

Ab-Initio Description of p-Shell Hypernuclei

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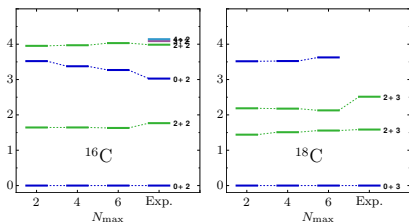
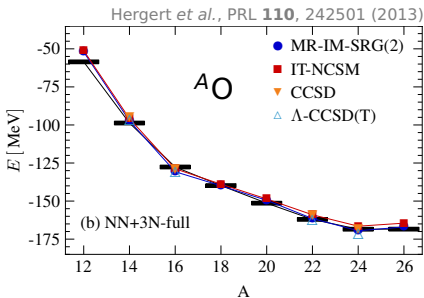
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UNIVERSITÄT
DARMSTADT

Motivation

Status of *ab initio* nuclear structure

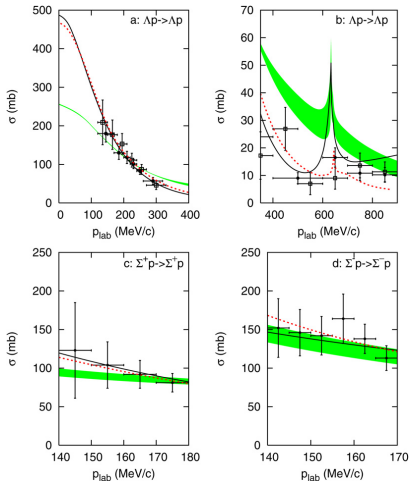
- Accurate NN+3N Hamiltonians from chiral EFT
- Unitary transformations for converged results
- Many-body methods with controlled uncertainties
- Access to binding energies, spectra, radii, transitions...

Extension to hypernuclei?



Roth *et al.*, Few-Body Syst. **55**, 659 (2014)

Hyperon-Nucleon Interaction

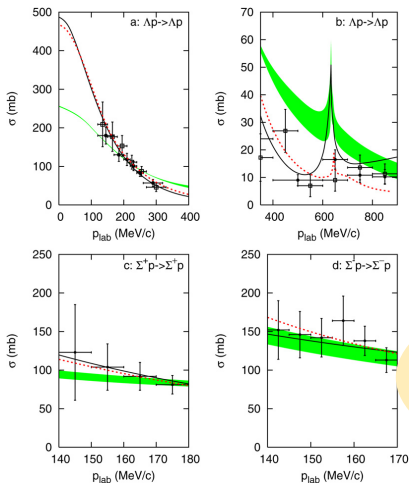


- Weaker than NN (~ 1 MeV/N)
- No YN bound state
- $\Lambda N \leftrightarrow \Sigma N$ conversion
- Spin singlet—triplet transition

Meson-exchange models and chiral EFT interactions available

Polinder *et al.*, Nucl. Phys. A **779**, 244 (2006)

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YN scattering experiments are challenging

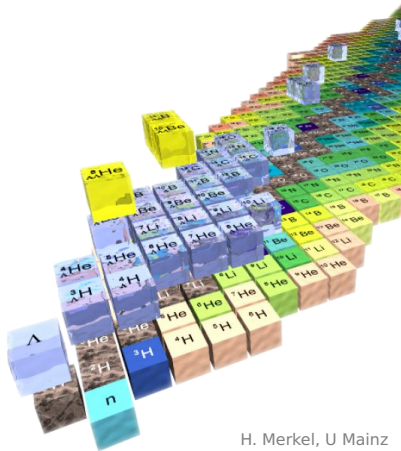
- ⇒ Few data points
- ⇒ Large error bars

Polinder *et al.*, Nucl. Phys. A **779**, 244 (2006)

Necessary Developments

Extend No-Core Shell Model to hypernuclei

- Account for different particle masses
- Include fully active Λ and Σ
⇒ Coupled-channel problem
- Adapt unitary transformation framework



H. Merkel, U Mainz

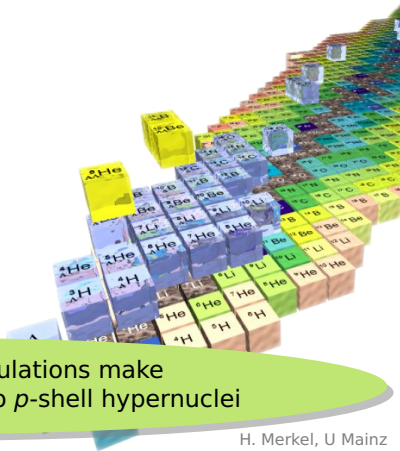
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Ab-initio many-body calculations make connection from YN interactions to p -shell hypernuclei

