Induced Hyperon-Nucleon-Nucleon Interactions and the Hyperon Puzzle

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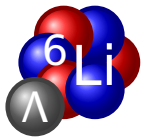
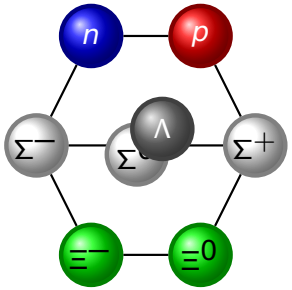
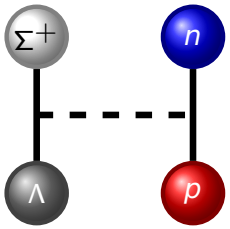
Motivation

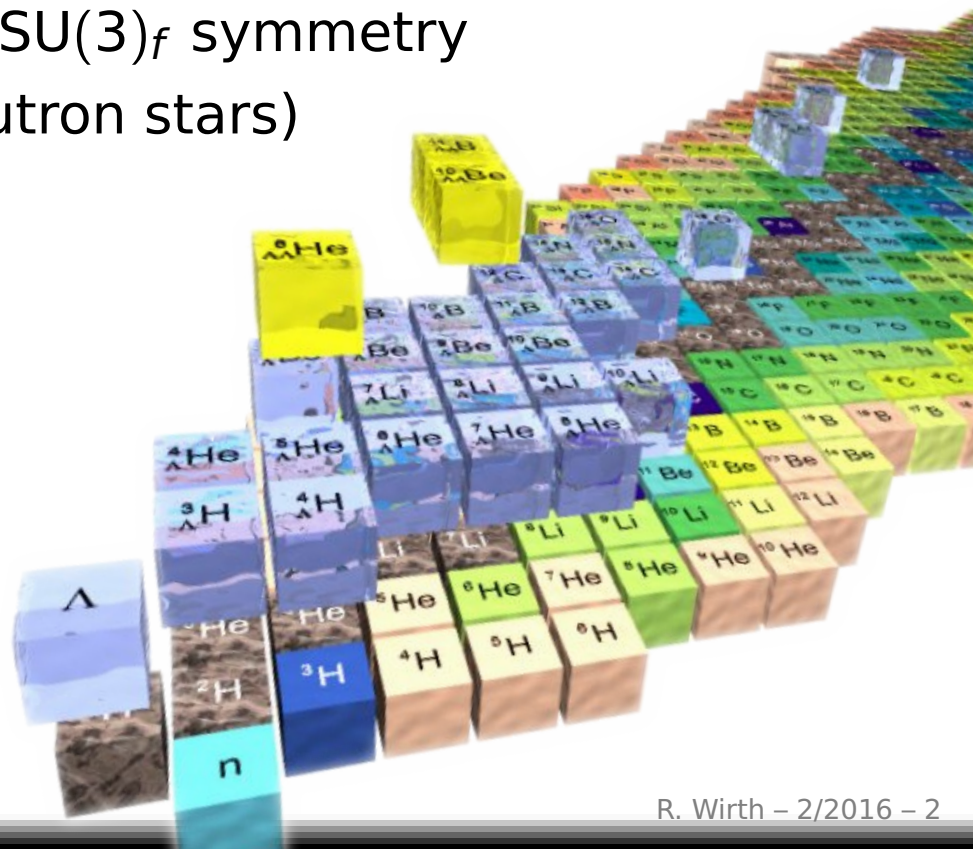






Why hypernuclei?

- Add new dimension to the nuclear chart
- New effects, e.g. Λ-Σ conversion
- Uncertainties in nuclear Hamiltonian under control
- Explore (broken) SU(3)$_f$ symmetry
- Astrophysics (neutron stars)



