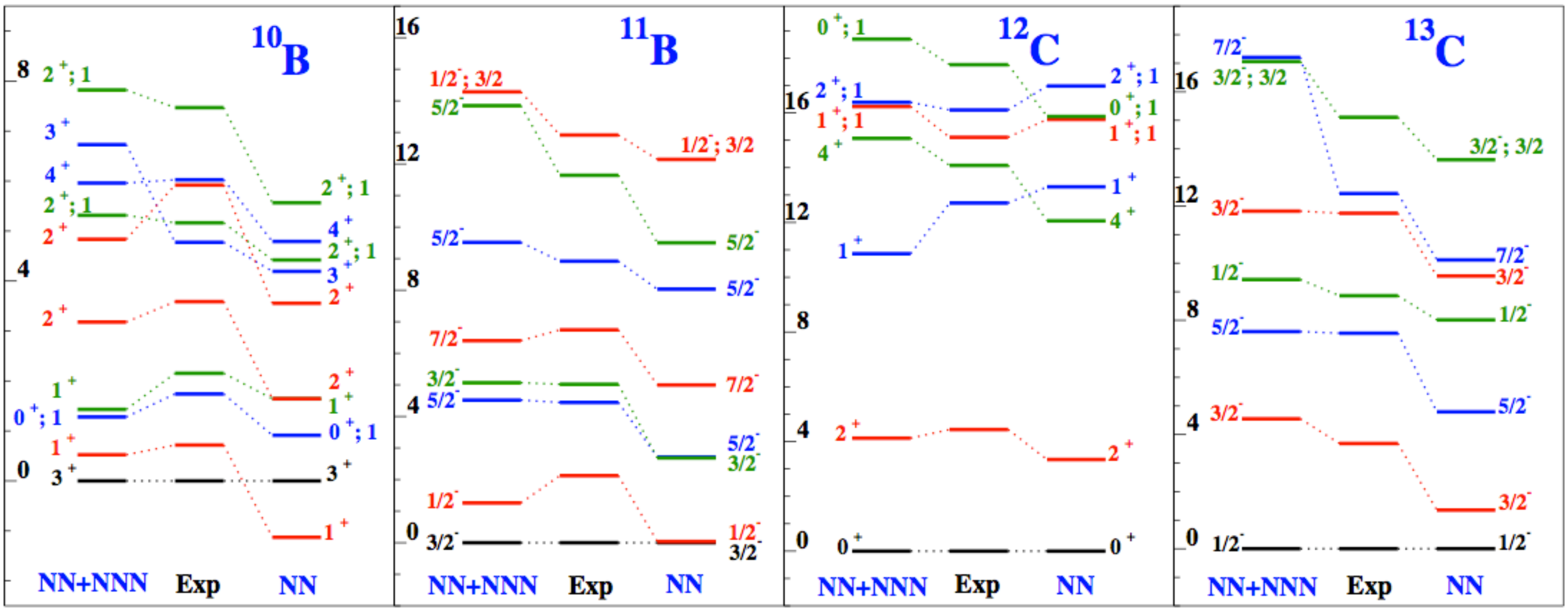
Importance of 3N forces for spectra of p-shell nuclei

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

c_D, c_E fit to triton binding energy and beta-decay half-life

Gazit, Quaglioni, Navratil (2009)

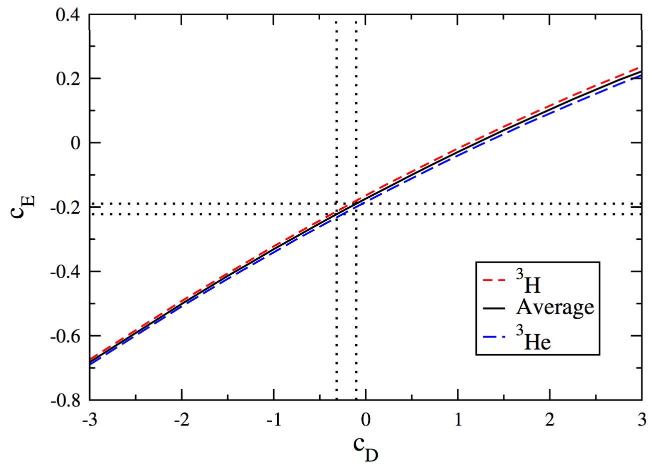


FIG. 2 (color online). c_D-c_E trajectories fitted to reproduce ^{3}H and ^{3}He experimental BE. The dotted lines show the region for which $|1 - \langle E_1^A \rangle_{\text{theor}} / \langle E_1^A \rangle_{\text{emp}}|$ is within the $\pm 0.54\%$ error bars.

