

# Ab-Initio Description of p-Shell Hypernuclei

Hypernuclear Workshop, JLab 2014

R. Wirth

Institut für Kernphysik



TECHNISCHE  
UNIVERSITÄT  
DARMSTADT

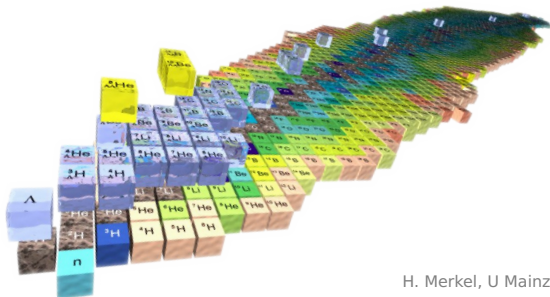
# Motivation

Contribution from theory so far:

- ab-initio few-body ( $A \lesssim 5$ )
- phenomenological models, e.g. shell, cluster & mean-field models

Advances in **nuclear** many-body theory:

- chiral EFT  
⇒ accurate NN+3N Hamiltonians
- unitary transformations  
⇒ computations feasible



H. Merkel, U Mainz

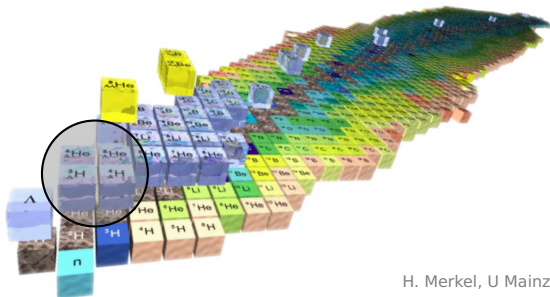
# Motivation

Contribution from theory so far:

- ab-initio few-body ( $A \lesssim 5$ )
- phenomenological models, e.g. shell, cluster & mean-field models

Advances in **nuclear** many-body theory:

- chiral EFT  
⇒ accurate NN+3N Hamiltonians
- unitary transformations  
⇒ computations feasible



H. Merkel, U Mainz

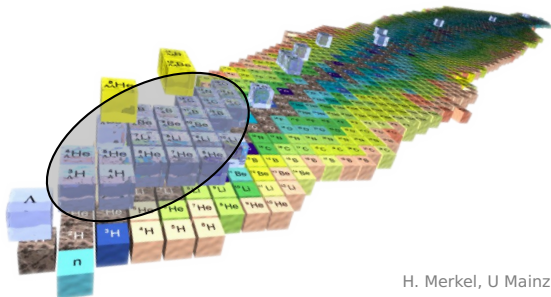
# Motivation

Contribution from theory so far:

- ab-initio few-body ( $A \lesssim 5$ )
- phenomenological models, e.g. shell, cluster & mean-field models

Advances in **nuclear** many-body theory:

- chiral EFT  
⇒ accurate NN+3N Hamiltonians
- unitary transformations  
⇒ computations feasible



H. Merkel, U Mainz

# Motivation

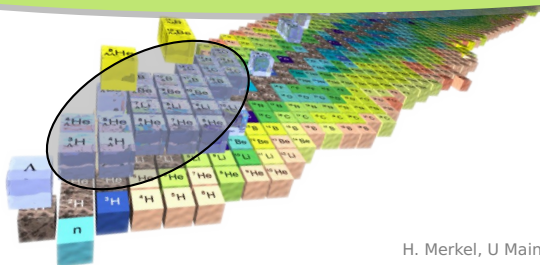
Contribution from theory so far:

- ab-initio few-body ( $A \lesssim 5$ )
- phenomenological models, e.g. shell, cluster & mean-field models

Advances in **nuclear** many-body theory:

- chiral EFT  
⇒ accurate NN+3N Hamiltonians
- unitary transformations  
⇒ computations feasible

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



H. Merkel, U Mainz

# Motivation

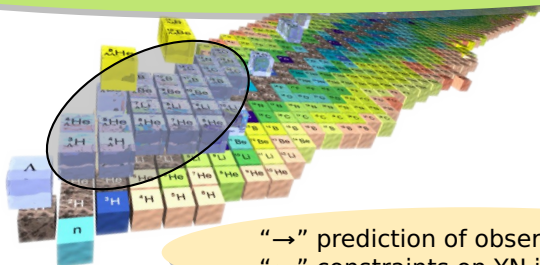
Contribution from theory so far:

- ab-initio few-body ( $A \lesssim 5$ )
- phenomenological models, e.g. shell, cluster & mean-field models

Advances in **nuclear** many-body theory:

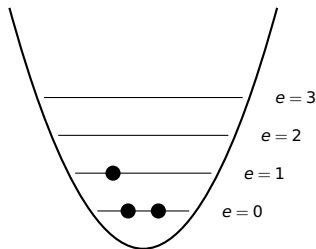
- chiral EFT  
⇒ accurate NN+3N Hamiltonians
- unitary transformations  
⇒ computations feasible