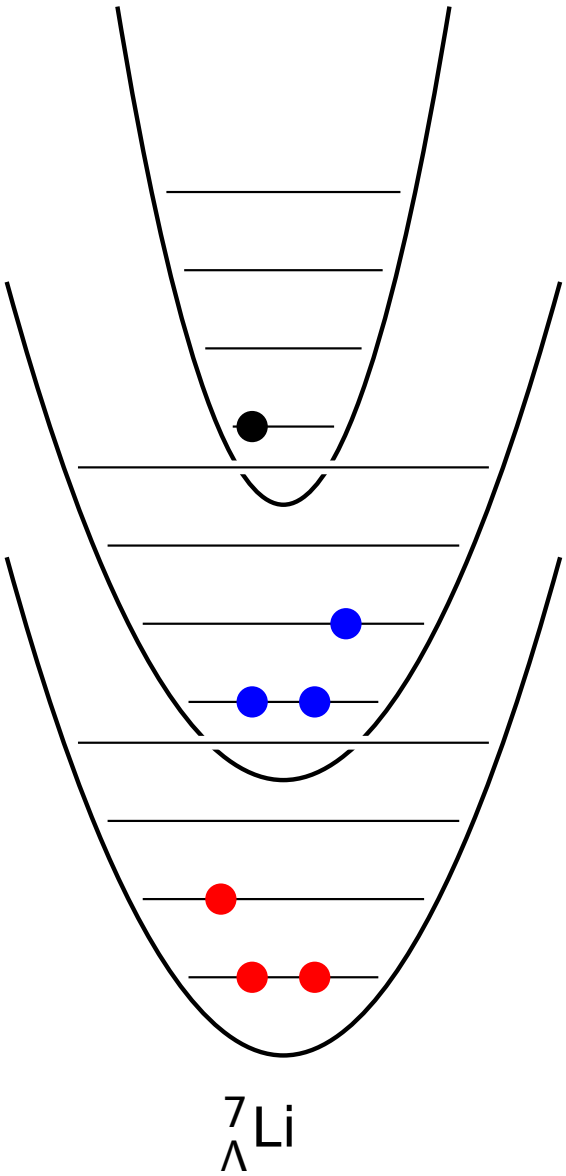
Hypernuclear Hamiltonian

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

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

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

Importance-Truncated No-Core Shell Model



- A-body Slater determinants from HO states

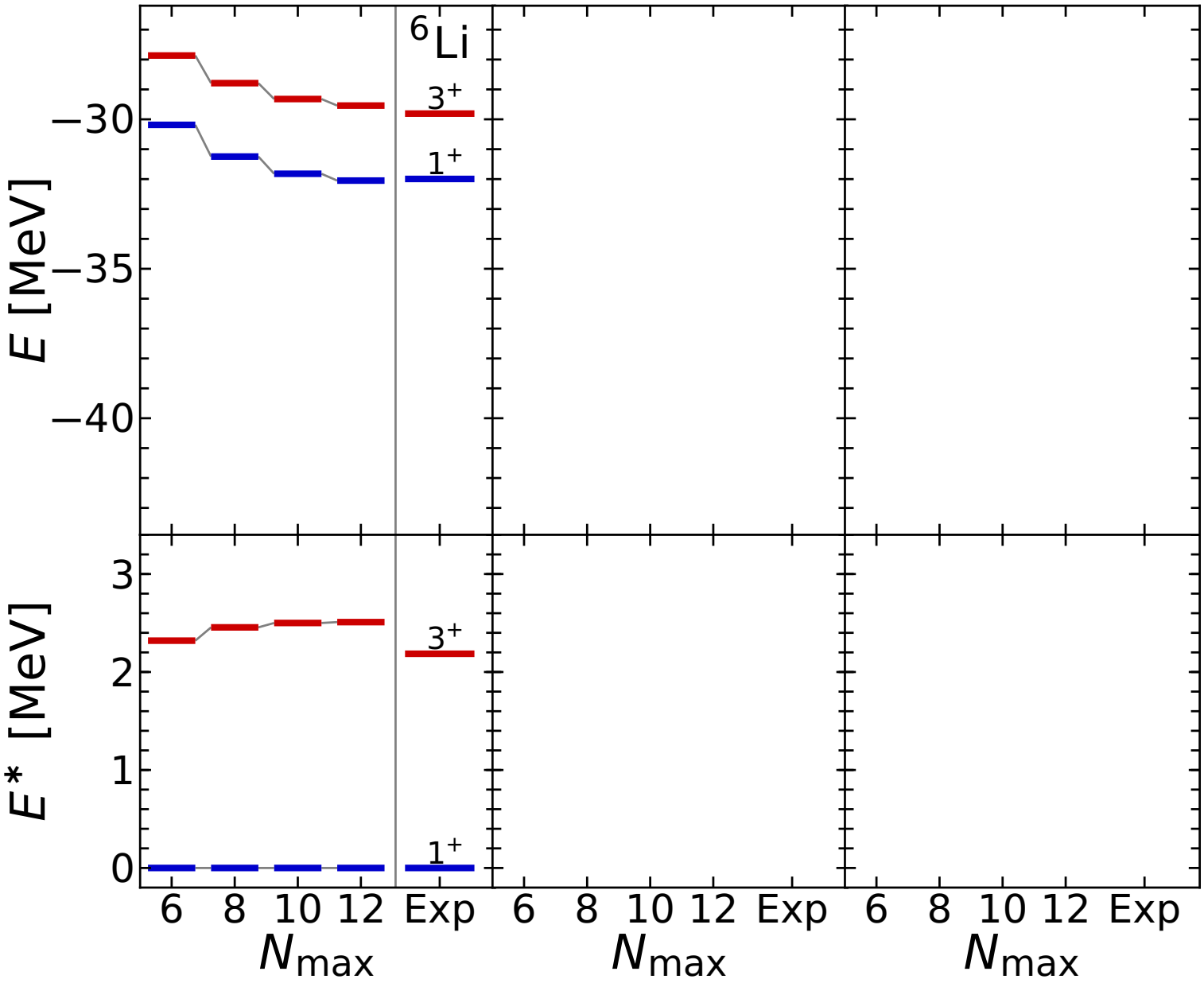
$$|s_1 s_2 \cdots s_A\rangle\,, \quad s_i \equiv |e(l\tfrac{1}{2})j\chi\rangle_i$$