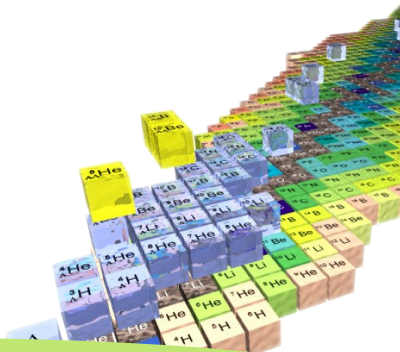
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Ab-initio many-body calculations make connection from YN interactions to p -shell hypernuclei

H. Merkel, U Mainz

“→” prediction of observables
“←” constraints on YN interactions

$$\mathbf{H} = \Delta\mathbf{M} + \mathbf{T}_{\text{int}} + \mathbf{V}_{\text{NN}} + \mathbf{V}_{\text{3N}} + \mathbf{V}_{\text{YN}}$$

■ NN: chiral N^3LO

Entem & Machleidt

Phys. Rev. C **68**, 041001(R) (2003)

$$\Lambda_{\text{NN}} = 500 \text{ MeV}$$

■ 3N: chiral N^2LO

Navrátil

Few-Body Syst. **41**, 117 (2007)

$$\Lambda_{\text{3N}} = 500 \text{ MeV}$$

■ YN: chiral LO

Polinder, Haidenbauer & Meißner

Nucl. Phys. A **779**, 244 (2006)

$$\Lambda_{\text{YN}} = 600 \text{ MeV}, 700 \text{ MeV}$$

OR Jülich'04

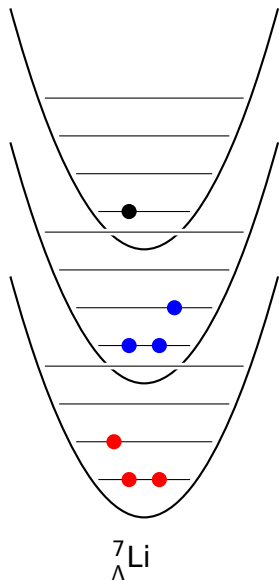
Haidenbauer & Meißner

Phys. Rev. C **72**, 044005 (2005)

meson-exchange

NN+3N yields quantitative description of p -shell nuclei

Importance-Truncated No-Core Shell Model



- A-body Slater determinants from HO states

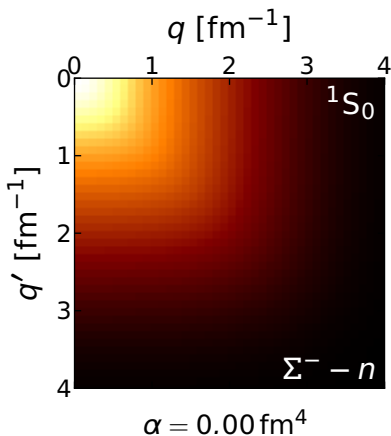
$$|s_1 s_2 \cdots s_A\rangle, \quad s_i \equiv |e(l\frac{1}{2})j\chi\rangle_i$$

- Λ - Σ conversion, e.g.

$$|pn\Lambda\rangle, |pp\Sigma^-\rangle, |nn\Sigma^+\rangle \in \mathcal{M}({}^3_{\Lambda}H)$$

- Impose N_{\max} truncation
- Importance truncation: discard irrelevant states + *a posteriori* extrapolation
- Diagonalize Hamilton matrix
 \Rightarrow Energies & wave functions

Similarity Renormalization Group

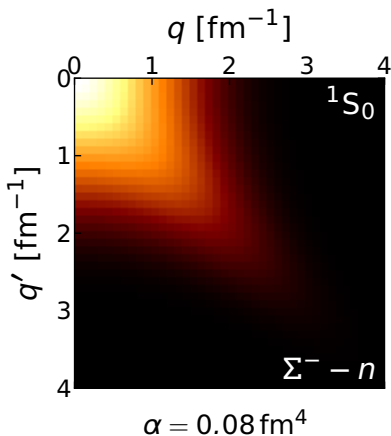


$$\partial_\alpha \mathbf{H}(\alpha) = [\boldsymbol{\eta}(\alpha), \mathbf{H}(\alpha)]$$

$$\boldsymbol{\eta}(\alpha) = m_N^2 [\mathbf{T}_{\text{int}}, \mathbf{H}(\alpha)]$$