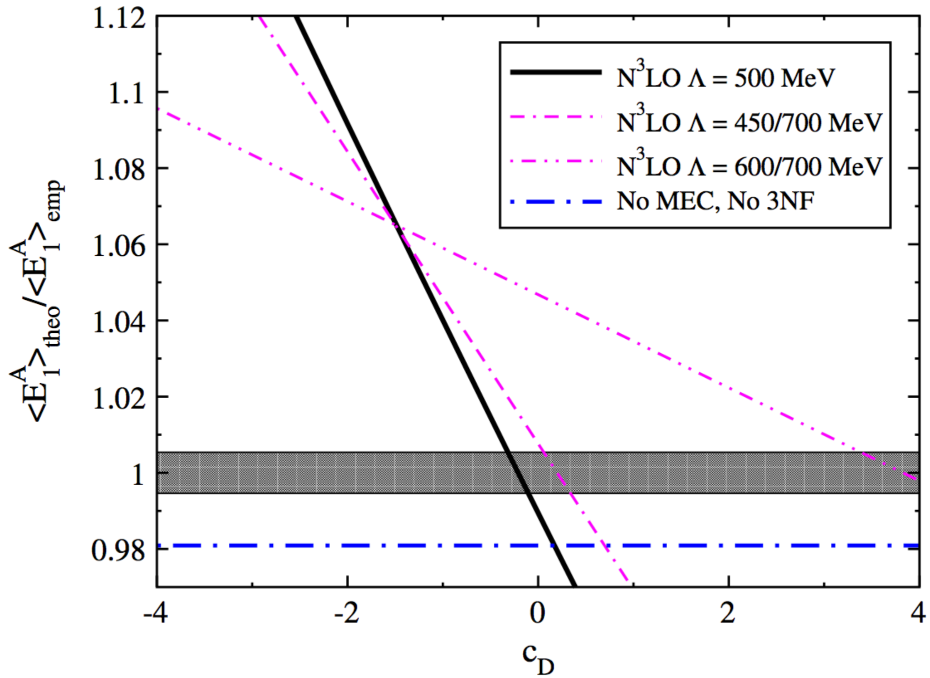
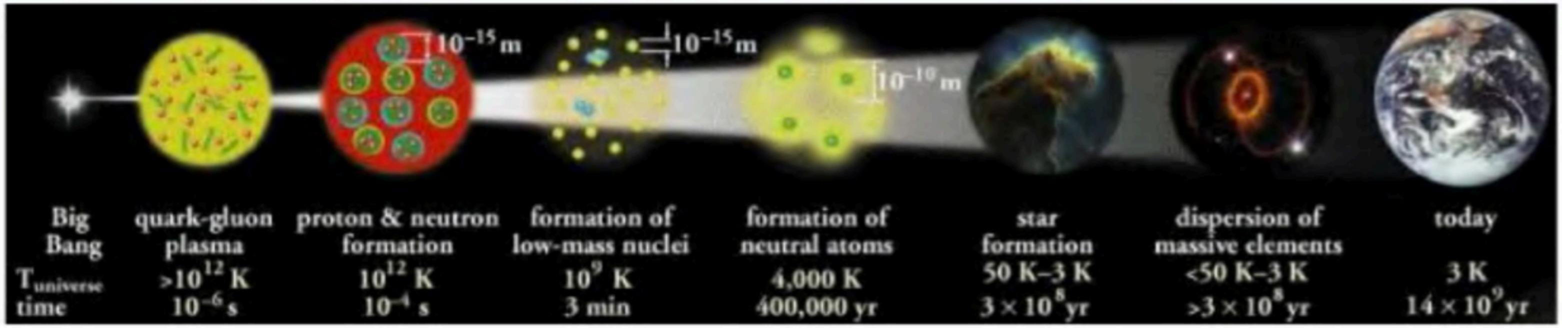


FIG. 21 (color online). The ratio $\langle E_1^A \rangle_{\text{theo}} / \langle E_1^A \rangle_{\text{emp}}$ that determines the ^{3}H half-life as a function of the low-energy coupling c_D, which relates the leading two-body axial currents and 3NFs (see Fig. 20). The empirical range is given by the horizontal band. Results are shown based on different N^{3}LO NN potentials and including N^{2}LO 3NFs and consistent two-body axial currents. For comparison, the result without 3NFs and without two-body currents (no MEC, no 3NF) is given. For details, see Gazit, Quaglioni, and Navrátil (2009).

(d) Why Bother?: Big-Bang Nucleo-Synthesis and $np \to d\gamma$ Chen/Savage 1999, Rupak 2000

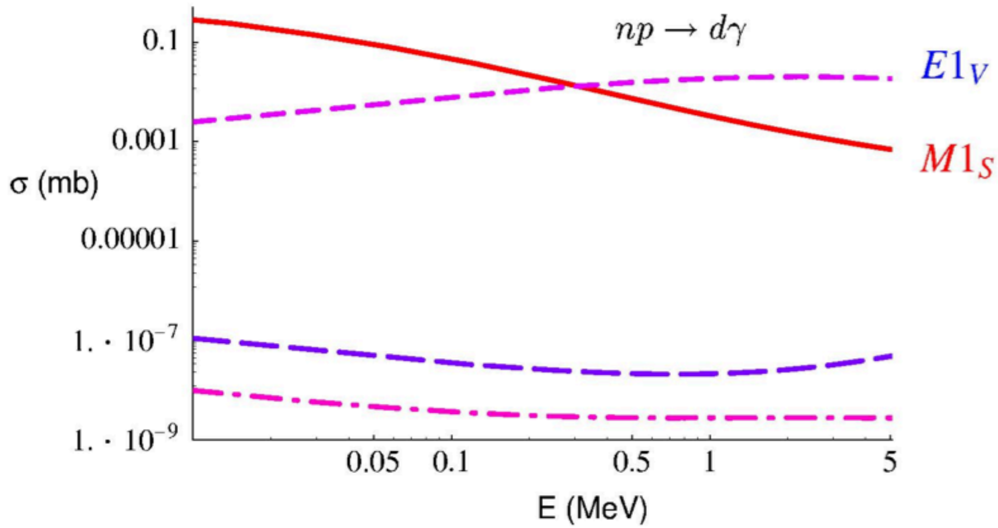


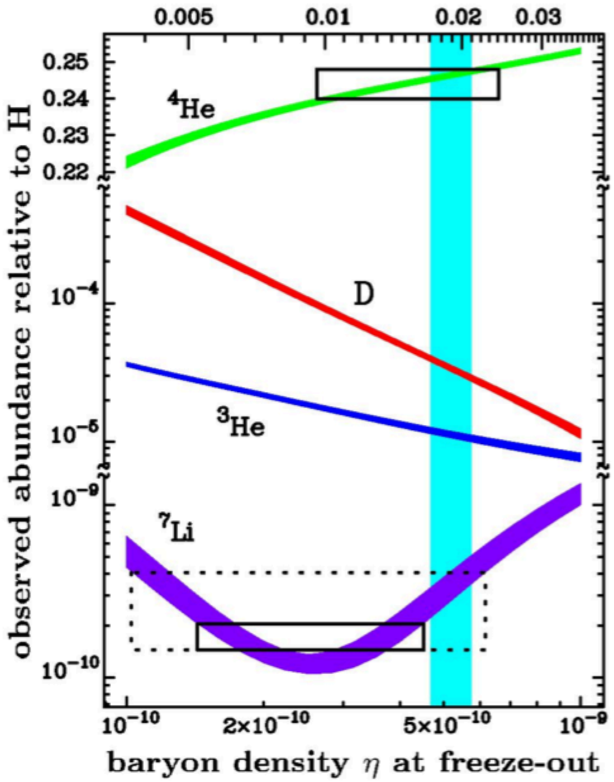
$E_{\text{typ}} \approx 0.02 - 0.2$ MeV, light-element abundances sensitive to baryon density.