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



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

# Importance-Truncated No-Core Shell Model



${}^6\text{Li}$  proton orbits

- A-body Slater determinants from HO states

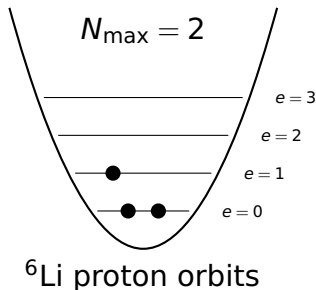
$$|s_1 s_2 \cdots s_A\rangle, \quad s_i \equiv |e(l\frac{1}{2})j\chi\rangle_i$$

- $\Lambda$ - $\Sigma$  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

# Importance-Truncated No-Core Shell Model



- A-body Slater determinants from HO states

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

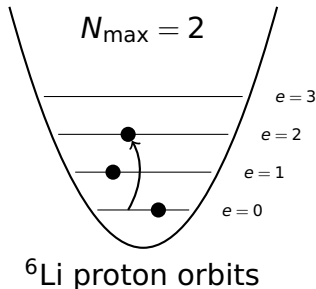
- $\Lambda$ - $\Sigma$  conversion, e.g.

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

- impose  $N_{\max}$  truncation
- importance truncation: discard irrelevant states + *a posteriori* extrapolation
- diagonalize Hamilton matrix  $\Rightarrow$  energies & wave functions



# Importance-Truncated No-Core Shell Model



- A-body Slater determinants from HO states

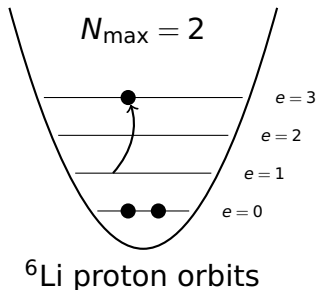
$$|s_1 s_2 \cdots s_A\rangle, \quad s_i \equiv |e(l\frac{1}{2})j\chi\rangle_i$$

- $\Lambda$ - $\Sigma$  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

# Importance-Truncated No-Core Shell Model



- A-body Slater determinants from HO states

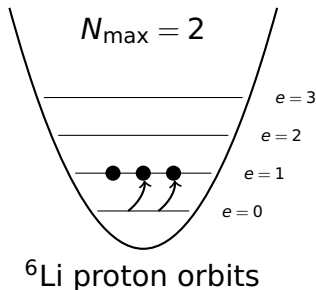
$$|s_1 s_2 \cdots s_A\rangle, \quad s_i \equiv |e(l\frac{1}{2})j\chi\rangle_i$$

- $\Lambda$ - $\Sigma$  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

# Importance-Truncated No-Core Shell Model



- A-body Slater determinants from HO states

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

- $\Lambda$ - $\Sigma$  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

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

## ■ NN: chiral N<sup>3</sup>LO

Entem & Machleidt

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

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

## ■ 3N: chiral N<sup>2</sup>LO

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

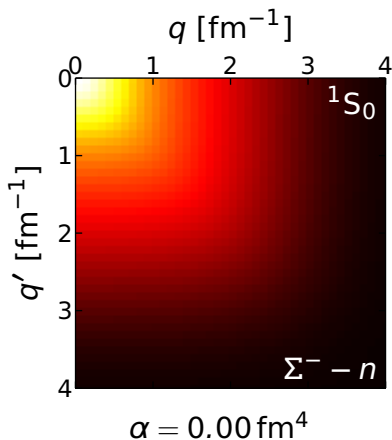
Haidenbauer & Meißner

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

meson-exchange

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

# Similarity Renormalization Group

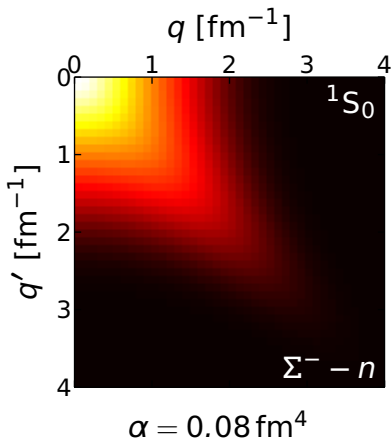


$$\partial_\alpha \mathbf{H}(\alpha) = [\boldsymbol{\eta}(\alpha), \mathbf{H}(\alpha)]$$

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

- up to 6 coupled channels
- decouples high and low momenta  
 $\Rightarrow$  improved  $N_{\text{max}}$  convergence
- BUT: induced many-body terms  
 $\Rightarrow$  assess via  $\alpha$ -dependence
- NN+3N: Induced terms negligible  
up to  $A \approx 10$