- Up to 6 coupled channels
- Decouples high and low momenta
⇒ Improved N_{max} convergence
- BUT: Induced many-body terms
⇒ Assess via α -dependence
- NN+3N: Induced terms negligible up to $A \approx 10$

Similarity Renormalization Group

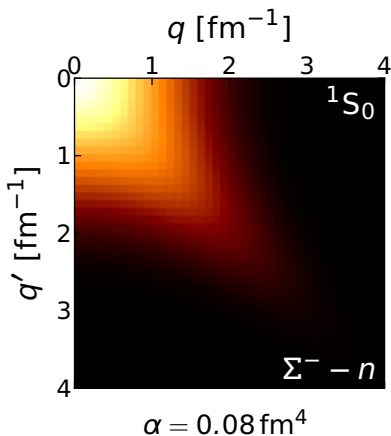


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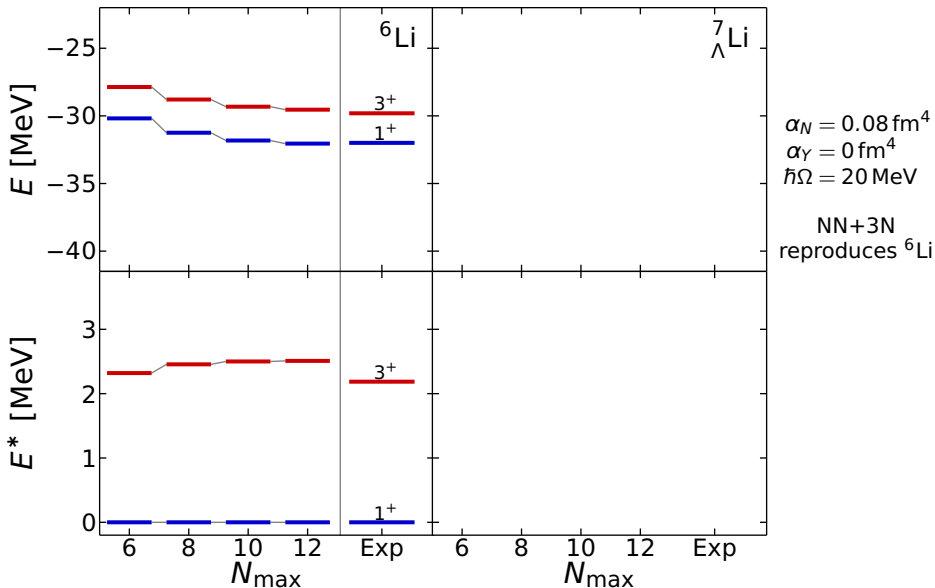
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Use $\alpha_N = 0.08 \text{ fm}^4$ for NN+3N
and $\alpha_Y = 0 \text{ fm}^4$ for YN

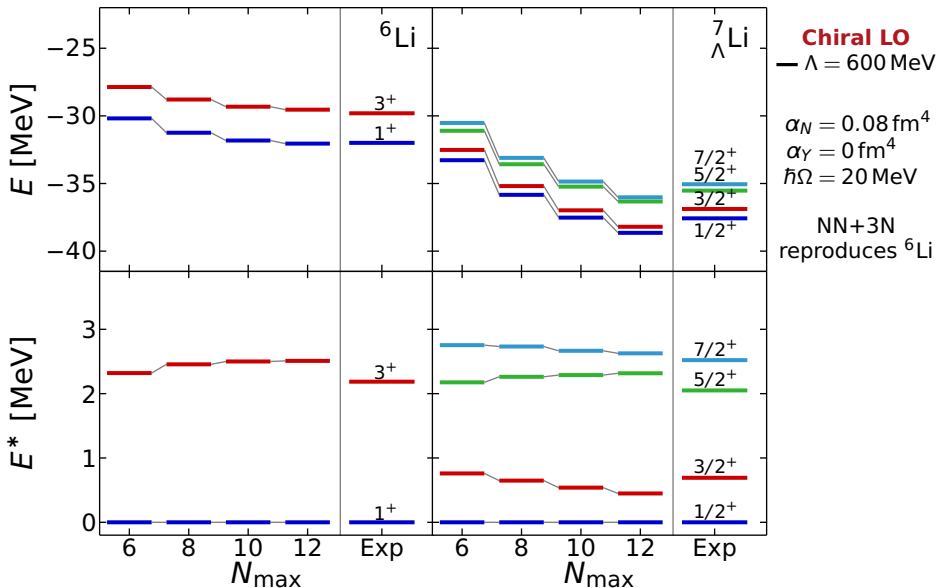
Results for Selected Hypernuclei

RW, D. Gazda, P. Navrátil, A. Calci, J. Langhammer, R. Roth, PRL 113, 192502 (2014)