- Λ-Σ conversion, e.g.

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

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

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



Bare YN
Evolved YN

$\alpha = 0.08\,\mathrm{fm}^4$

$\hbar\Omega = 20\,\mathrm{MeV}$

$\Lambda_{\mathrm{YN}} = 700\,\mathrm{MeV}$

Nucleonic parent reproduced

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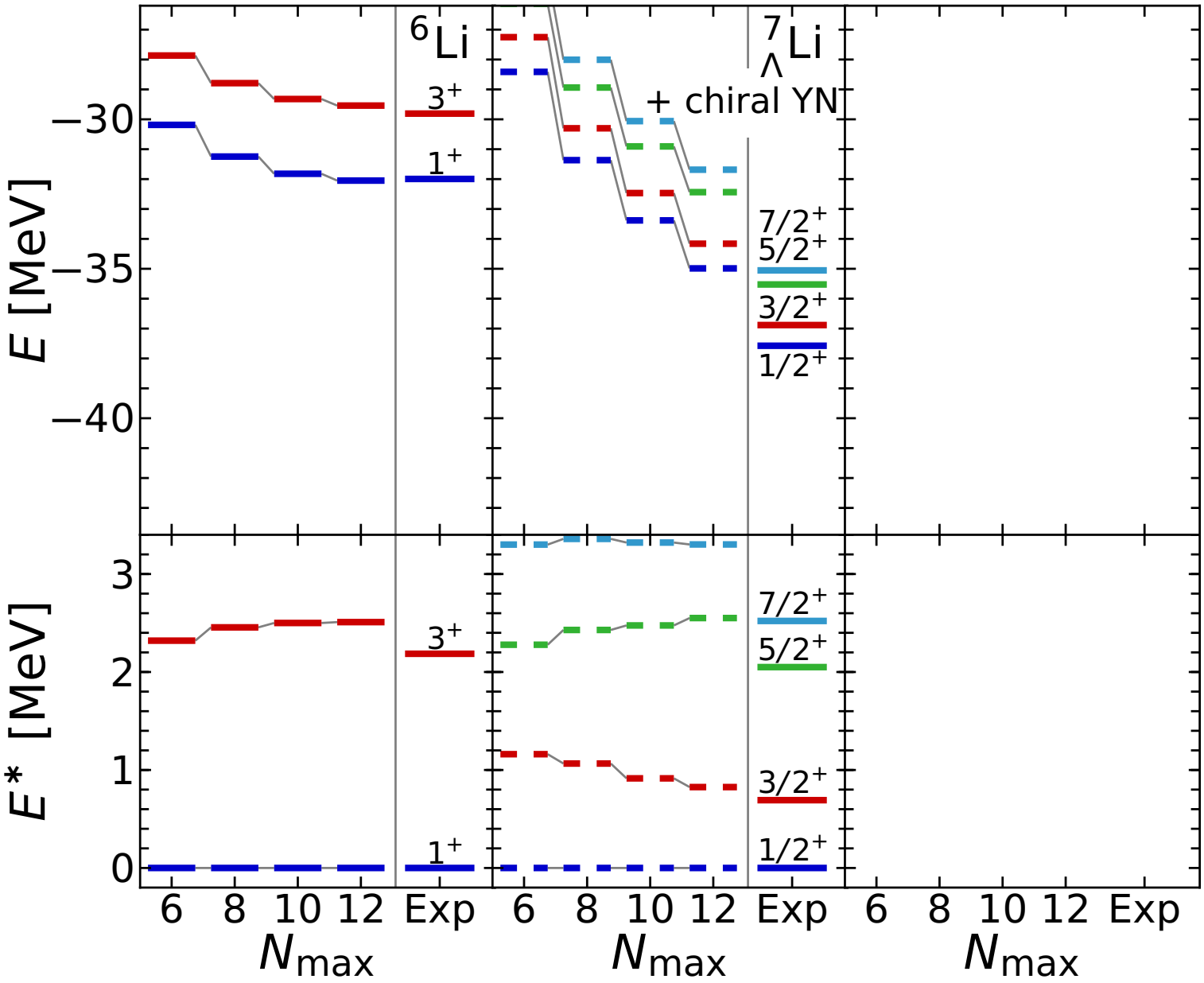