# Similarity Renormalization Group

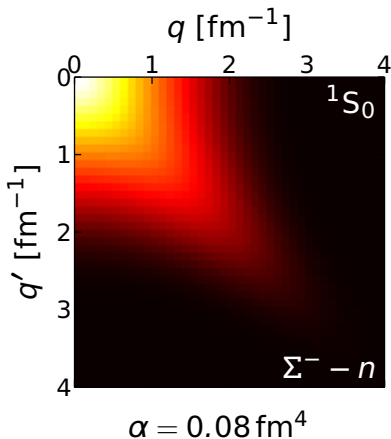


$$\partial_\alpha \mathbf{H}(\alpha) = [\boldsymbol{\eta}(\alpha), \mathbf{H}(\alpha)]$$

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

- up to 6 coupled channels
- decouples high and low momenta  
⇒ improved  $N_{\text{max}}$  convergence
- BUT: induced many-body terms  
⇒ assess via  $\alpha$ -dependence
- NN+3N: Induced terms negligible  
up to  $A \approx 10$

# Similarity Renormalization Group



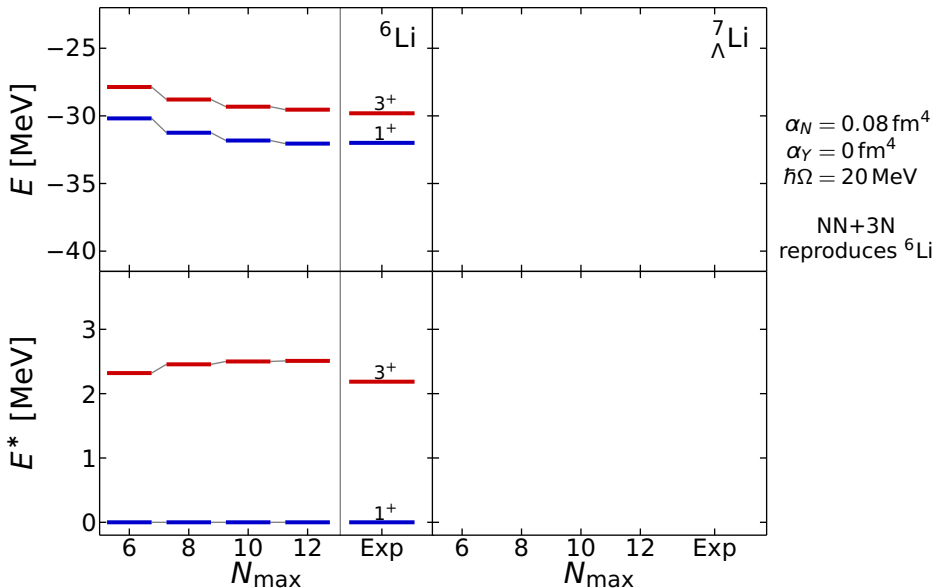
$$\partial_\alpha \mathbf{H}(\alpha) = [\boldsymbol{\eta}(\alpha), \mathbf{H}(\alpha)]$$

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

- up to 6 coupled channels
- decouples high and low momenta  
 $\Rightarrow$  improved  $N_{\text{max}}$  convergence
- BUT: induced many-body terms  
 $\Rightarrow$  assess via  $\alpha$ -dependence
- NN+3N: Induced terms negligible  
up to  $A \approx 10$

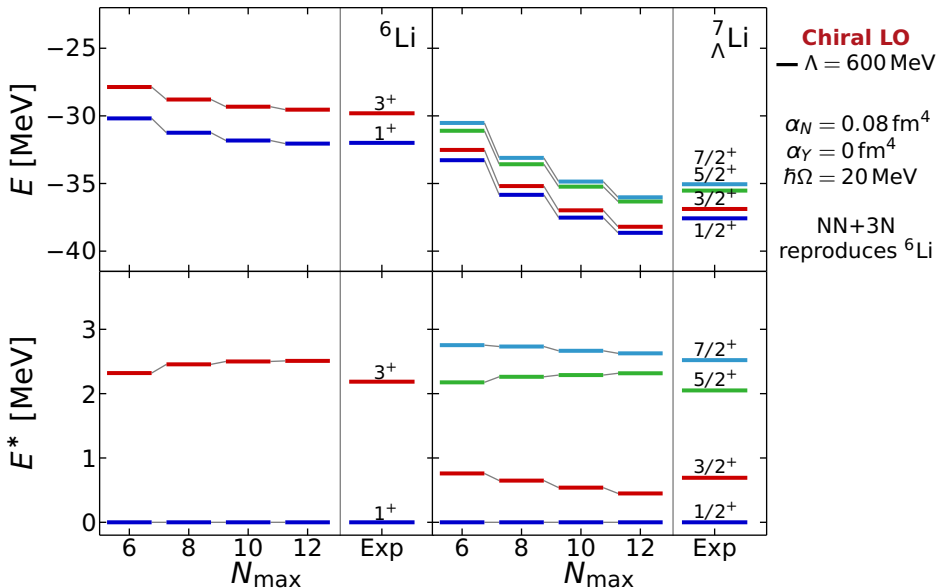
Use  $\alpha_N = 0.08 \text{ fm}^4$  for NN+3N  
and  $\alpha_Y = 0 \text{ fm}^4$  for YN