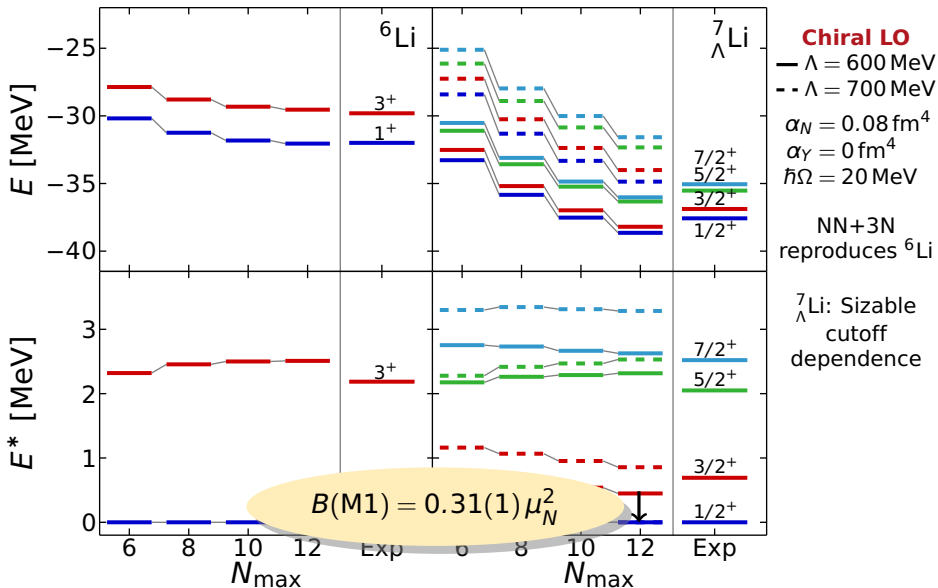
${}^7_{\Lambda}\text{Li}$ — Energies and Spectra



