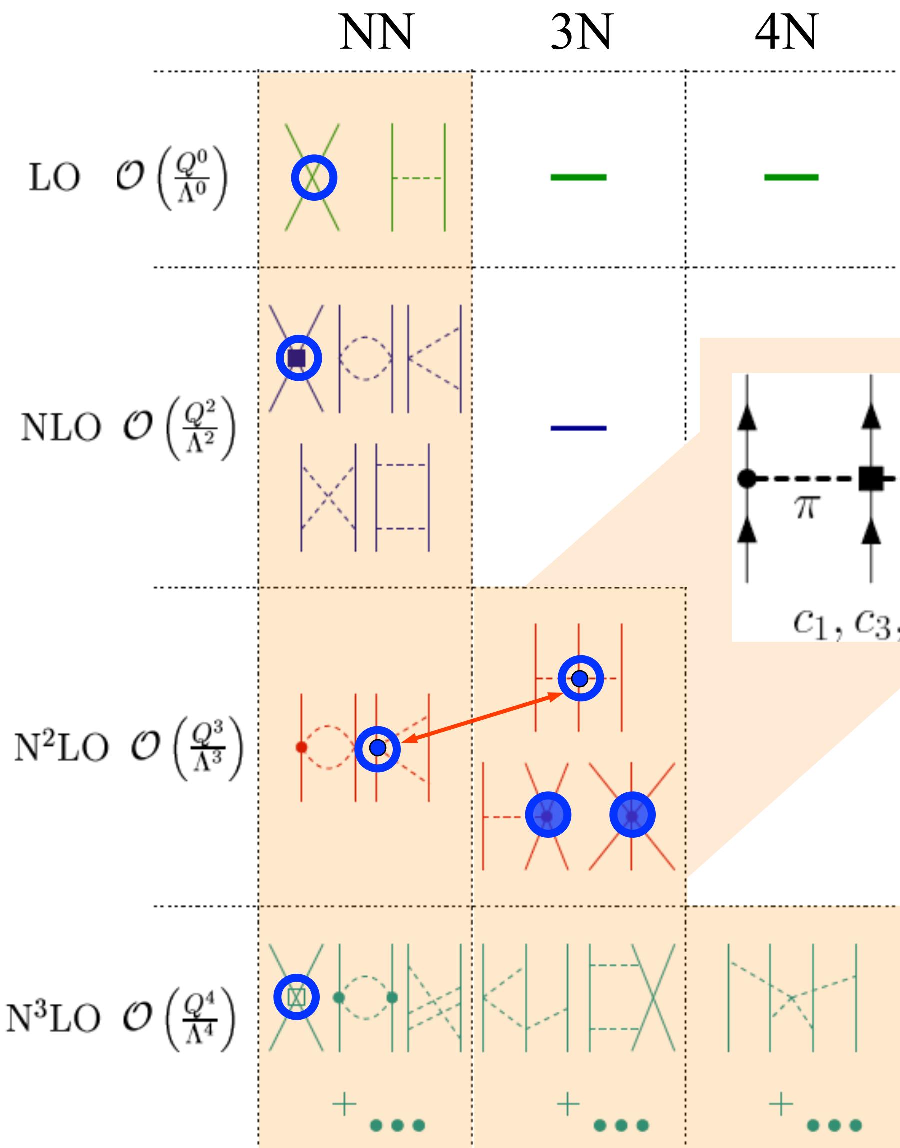


FIG. 23 Order of 3NF contributions in pionless and chiral EFT and in EFT with explicit Δ degrees of freedom (chiral+Δ). Open vertices in the last column indicate the differences of the low-energy constants in chiral and chiral+Δ EFT.

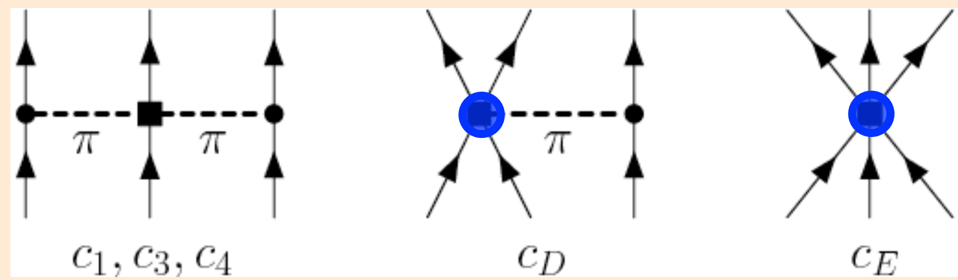
Chiral effective field theory and **many-body forces**

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



consistent NN-3N-4N interactions

3N,4N: 2 new couplings to N^{3}LO



c_i from πN and NN Meissner et al. (2007)

$$c_1 = -0.9^{+0.2}_{-0.5}\,,\; c_3 = -4.7^{+1.2}_{-1.0}\,,\; c_4 = 3.5^{+0.5}_{-0.2}$$

single-Δ: $c_1=0$, $c_3=-c_4/2=-3$ GeV^{-1}

c_D, c_E fit to ^{3}H, ^{4}He properties only

Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…

Range of c_i couplings

	c_1	c_3	c_4	
Fettes *et al.* (1998) (Fit 1)	-1.2	-5.9	3.5	πN
Büttiker and Meißner (2000)	-0.8	-4.7	3.4	πN
Meißner (2007)	-0.9	-4.7	3.5	πN
Rentmeester *et al.* (2003)	-0.8	-4.8	4.0	NN
Entem and Machleidt (2002)	-0.8	-3.4	3.4	NN
Entem and Machleidt (2003)	-0.8	-3.2	5.4	NN
Epelbaum *et al.* (2005)	-0.8	-3.4	3.4	NN
Bernard *et al.* (1997)	-0.9	-5.3	3.7	res

High-order analysis Krebs et al. (KGE) (2012)