Accurate theoretical determination necessary: error-estimate!

$np \to d\gamma$ biggest uncertainty, but "impossible" to measure.

EFT($\not\pi$) to N^{4}LO in closed form: accuracy $\lesssim 1\%$. Rupak 1999

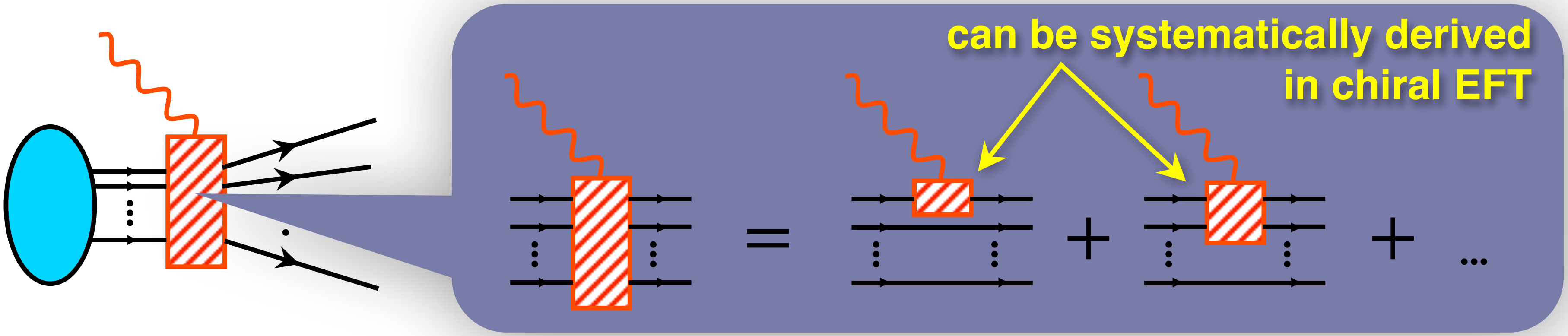




slide from H. Griesshammer

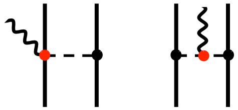
Electromagnetic currents

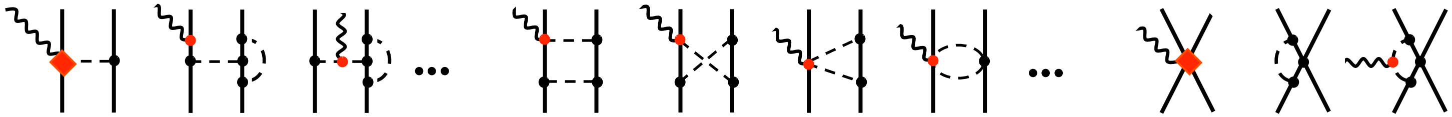
(one-photon exchange approximation)



for Compton scattering see talks by Harald Grießhammer and Winfried Leidemann

Electromagnetic exchange currents

Order eQ^{-1} :  ← well known since decades Chemtob, Rho, Friar, Riska, Adam, …

Order eQ : 

- **First ChPT calculations**

  Park, Min, Rho '95; Park, Kubodera, Min, Rho; Song, Lazauskas, Park, Min, ...

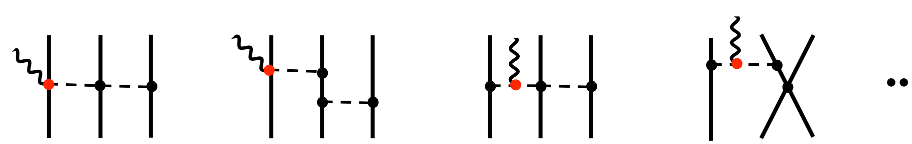
  Application to $np \to d\gamma$ at threshold: $\sigma_{1N} = 306.6 \text{ mb} \quad \longrightarrow \quad \sigma_{1N+2N} = 334 \pm 3 \text{ mb}$

  to be compared with $\sigma_{\exp} = 334.2 \pm 0.5 \text{ mb}$

- **More recent calculations, general kinematics** $\omega \sim M_\pi^2/m, \quad |\vec{q}| \sim M_\pi$

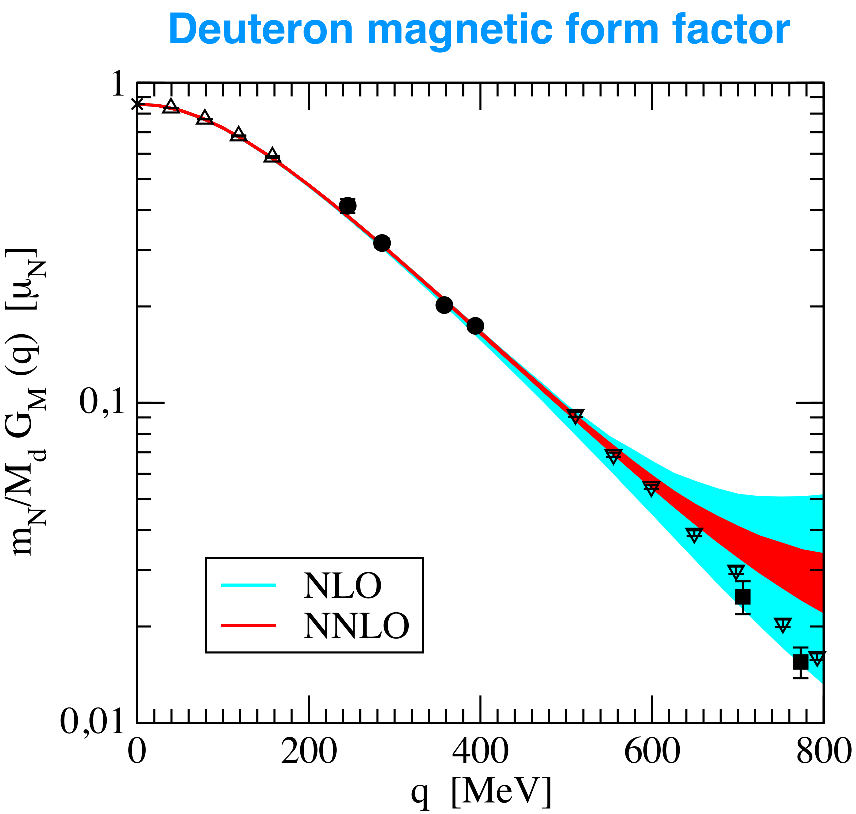
  TOPT: Pastore, Schiavilla, Girlanda, Viviani; UT: Kölling, Krebs, EE, Meißner