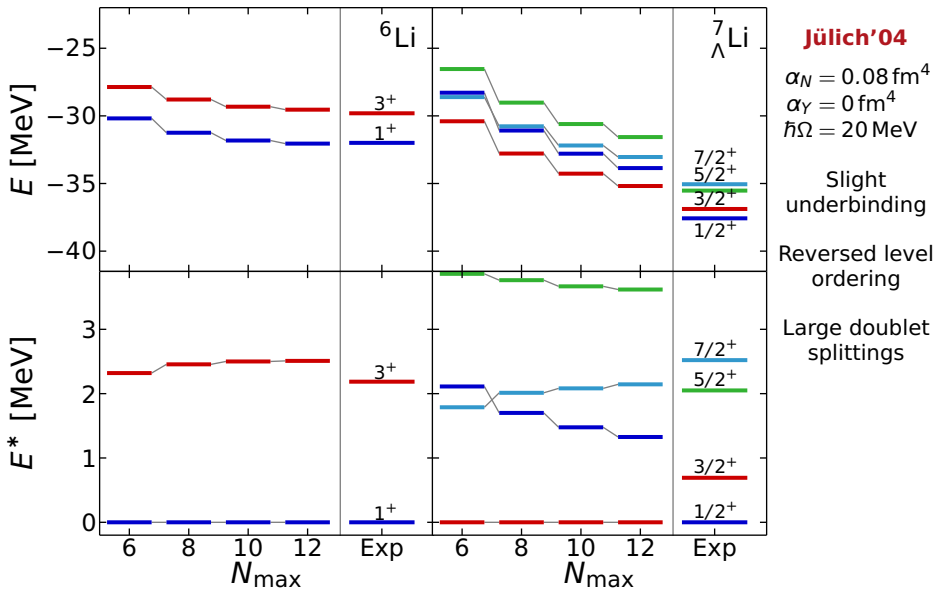
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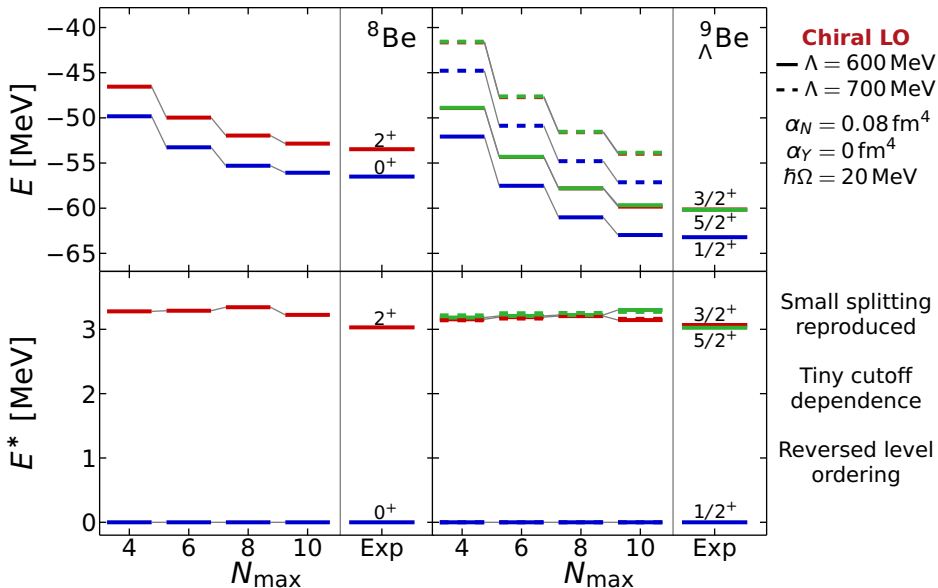
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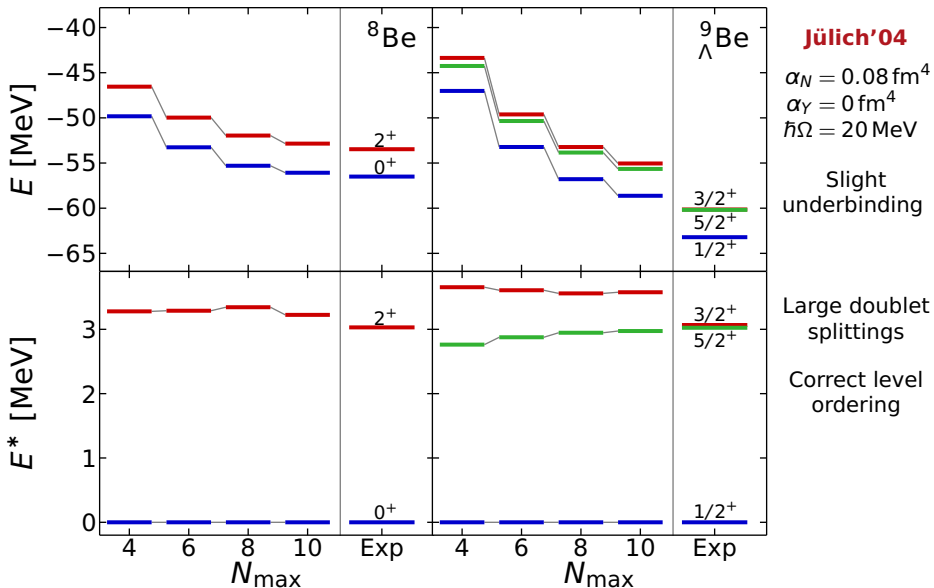
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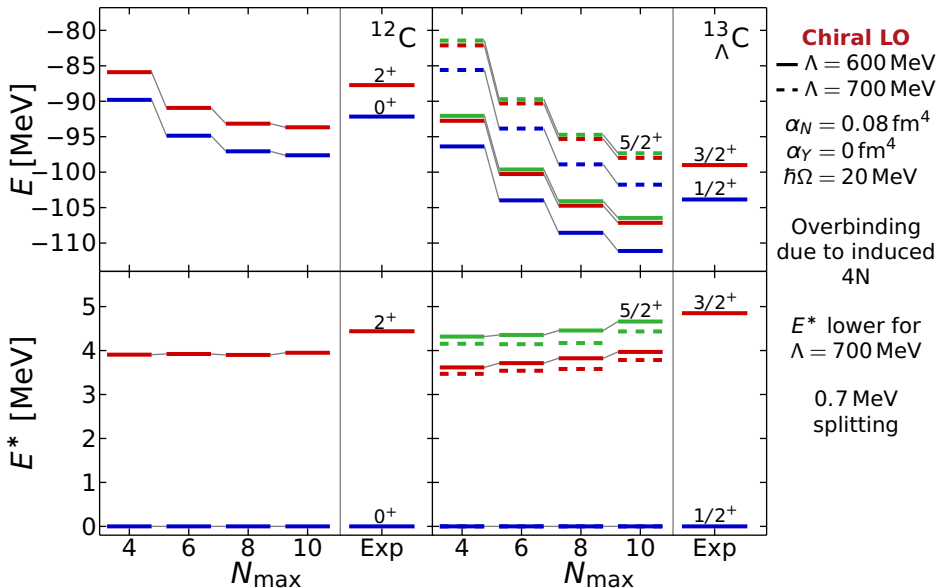
${}^9_{\Lambda}\text{Be}$ — Energies and Spectra