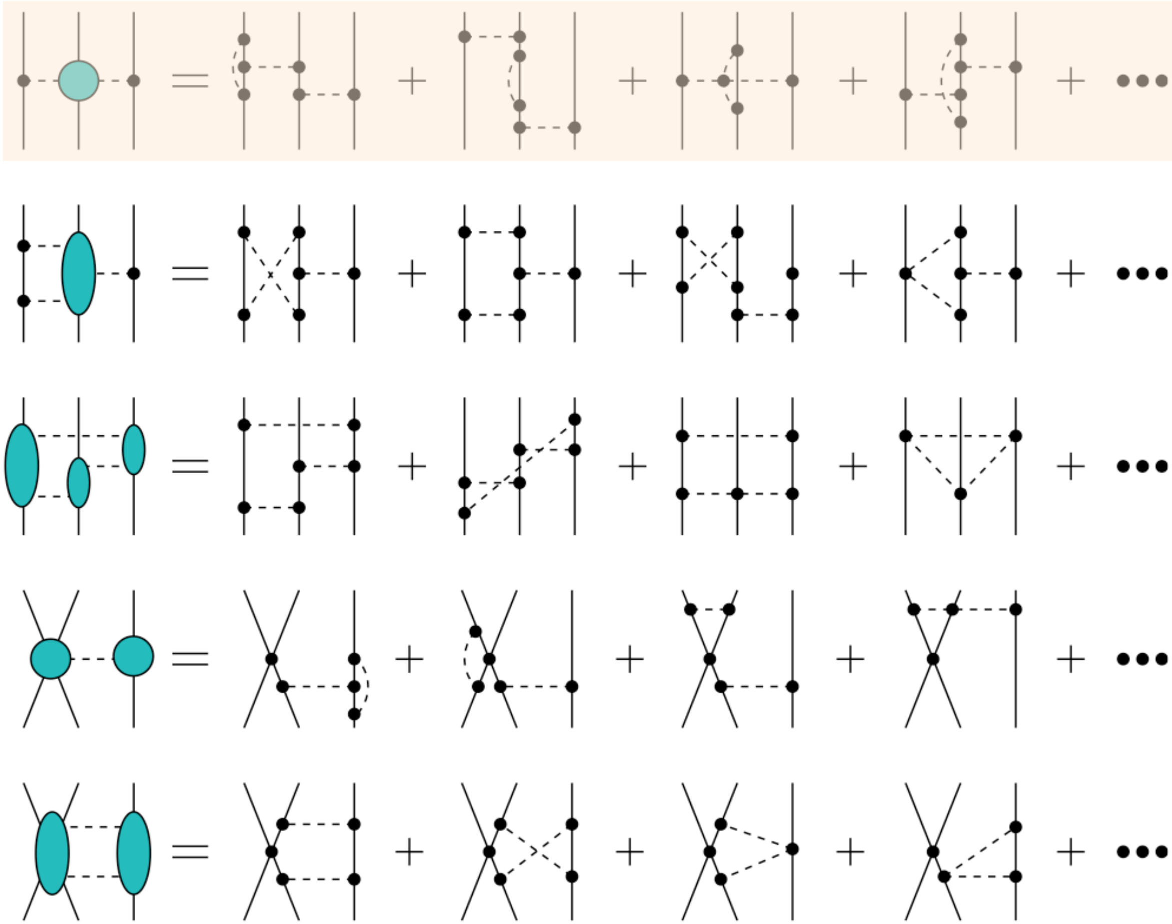
	c_1 [GeV^{-1}]	c_3 [GeV^{-1}]
N^{2}LO/N^{3}LO EGM NN [31, 32]	-0.81	-3.40
N^{3}LO EM NN [33, 34]	-0.81	-3.20
N^{2}LO KGE [39]	$-(0.26-0.58)$	$-(2.80-3.14)$
'N^{2}LO' KGE (recom.) [39]	$-(0.37-0.73)$	$-(2.71-3.38)$
N^{3}LO KGE [39]	$-(0.75-1.13)$	$-(4.77-5.51)$

Subleading chiral 3N forces

parameter-free N^3LO Bernard et al. (2007,2011), Ishikawa, Robilotta (2007)

one-loop contributions:

2π-exchange, 2π-1π-exchange, rings, contact-1π-, contact-2π-exchange



decrease c_i strengths
$\delta c_3 = -\delta c_4 = 1\ \mathrm{GeV}^{-1}$
comparable to
N^2LO uncertainty