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

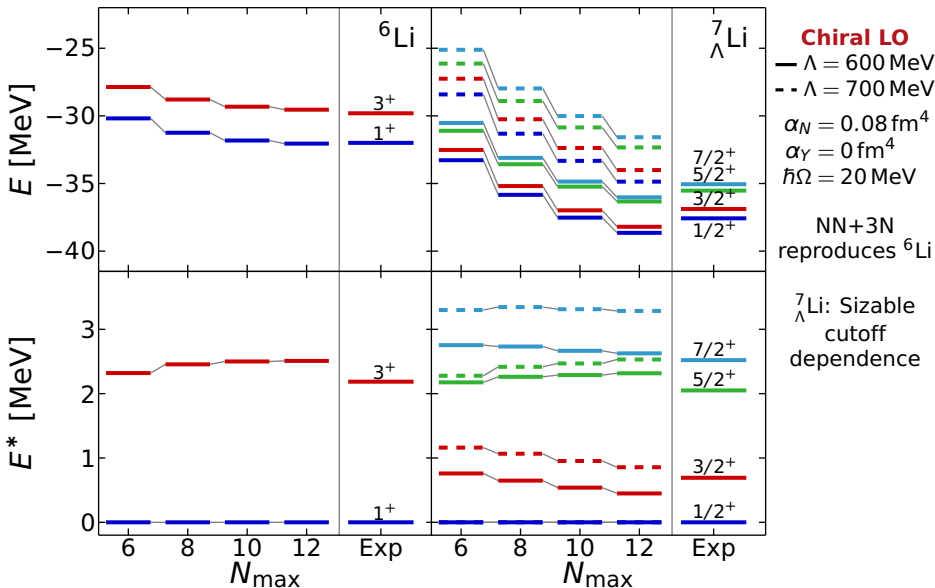




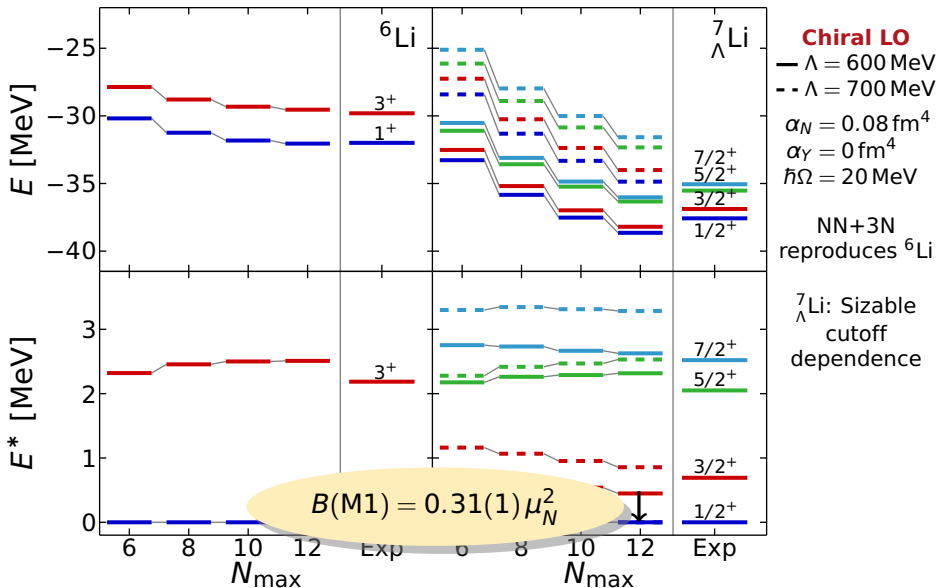
# ${}^7_\Lambda\text{Li}$ — Energies and Spectra