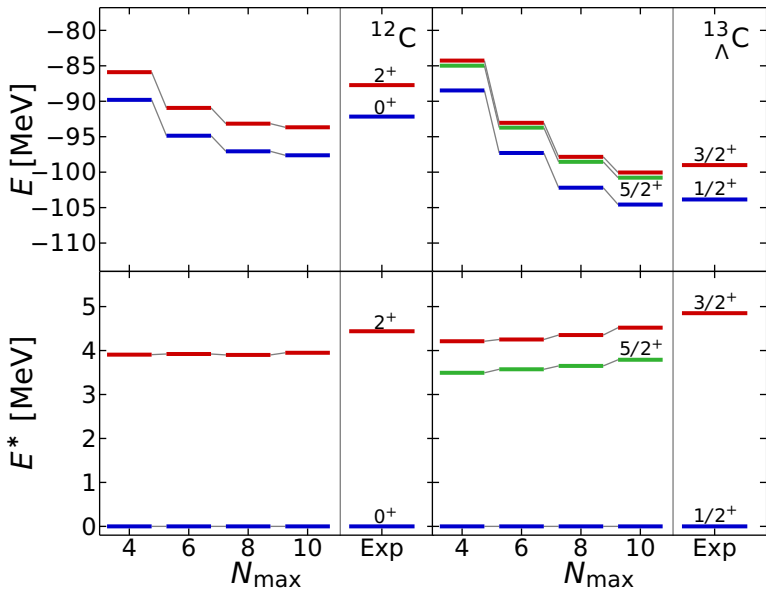
${}^9_{\Lambda}\text{Be}$ — Energies and Spectra