1/m corrections: spin-orbit parts, interesting for A_y puzzle

neutron-deuteron scattering at NLO and N^{2}LO

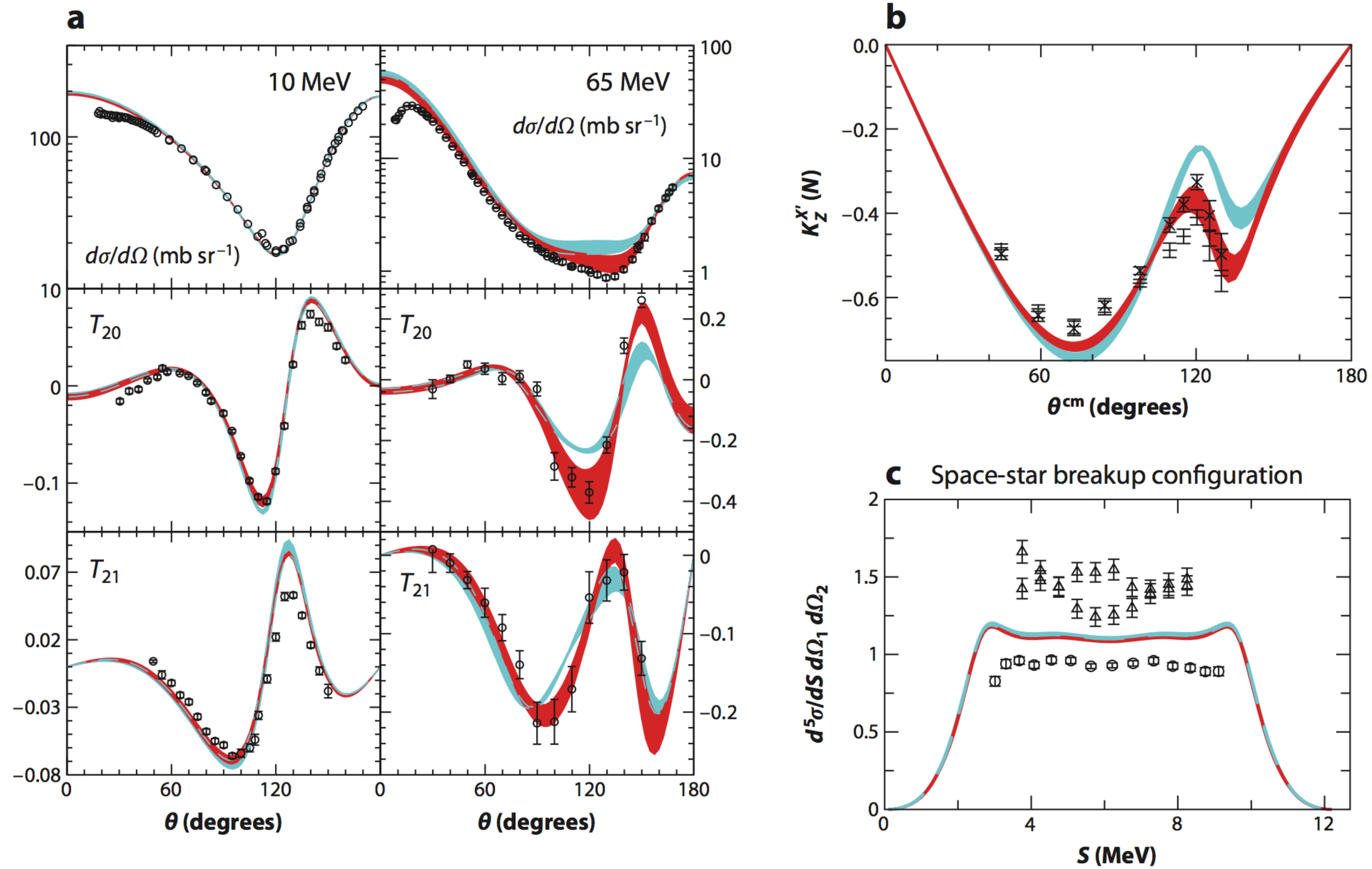


Figure 6

(*a*) Differential cross section and tensor analyzing powers T_{20} and T_{21} for elastic nucleon-deuteron (*Nd*) scattering at $E_{\rm lab}^{N} = 10$ and 65 MeV. (*b*) The nucleon-to-nucleon polarization transfer coefficient in elastic *Nd* scattering at $E_{\rm lab}^{N} = 22.7$ MeV [the proton-deuteron (*pd*) data are from Reference 72]. (*c*) *Nd* breakup cross section in the space-star configuration (upper sets of data, *nd*; lower sets of data, *pd*). The blue and red shaded bands show the results from the chiral effective field theory at next-to-leading order and next-to-next-to-leading order, in order. The precise kinematical description and references to data can be found in Reference 70.

figure from E. Epelbaum and U.-G. Meißner, experiment in a and b is Coulomb corrected p-d

Importance of 3N forces for light nuclei

Quantum Monte-Carlo calculations Pieper et al. (2010).