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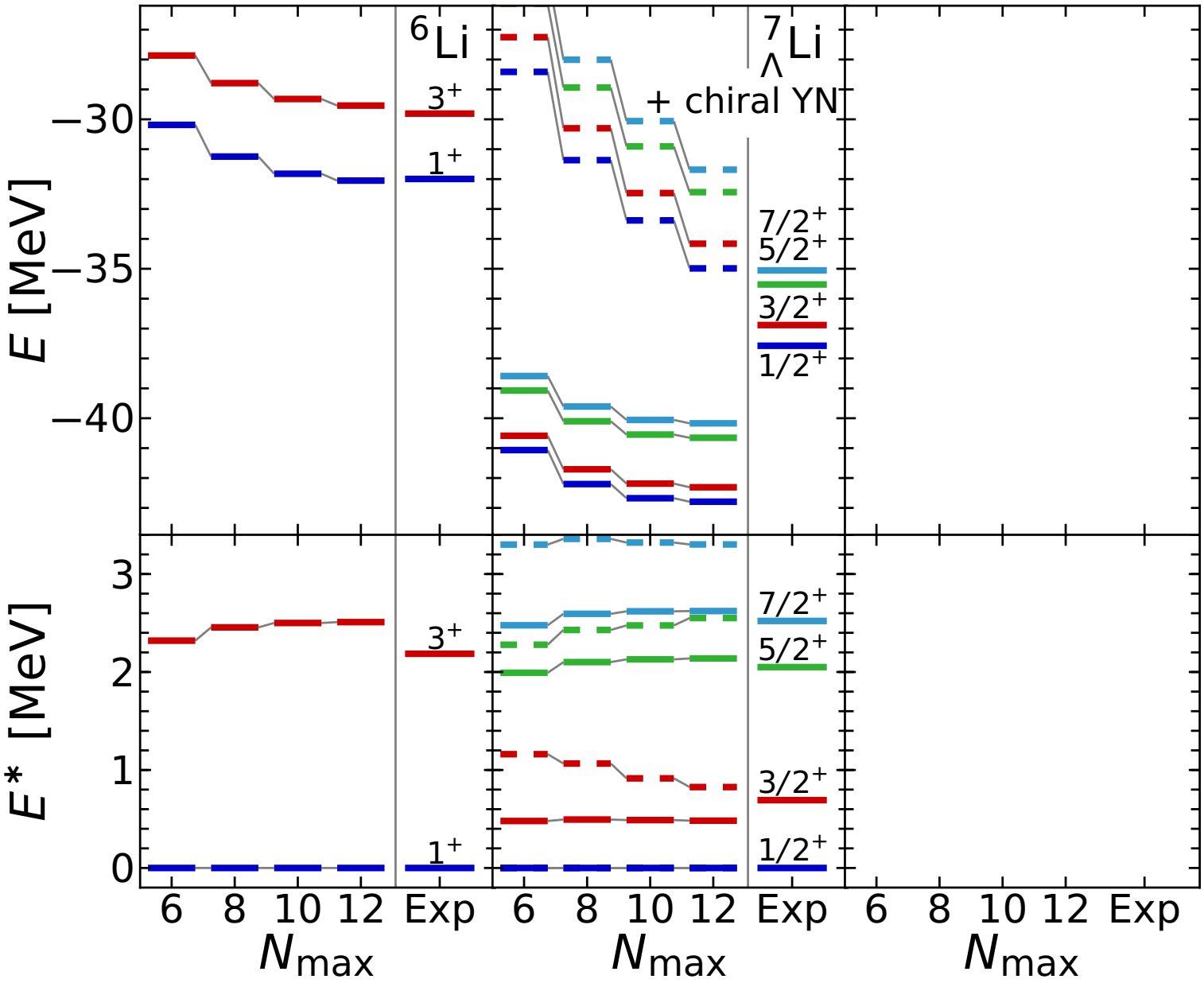