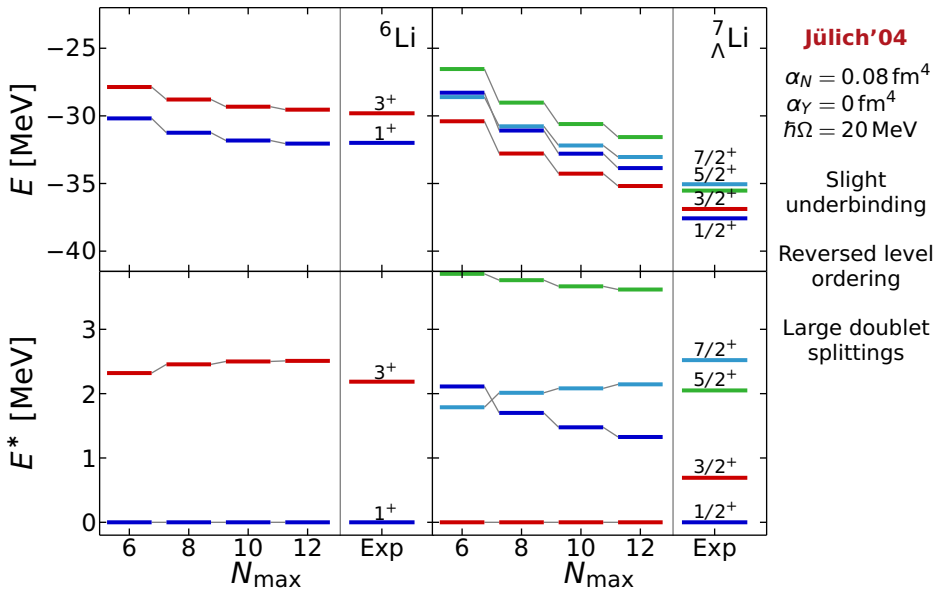
# ${}^7_\Lambda\text{Li}$ — Energies and Spectra



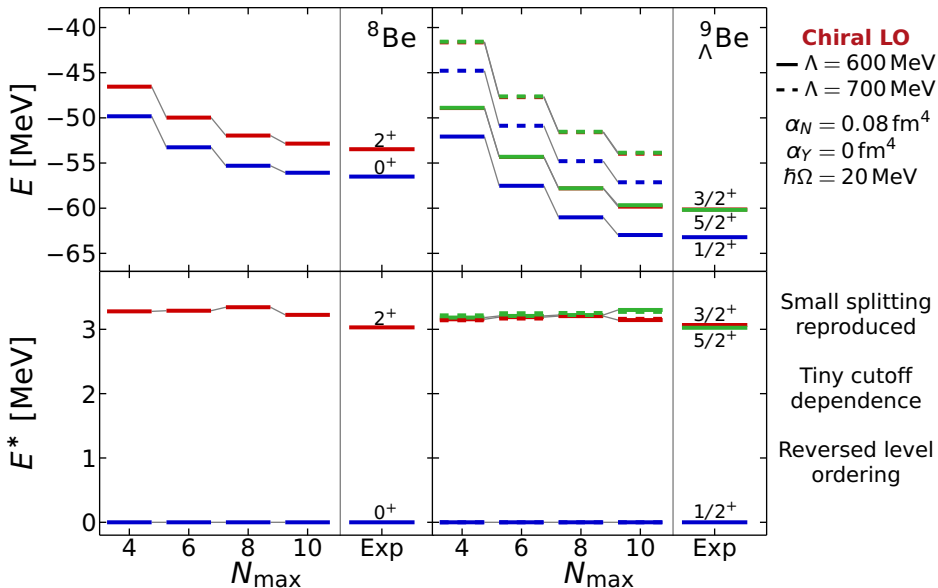
# ${}^7_\Lambda\text{Li}$ — Energies and Spectra



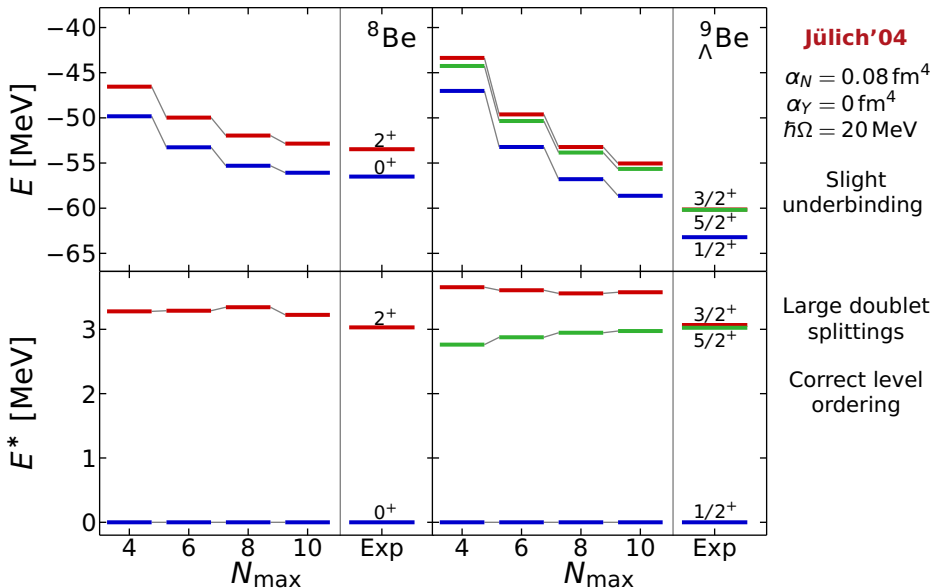
# ${}^7_\Lambda\text{Li}$ — Energies and Spectra