based on phenomenological potentials: NN: Argonne v_{18} + 3N: Illinois-7

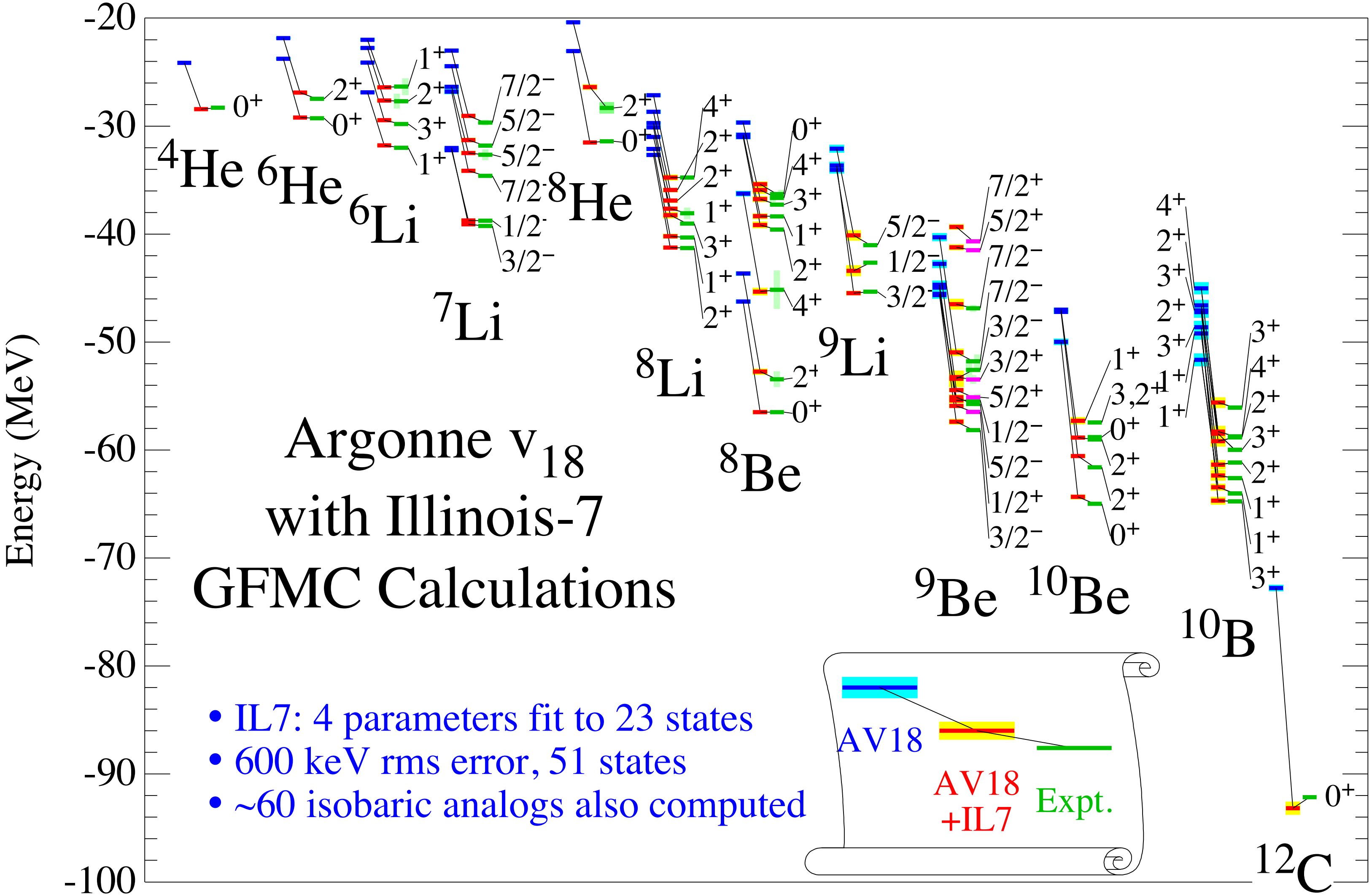


figure from R. Wiringa

Importance of 3N forces for spectra