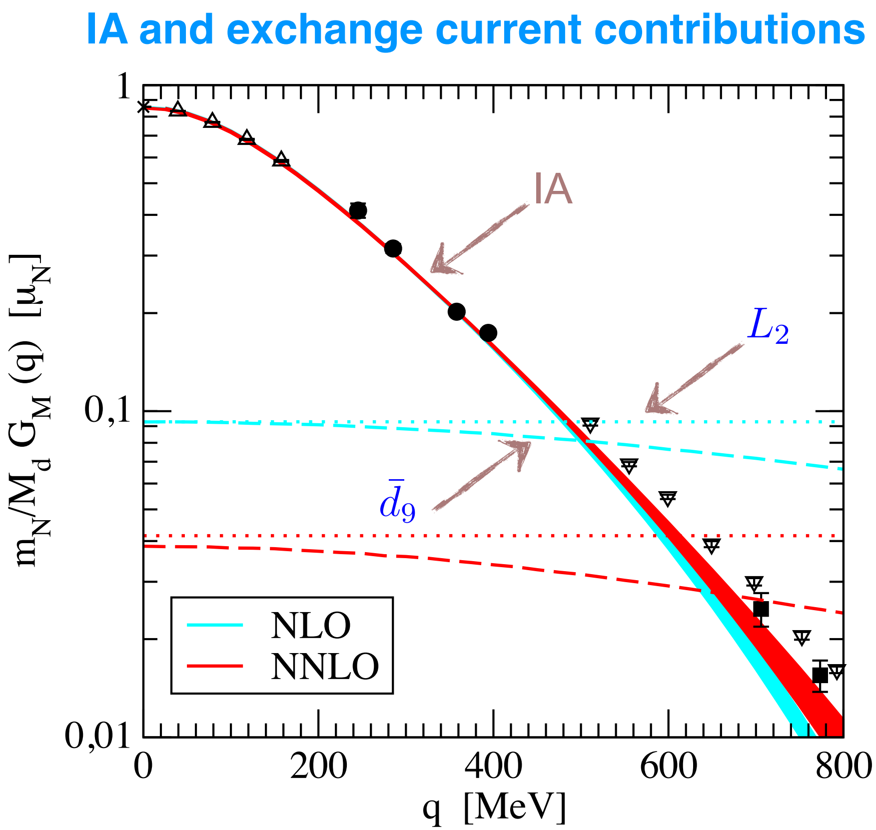
Notice: 3N diagrams do not yield currents at this order...



Em currents and the deuteron form factors

Kölling, EE, Phillips ’12





- 1N form factors from Belushkin, Hammer, Meißner ’07
- $\bar{d}_9,\ L_2$ fitted to the deuteron magnetic moment and FF for q < 400 MeV:

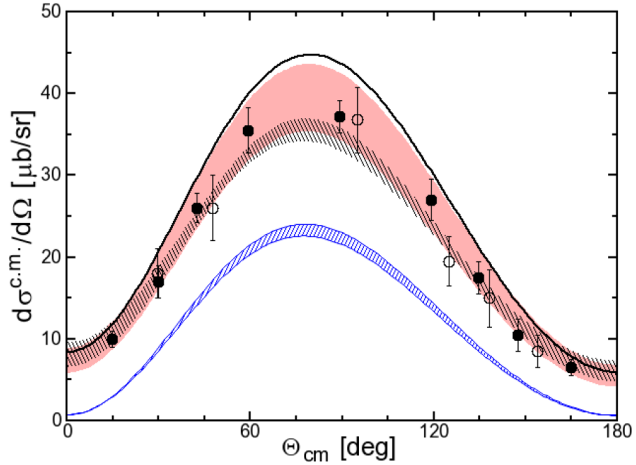
$\bar{d}_9 = -0.01 \ldots 0.01\ \text{GeV}^{-2}$ $\quad L_2 = 0.28 \ldots 0.48\ \text{GeV}^{-4}$ (NNLO WF)

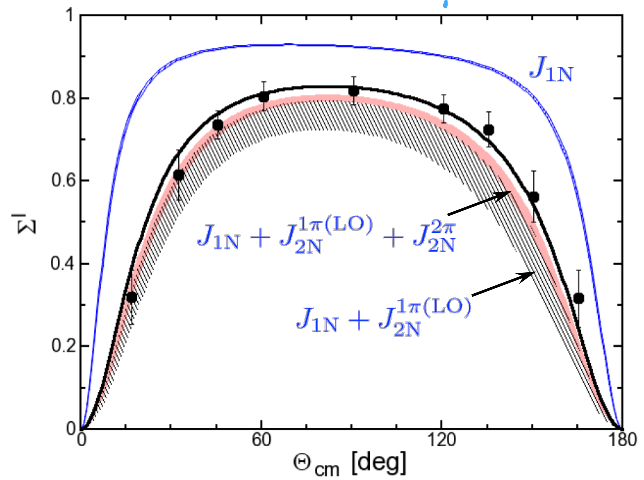
Pion photoproduction: $\bar{d}_9 = -0.06\ \text{GeV}^{-2}$ Gasparyan, Lutz ’10