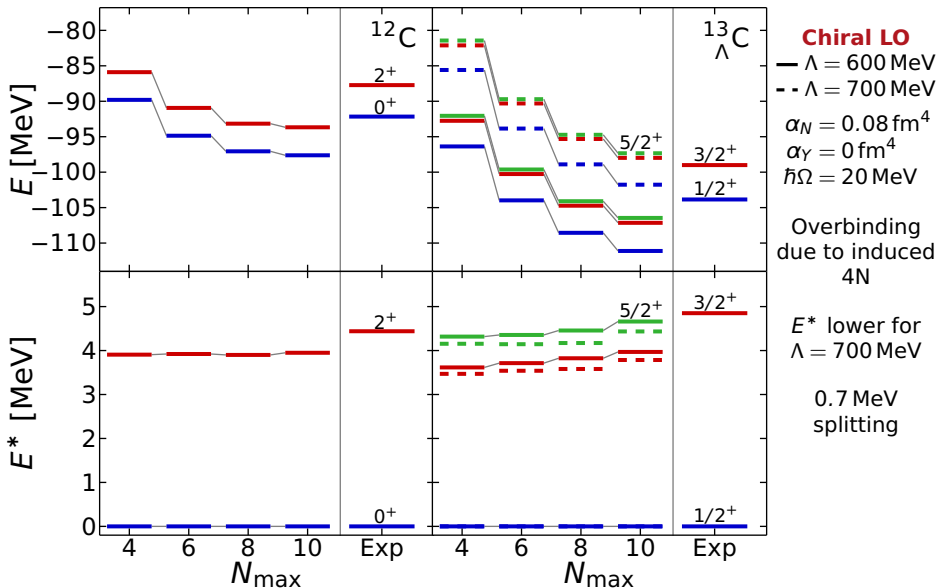
# ${}^9_{\Lambda}\text{Be}$ — Energies and Spectra



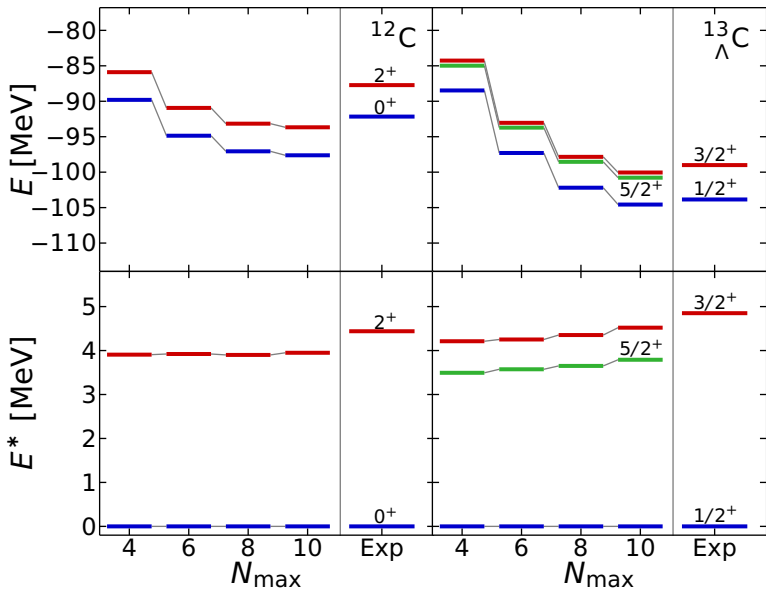
# ${}^9_{\Lambda}\text{Be}$ — Energies and Spectra