spectra too compressed without 3N forces, ^{10}B 1^+ vs. 3^+

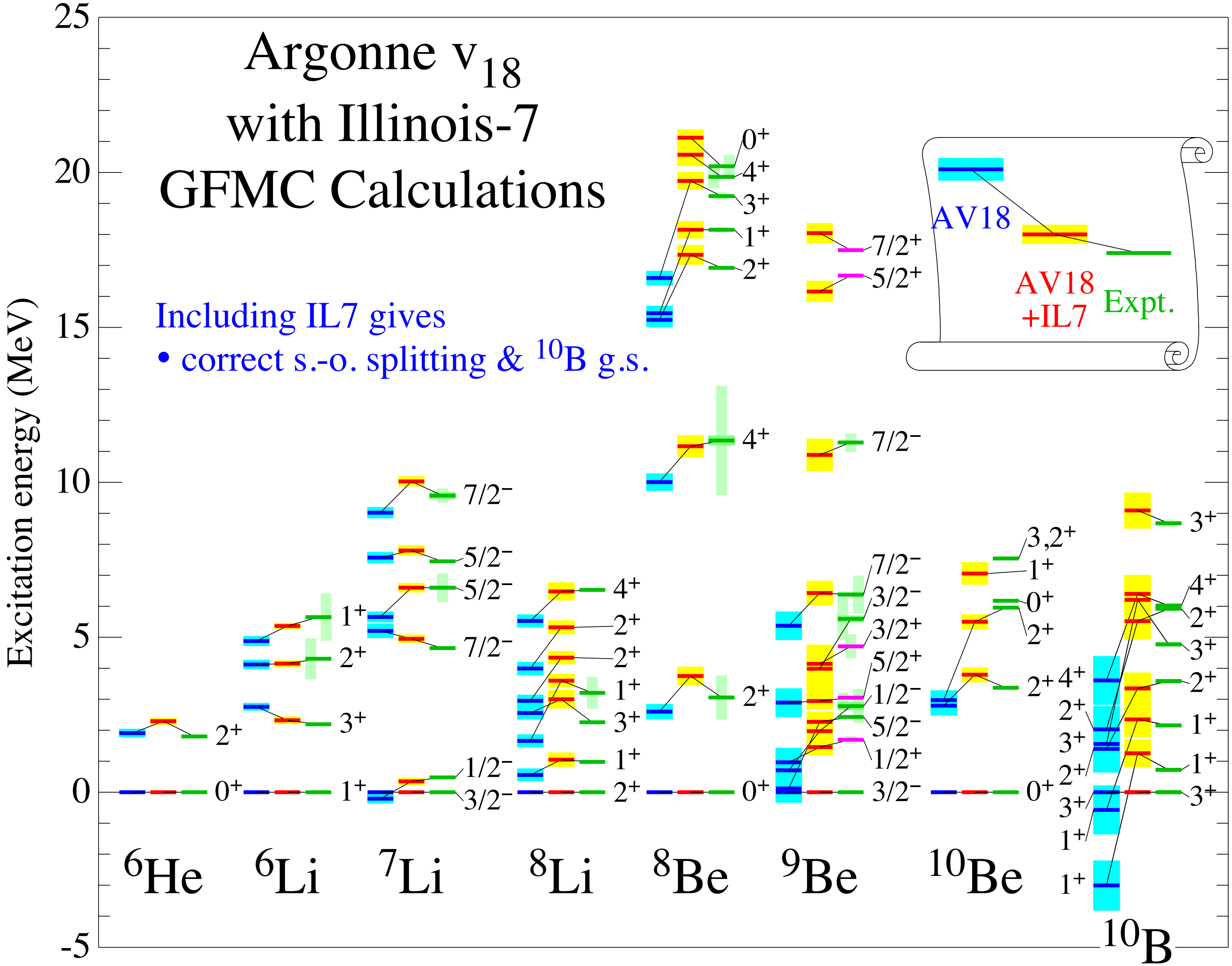
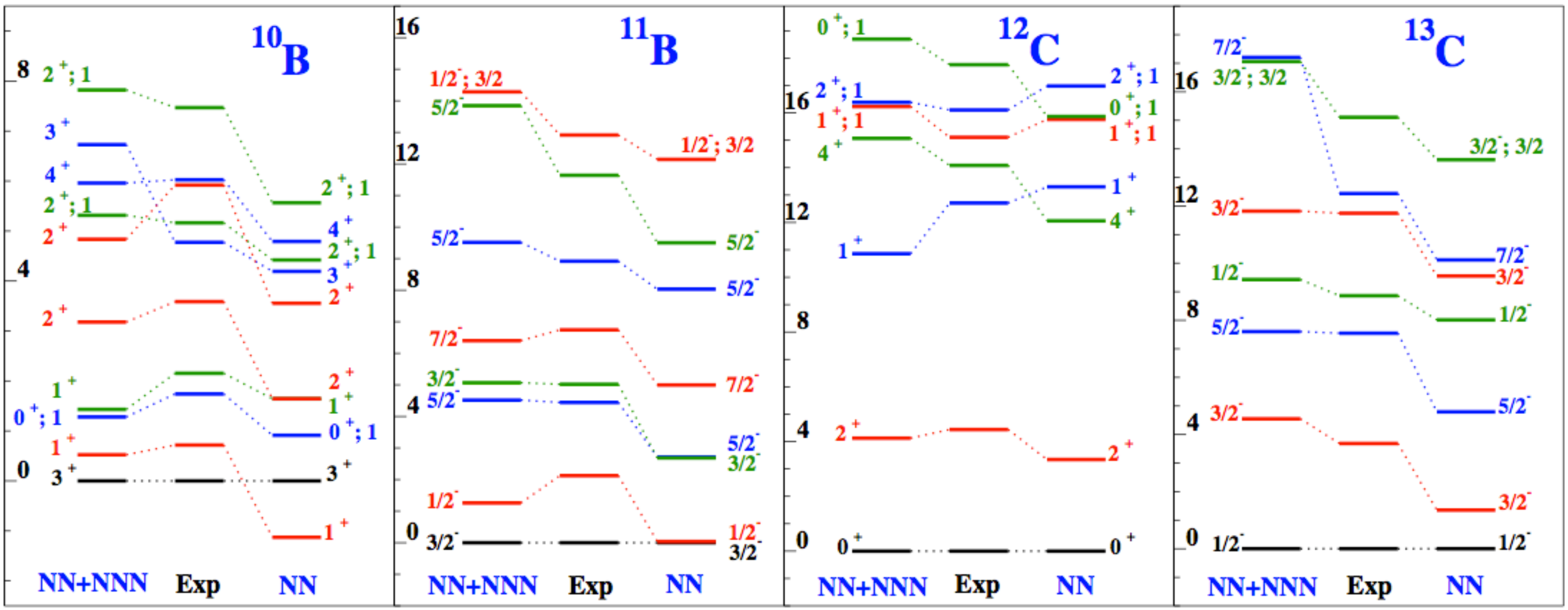