Deuteron photodisintegration

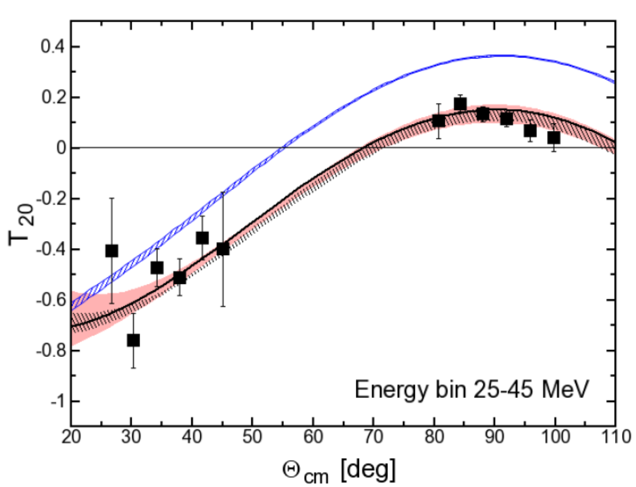
Rozpedzik, Golak, Kölling, EE, Skibinski, Witala, Nogga ’11

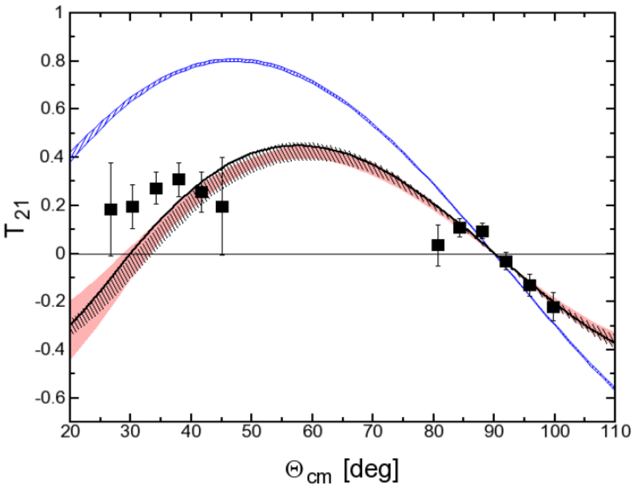
Cross section and photon analyzing power at E_γ =30 MeV





Deuteron tensor analyzing powers



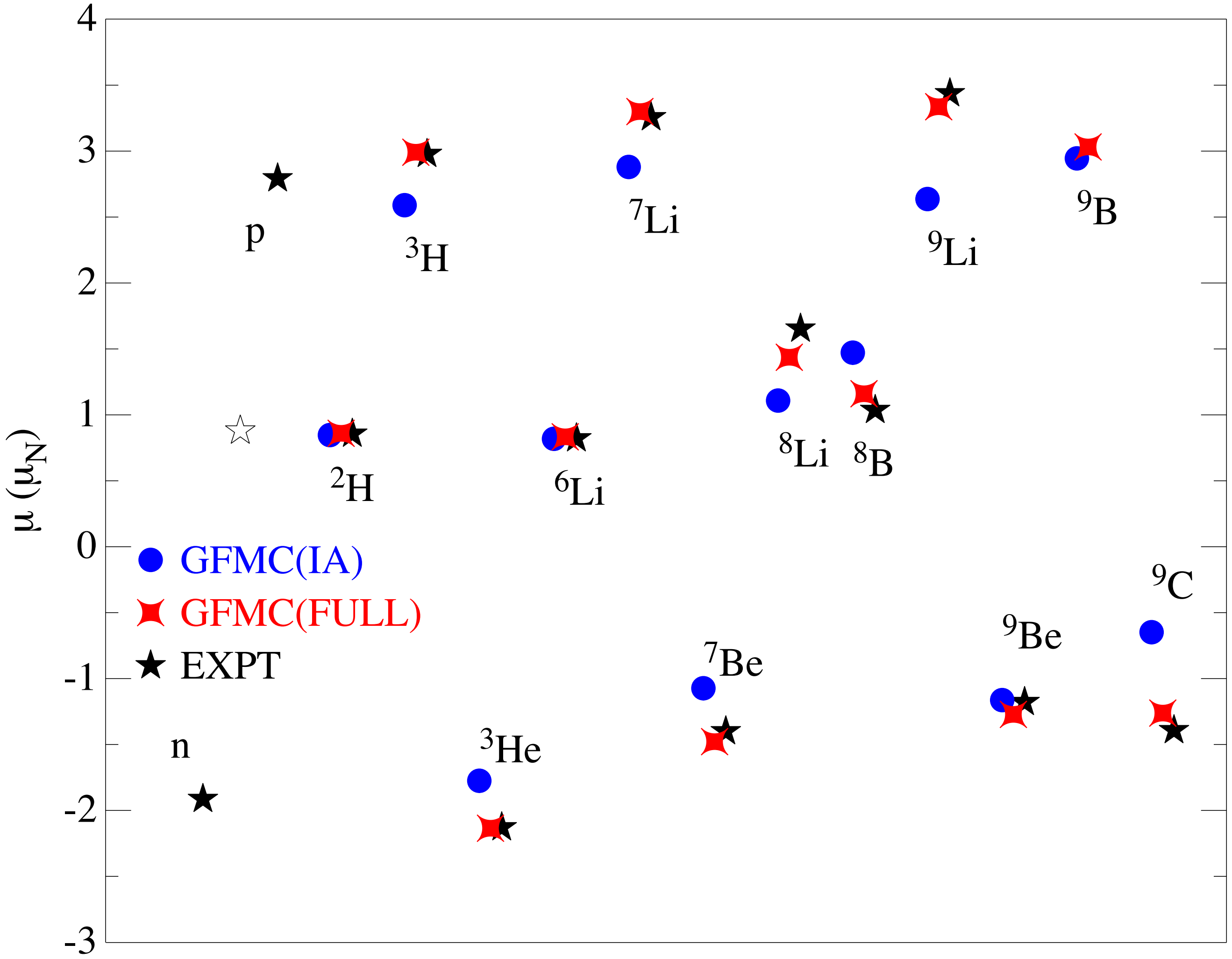


large sensitivity to MEC; short-range & 1π-exchange terms still to be included

Magnetic moments w/ χEFT exchange currents

Hybrid calculations using AV18+IL7 wave functions and χEFT exchange currents developed in:

Pastore, Schiavilla, & Goity, PRC **78**, 064002 (2008) ; Pastore, *et al.*, PRC **80**, 034004 (2009)

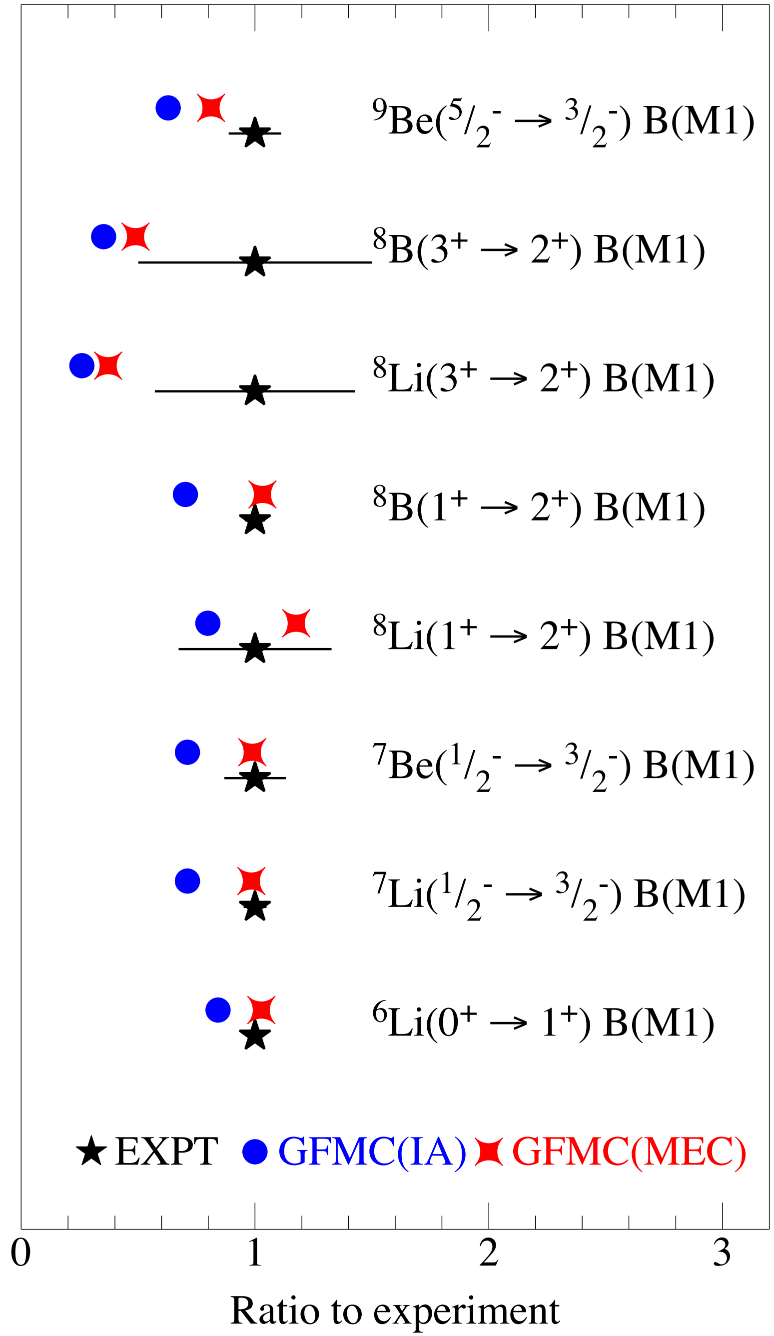


slide from R. Wiringa

$M1$ TRANSITIONS W/ χEFT

- dominant contribution is from OPE
- five LECs at N3LO
- d_2^V and d_1^V are fixed assuming Δ resonance saturation
- d^S and c^S are fit to experimental μ_d and $\mu_S(^3\text{H}/^3\text{He})$
- c^V is fit to experimental $\mu_V(^3\text{H}/^3\text{He})$
- $\Lambda = 600$ MeV

Pastore, Pieper, Schiavilla & Wiringa (in preparation)



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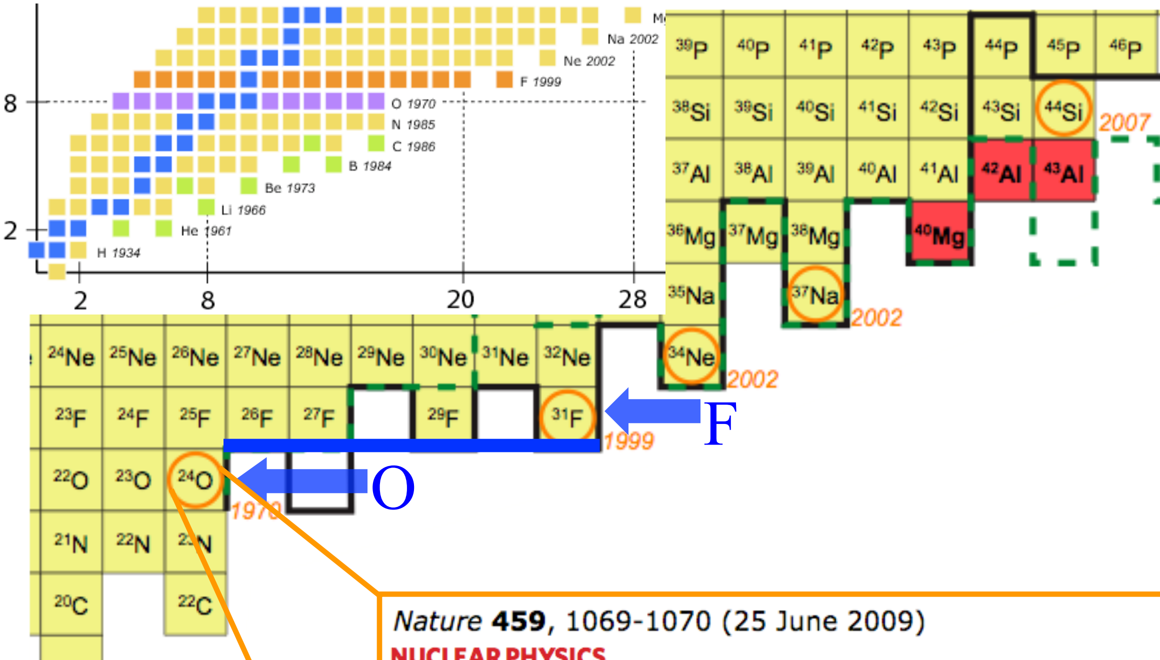
The oxygen anomaly