# $^{13}\text{C}$ — Energies and Spectra



# $^{13}\text{C}$ — Energies and Spectra



**Jülich'04**

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

$$\alpha_Y = 0 \text{ fm}^4$$

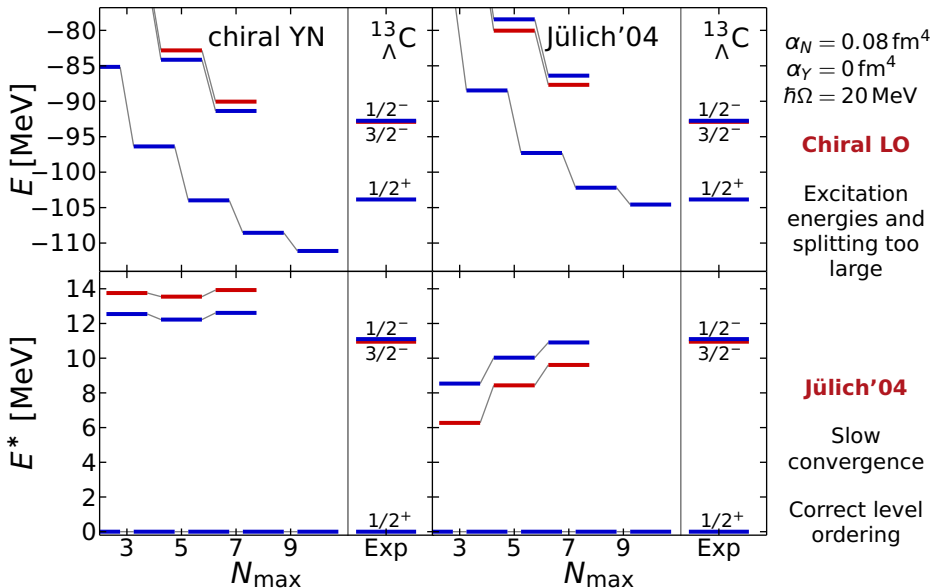
$$\hbar\Omega = 20 \text{ MeV}$$

Very similar to  
chiral LO

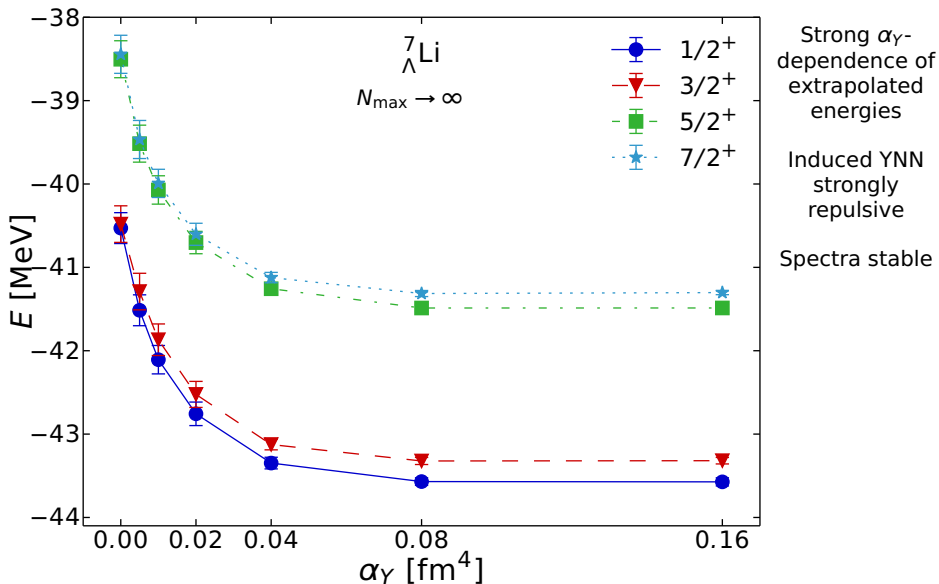
Opposite level  
ordering



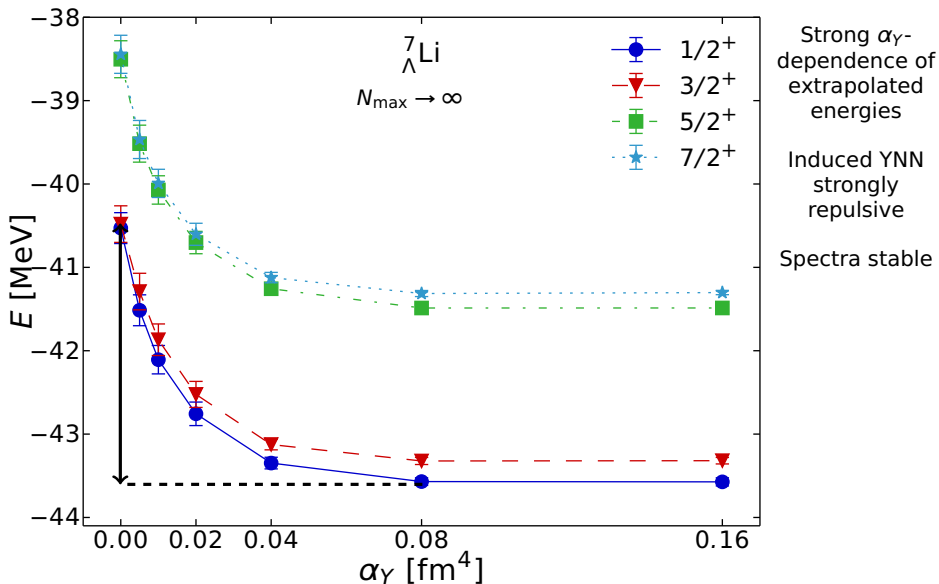
# $^{13}\text{C}$ — Negative-Parity States