figure from R. Wiringa

Importance of 3N forces for spectra of p-shell nuclei

large-basis Hamiltonian diagonalization
using "No-Core Shell Model" Navratil et al., Phys. Rev. Lett. **99**, 042501 (2007).

NN interactions at N^3LO and 3N interactions at N^2LO



agreement supports chiral EFT interactions

3N forces: ^{10}B 1^+ vs. 3^+, spin-orbit splitting $p_{3/2}$-$p_{1/2}$ in ^{13}C

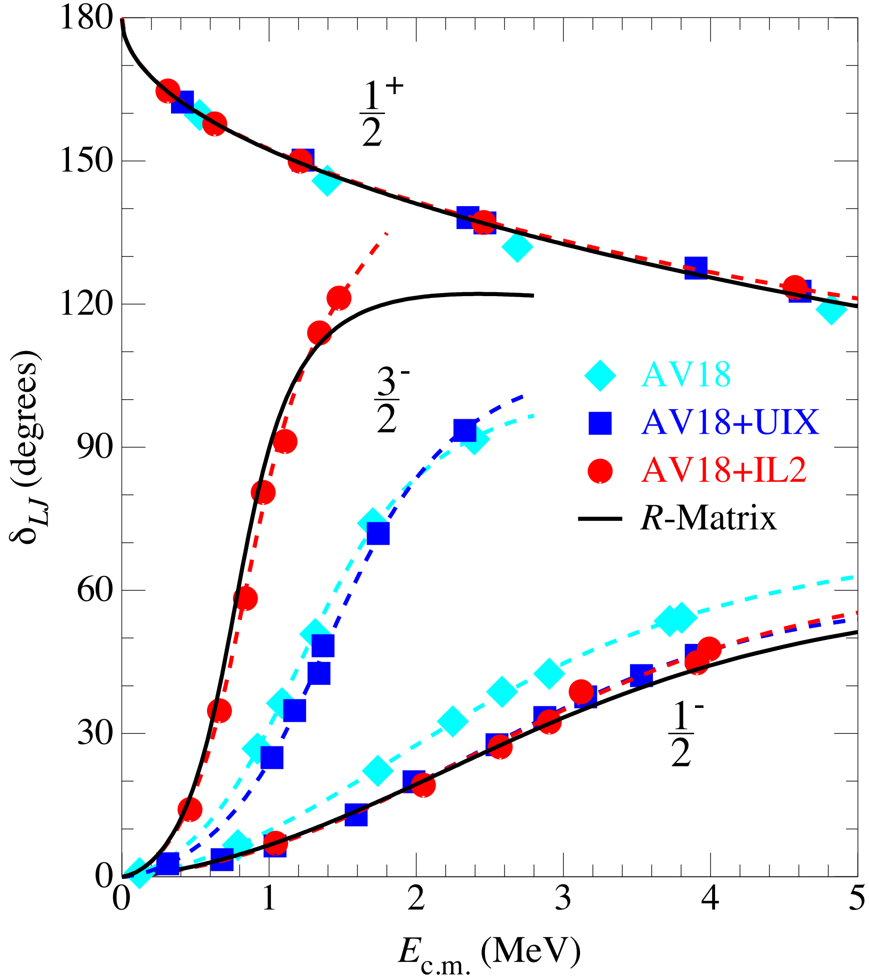
^{5}He AS n+^{4}He SCATTERING

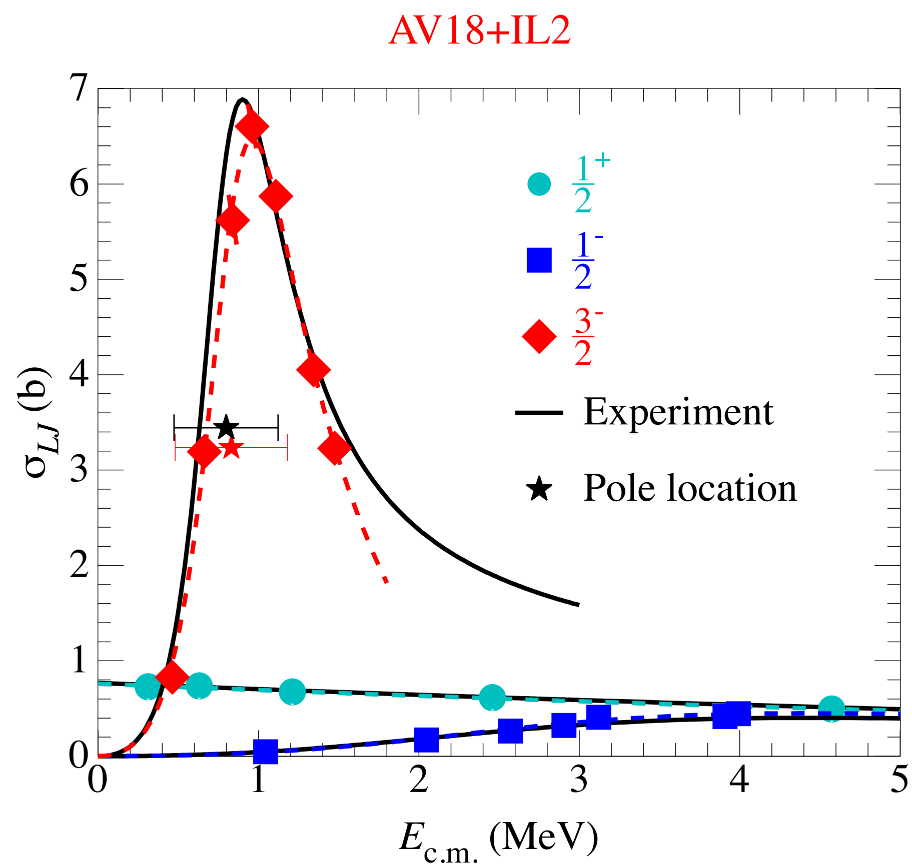
Black curves: Hale phase shifts from R-matrix analysis up to $J = \frac{9}{2}$ of data

AV18 with no V_{ijk} underbinds ^{5}He(3/2$^-$) & overbinds ^{5}He(1/2$^-$)

AV18+UIX improves ^{5}He(1/2$^-$) but still too small spin-orbit splitting

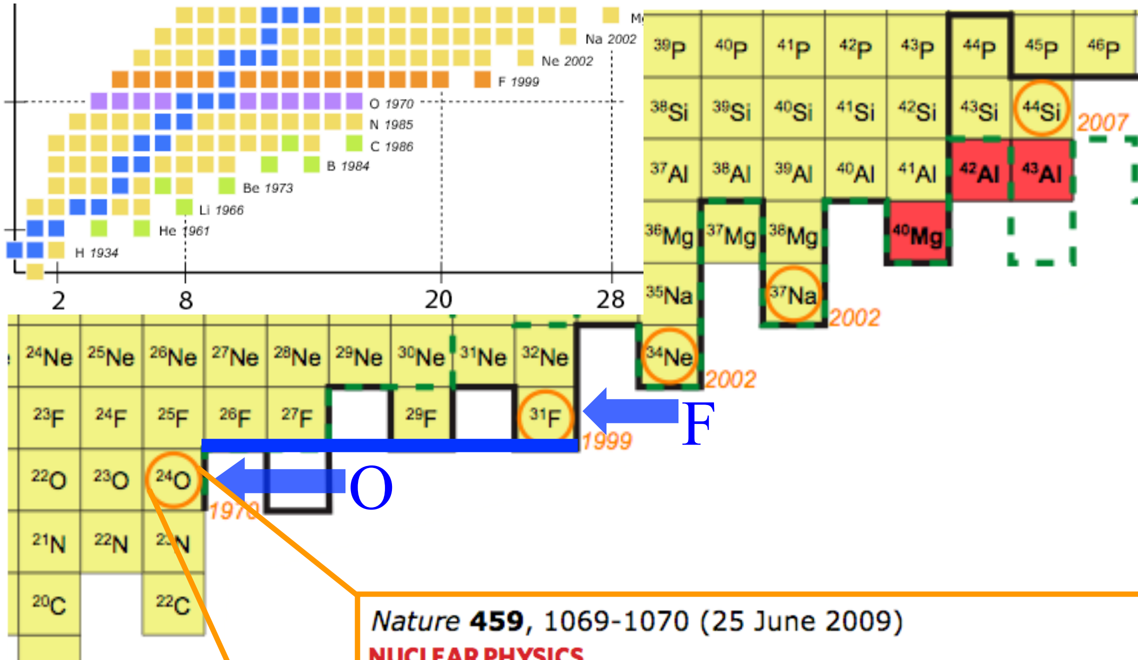
AV18+IL2 reproduces locations and widths of both P-wave resonances





Nollett, Pieper, Wiringa, Carlson, & Hale, PRL **99**, 022502 (2007) figure from R. Wiringa