^{13}C — Energies and Spectra



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Jülich'04

$$\alpha_N = 0.08 \text{ fm}^4$$

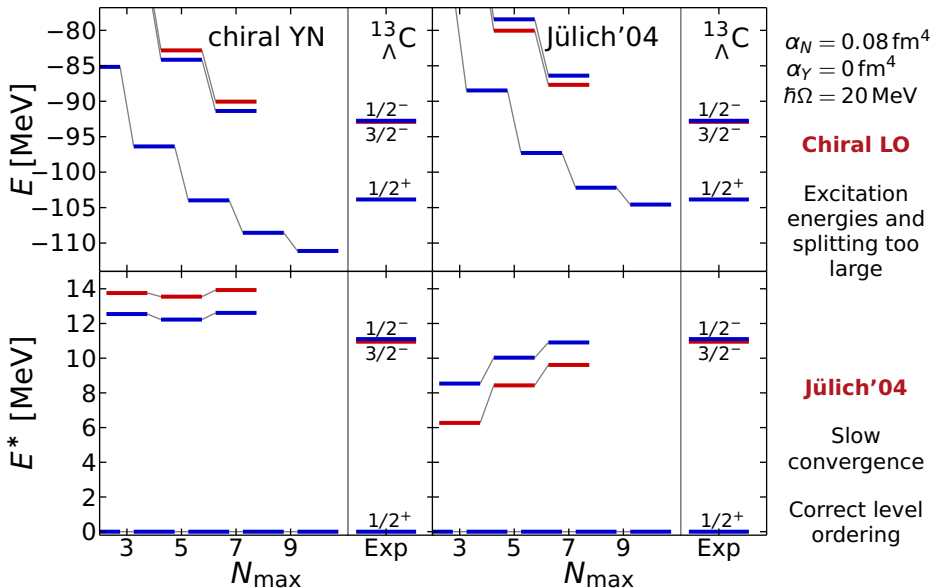
$$\alpha_\gamma = 0 \text{ fm}^4$$

$$\hbar\Omega = 20 \text{ MeV}$$

Very similar to
chiral LO

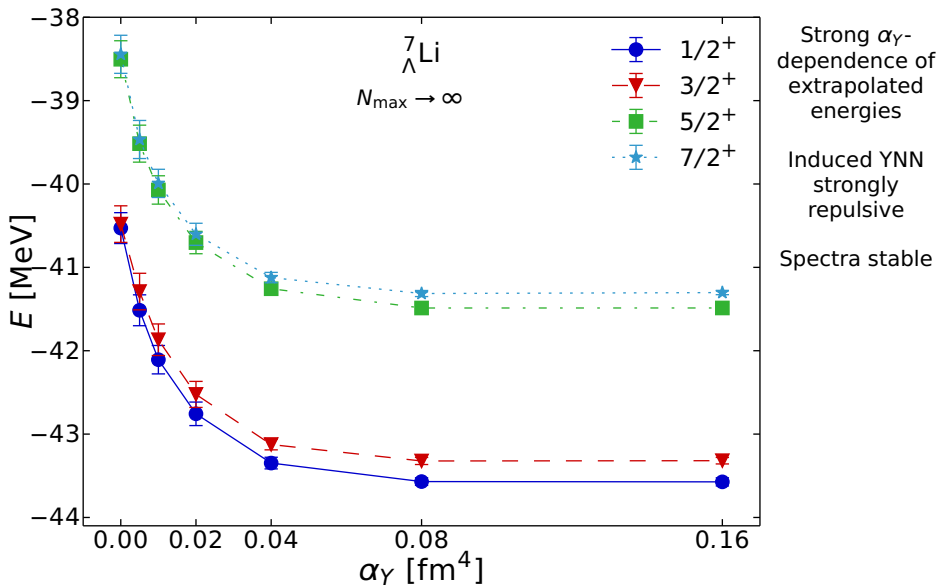
Opposite level
ordering

^{13}C — Negative-Parity States

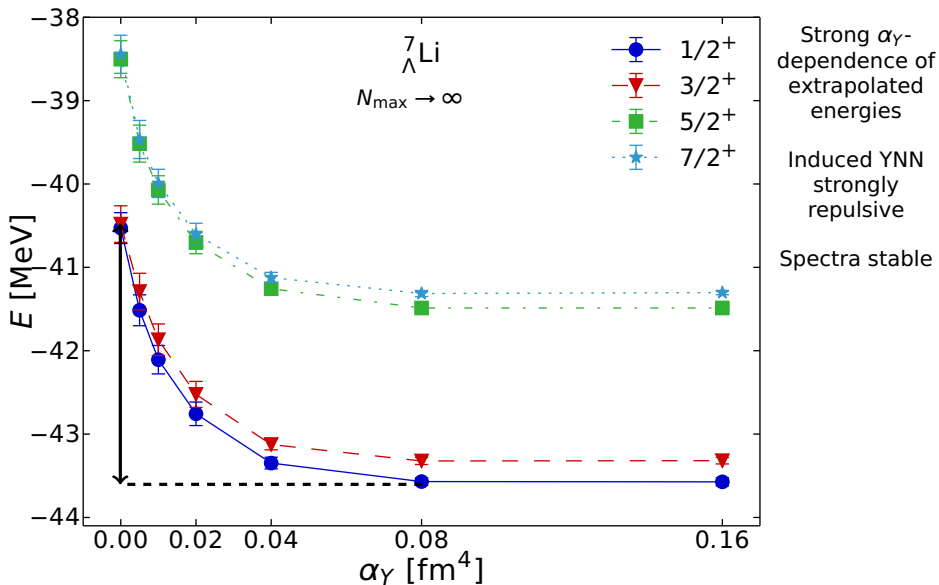


SRG-Induced YNN Interactions

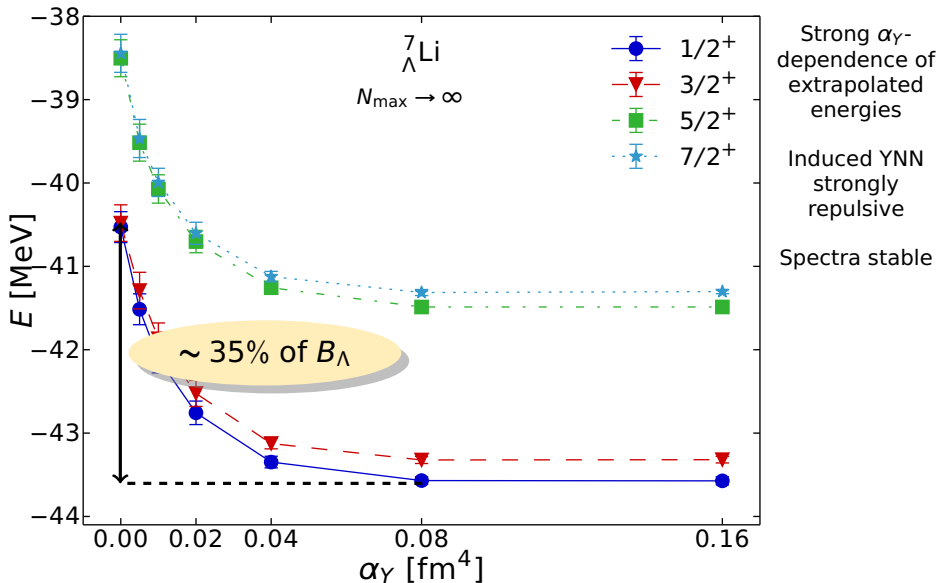
Variation of α_γ



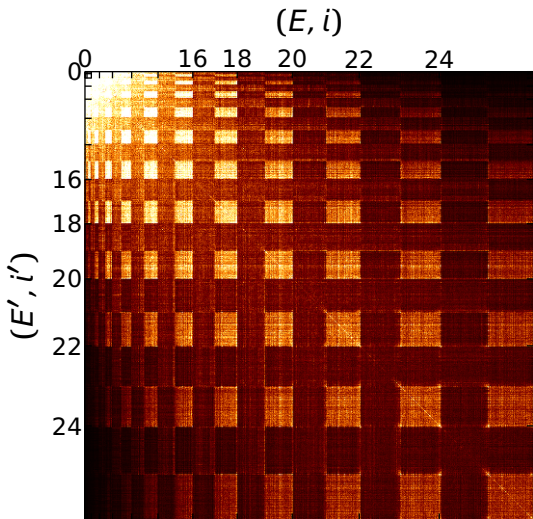
Variation of α_γ



Variation of α_γ



Work In Progress: SRG at the Three-Body Level

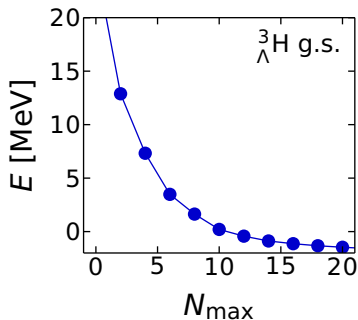


$${}_a \langle Ei | \mathbf{H} - \mathbf{T}_{\text{int}} - \mathbf{M} | E' i' \rangle_a$$

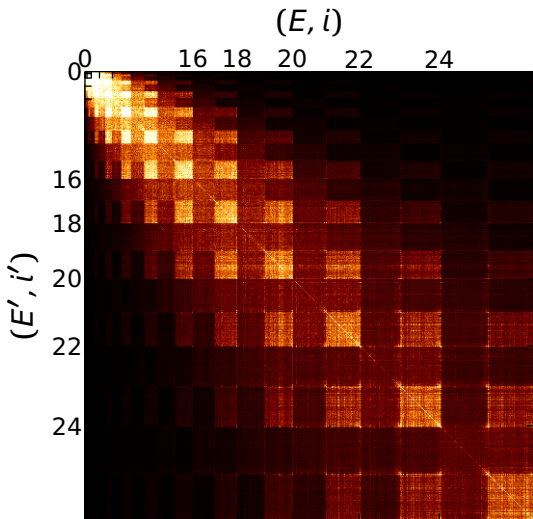
$$\hbar\Omega = 32 \text{ MeV}$$

$$J^{\Pi T} = \frac{1}{2}^+ 0$$

$$\alpha = 0.00 \text{ fm}^4$$



Work In Progress: SRG at the Three-Body Level

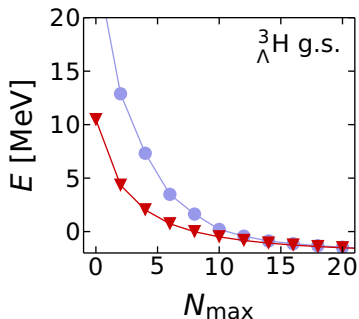


$${}_a \langle Ei | \mathbf{H} - \mathbf{T}_{\text{int}} - \mathbf{M} | E' i' \rangle_a$$

$$\hbar\Omega = 32 \text{ MeV}$$

$$J^{\Pi T} = \frac{1}{2}^+ 0$$

$$\alpha = 0.08 \text{ fm}^4$$



Summary & Outlook

- First ab-initio calculations of hypernuclei in the p shell
- Prediction of observables
- Dependence on YN interaction \Rightarrow constraints
- SRG of YN induces strong YNN terms
Possible implications for soft Λ N interactions and the hyperon puzzle
- Next: NLO chiral YN interaction & treat induced YNN terms explicitly

■ Thanks to my group & collaborators

- S. Alexa, J. Braun, B. Dörig, E. Gebrerufael, T. Hüther, L. Kreher, **J. Langhammer**, **R. Roth**, S. Schulz, H. Spiess, C. Stumpf, A. Tichai, R. Trippel, K. Vobig
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- **D. Gazda**
ECT* Trento, Italy
- H. Hergert
Michigan State University, USA
- H. Feldmeier, T. Neff
GSI Helmholtzzentrum



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