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

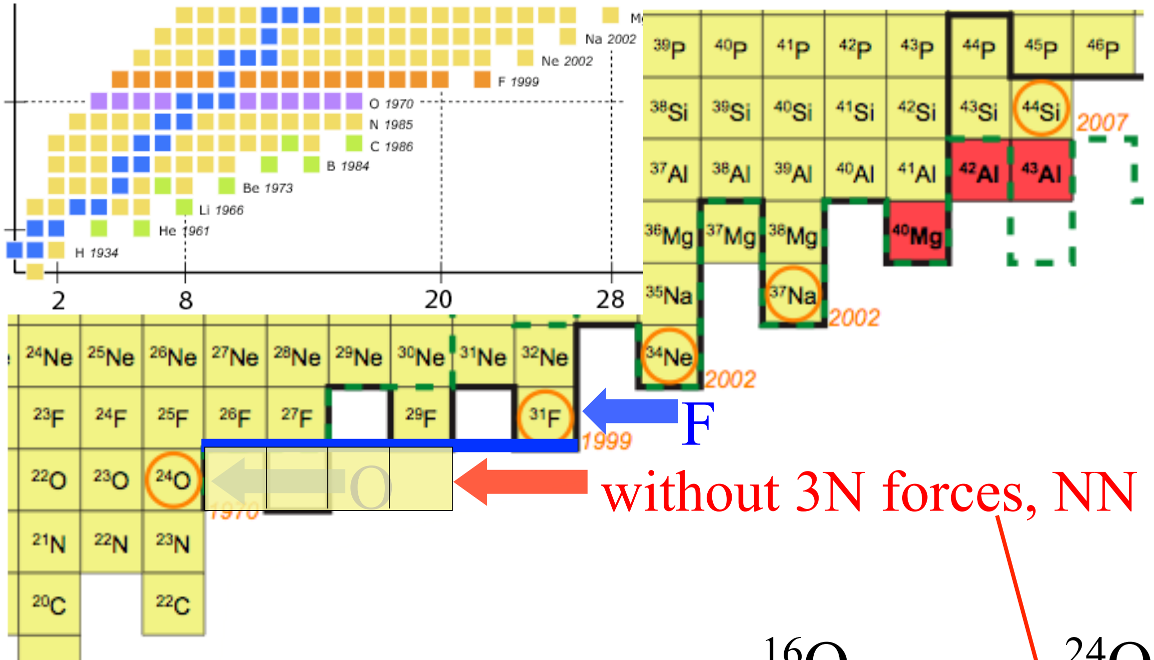
NUCLEAR PHYSICS

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.

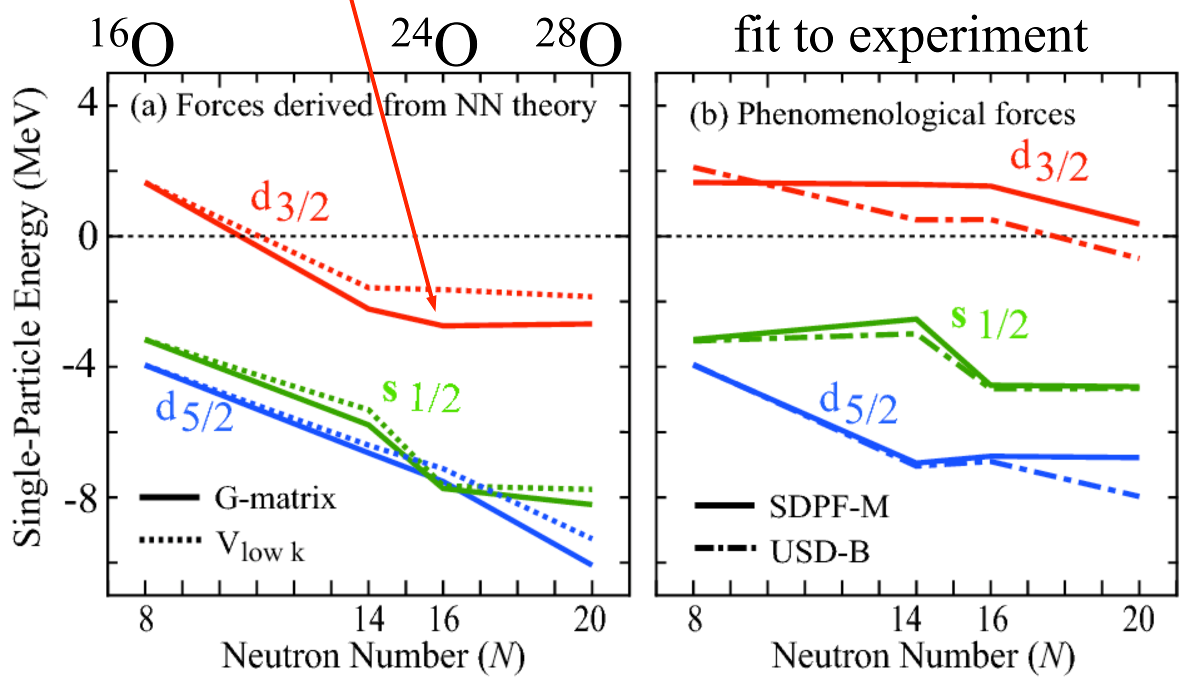
The oxygen anomaly - not reproduced without 3N forces