The oxygen anomaly



Nature **459**, 1069-1070 (25 June 2009)

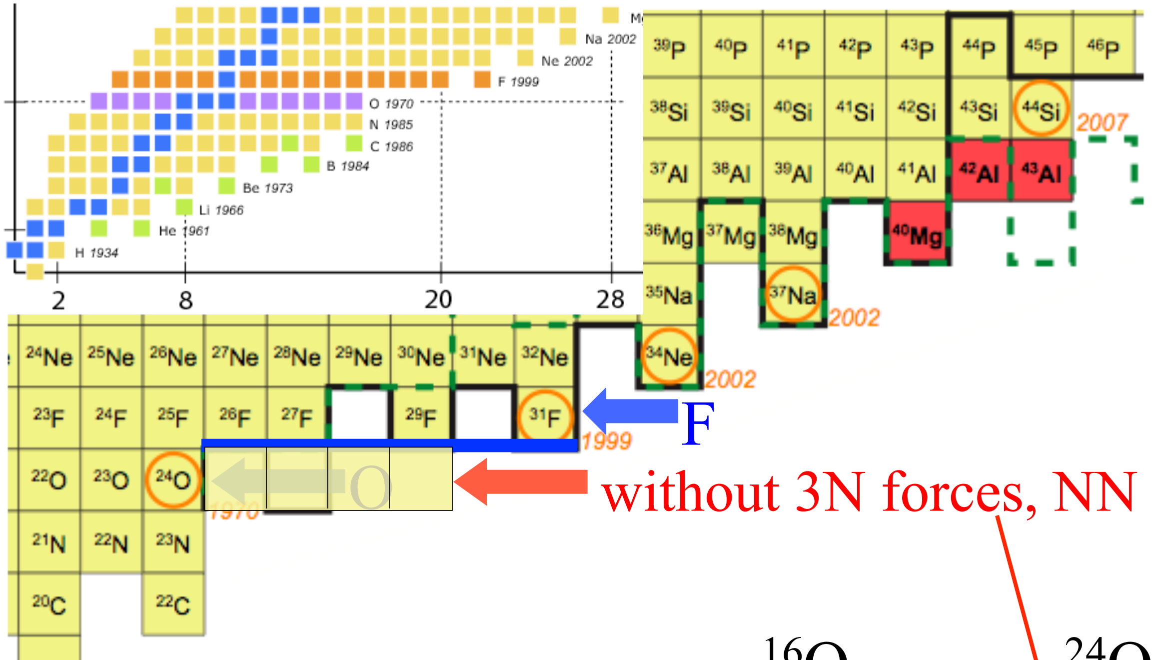
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

Robert V. F. Janssens

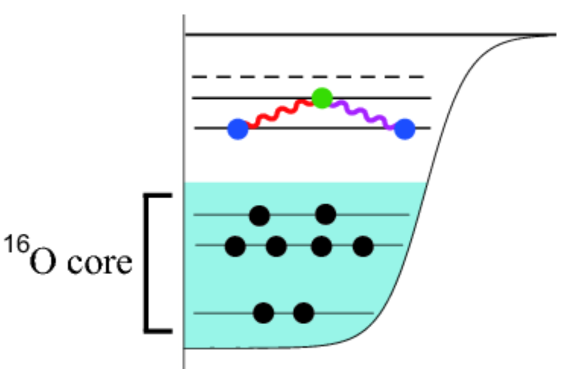
Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.

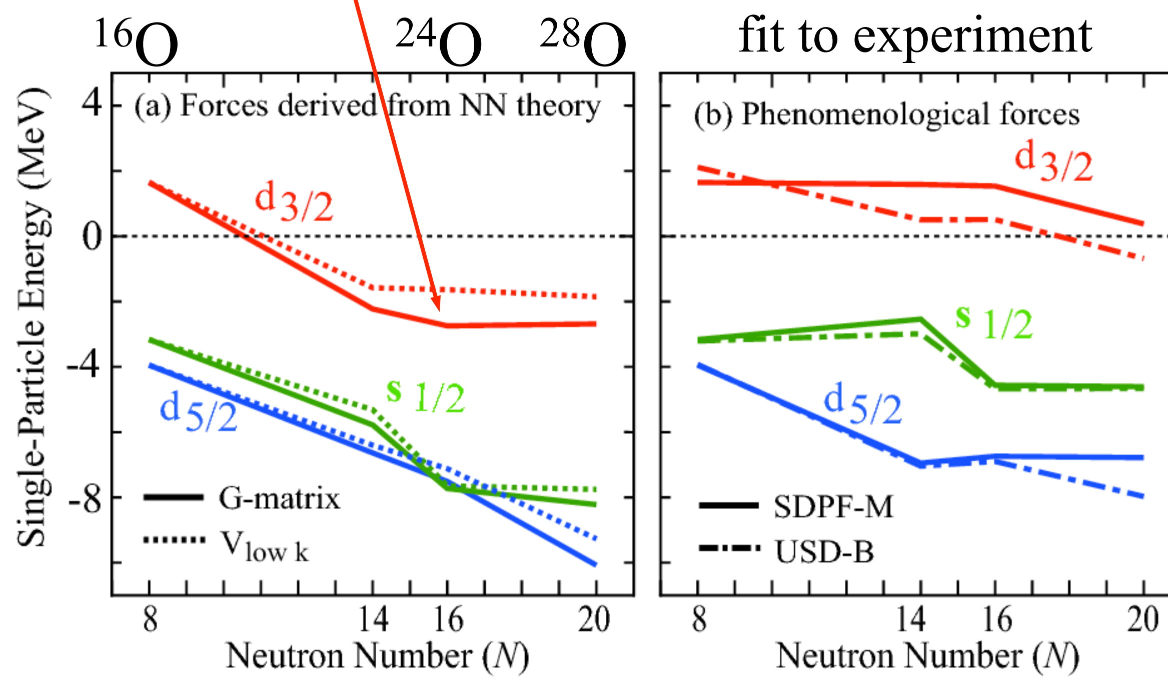
The oxygen anomaly - not reproduced without 3N forces