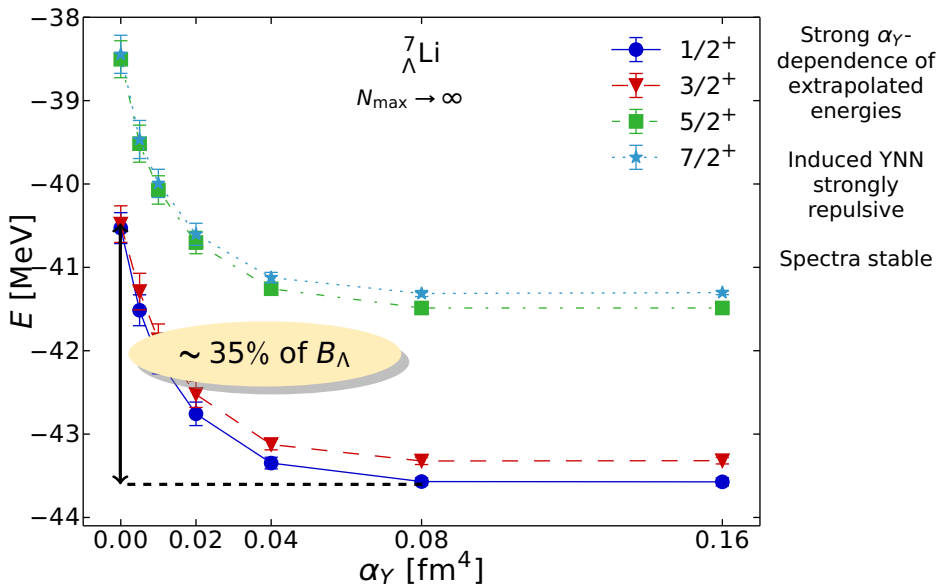
# SRG-Induced YNN Interactions



# SRG-Induced YNN Interactions



# SRG-Induced YNN Interactions



- Aim: enable benchmarks & predictions for  $p$ -shell hypernuclei
- IT-NCSM with SRG-evolved interactions for hypernuclei

## Test chiral LO and Jülich'04 interactions

- different level orderings
  - gross properties reproduced (LO seems to work better)
  - BUT: large cutoff dependence, overbinding, level ordering issues
- 
- SRG of YN induces strong YNN terms
  - possible implications for soft  $\Lambda$ N interactions and the hyperon puzzle

## Interaction

- move to NLO
  - include induced YNN terms
  - variation of LECs
- 
- hyperon–nucleus scattering from NCSM/RGM
  - investigate origin of induced YNN & connection to hyperon puzzle
  - look at other hypernuclei

We are open for suggestions from experiment!

## Interaction

- move to NLO
  - include induced YNN terms
  - variation of LECs
- 
- hyperon–nucleus scattering from NCSM/RGM
  - investigate origin of induced YNN & connection to hyperon puzzle
  - look at other hypernuclei

We are open for suggestions from experiment!

Thank you for your attention!

## ■ Thanks to my group & collaborators

■ S. Binder, J. Braun, **A. Calci**, E. Gebrerufael, V. Klaer, L. Kreher, **J. Langhammer**, **R. Roth**, S. Schulz, H. Spiess, C. Stumpf, A. Tichai, R. Trippel, K. Vobig  
Institut für Kernphysik, TU Darmstadt

■ **P. Navrátil**  
TRIUMF Vancouver, Canada

■ J. Vary, P. Maris  
Iowa State University, USA

■ S. Quaglioni  
LLNL Livermore, USA

■ P. Piecuch  
Michigan State University, USA

■ **D. Gazda**  
Nuclear Physics Institute Řež, CZ

■ H. Hergert  
Ohio State University, USA

■ P. Papakonstantinou  
IBS/RISP, Korea

■ H. Feldmeier, T. Neff  
GSI Helmholtzzentrum



COMPUTING TIME



Deutsche  
Forschungsgemeinschaft  
**DFG**

**HIC** | **FAIR**  
for  
Helmholtz International Center












Exzellente Forschung für  
Hessens Zukunft

 **HELMHOLTZ**  
| **GEMEINSCHAFT**

 Bundesministerium  
für Bildung  
und Forschung












# Induced YNN — Possible Explanation

	$\Lambda n$	$\Sigma^0 n$	$\Sigma^- p$
$\Lambda n$			
$\Sigma^0 n$			
$\Sigma^- p$			

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

- decouples particle species
- interactions phase-shift equivalent
- same effect as fit to  $\Lambda$ -only interaction

# Induced YNN — Possible Explanation

	$\Lambda n$	$\Sigma^0 n$	$\Sigma^- p$
$\Lambda n$			
$\Sigma^0 n$			
$\Sigma^- p$			

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

- decouples particle species
- interactions phase-shift equivalent
- same effect as fit to  $\Lambda$ -only interaction