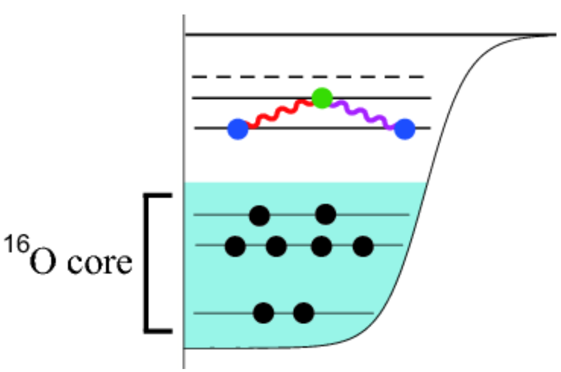


without 3N forces, NN interactions too attractive

many-body theory based on two-nucleon forces:

drip-line incorrect at ^{28}O

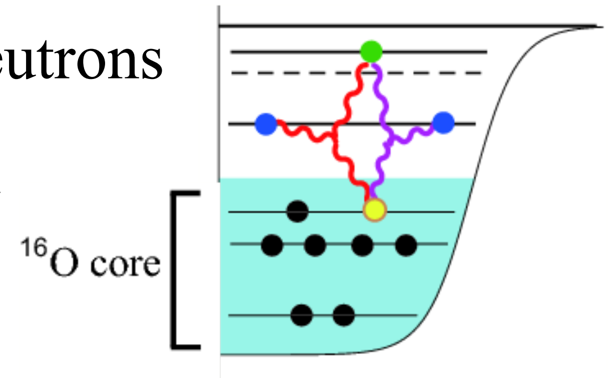




The shell model - impact of 3N forces

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

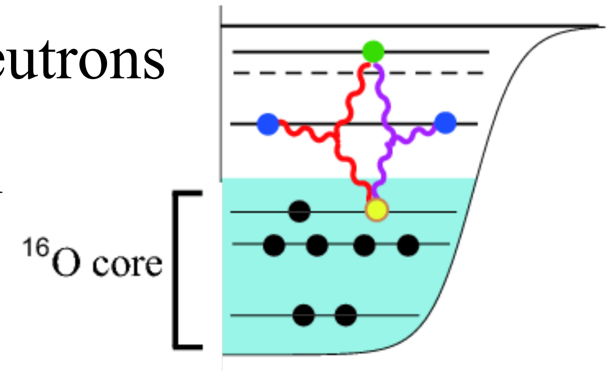
Oxygen isotopes - impact of 3N forces

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

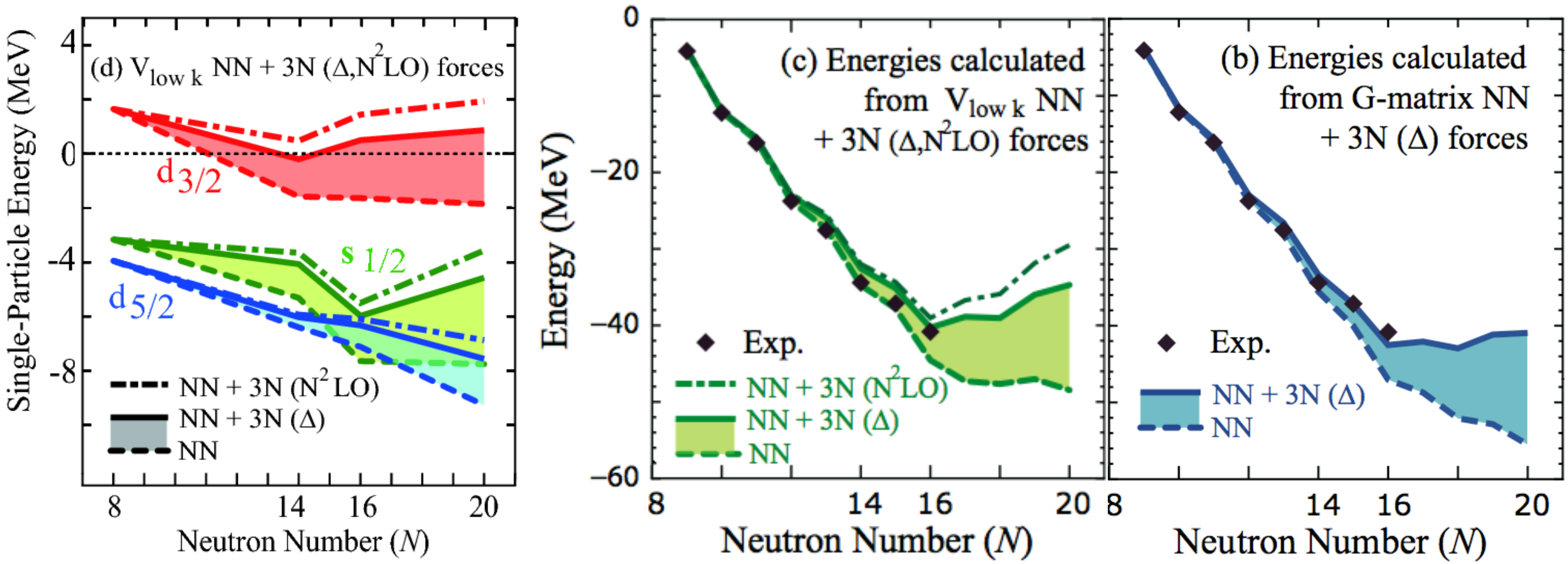
leads to repulsive interactions between valence neutrons

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)