without 3N forces, NN interactions too attractive

many-body theory based on two-nucleon forces:
drip-line incorrect at ^{28}O

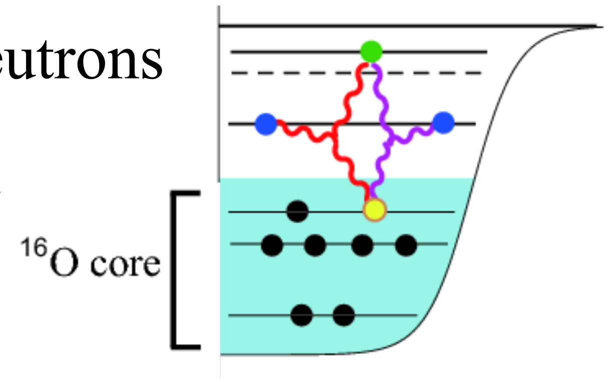




The shell model - impact of 3N forces

include 'normal-ordered' 2-body part of 3N forces (enhanced by core A)

leads to repulsive interactions between valence neutrons



contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{valence}/N_{core}$

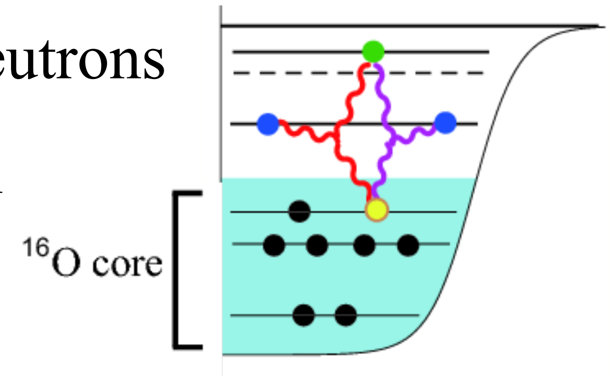
Friman, AS (2011)

residual 3N amplified in most neutron-rich nuclei

Oxygen isotopes - impact of 3N forces

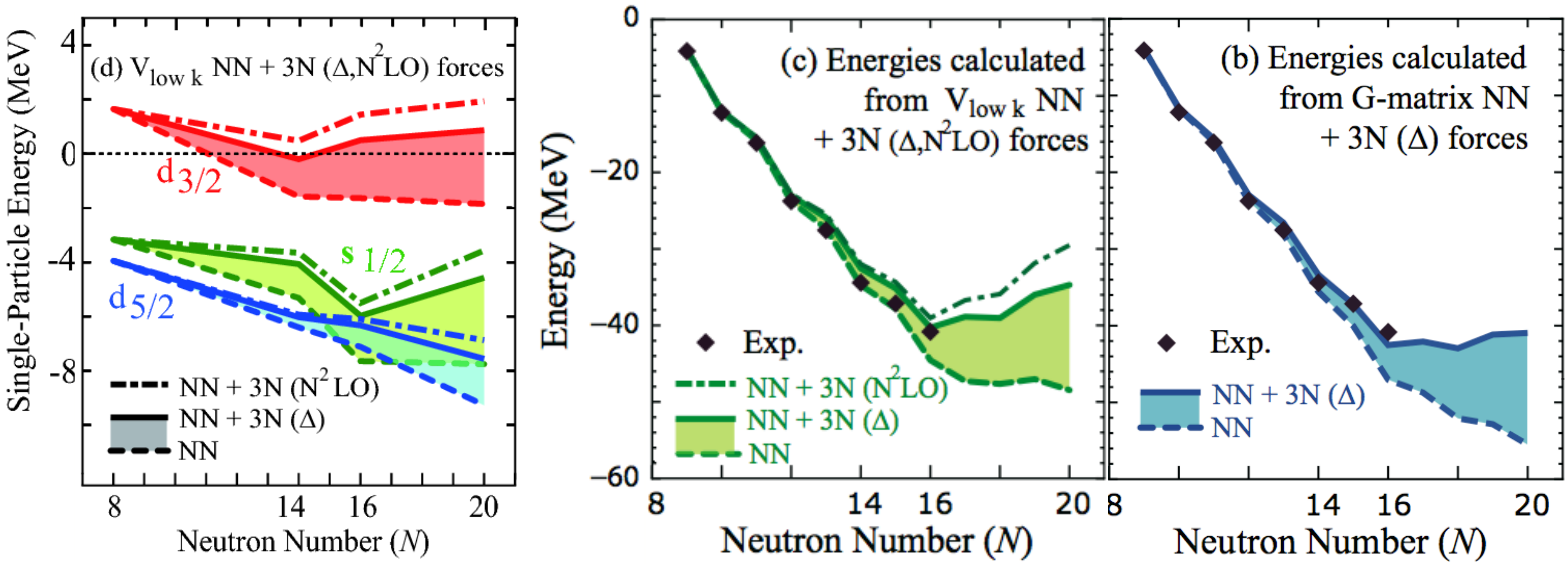
include ‘normal-ordered’ 2-body part of 3N forces (enhanced by core A)

leads to repulsive interactions between valence neutrons



contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{valence}/N_{core}$
Friman, AS (2011)

$d_{3/2}$ orbital remains unbound from ^{16}O to ^{28}O



microscopic explanation of the oxygen anomaly Otsuka et al. (2010)

New ab-initio methods extend reach

impact of 3N forces confirmed in large-space calculations:

Coupled Cluster theory with phenomenological 3N forces Hagen et al. (2012)

In-Medium Similarity RG based on chiral NN+3N Hergert et al. (2013)

Green's function methods based on chiral NN+3N Cipollone et al. (2013)