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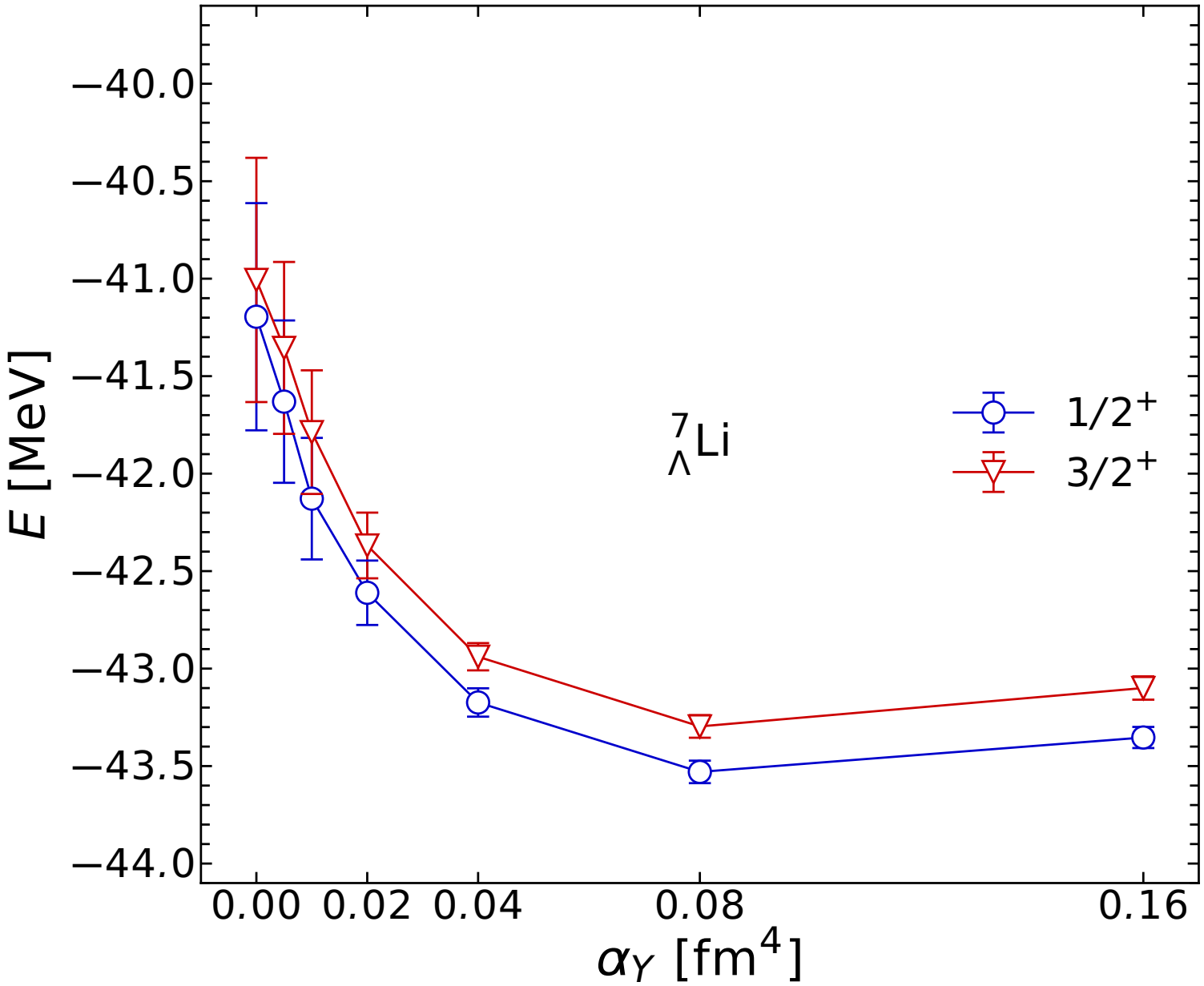
Evolved YN overbinds

SRG Evolution of the YN Interaction



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Strong α_γ-dependence of extrapolated energies

Induced YNN strongly repulsive

Spectra stable

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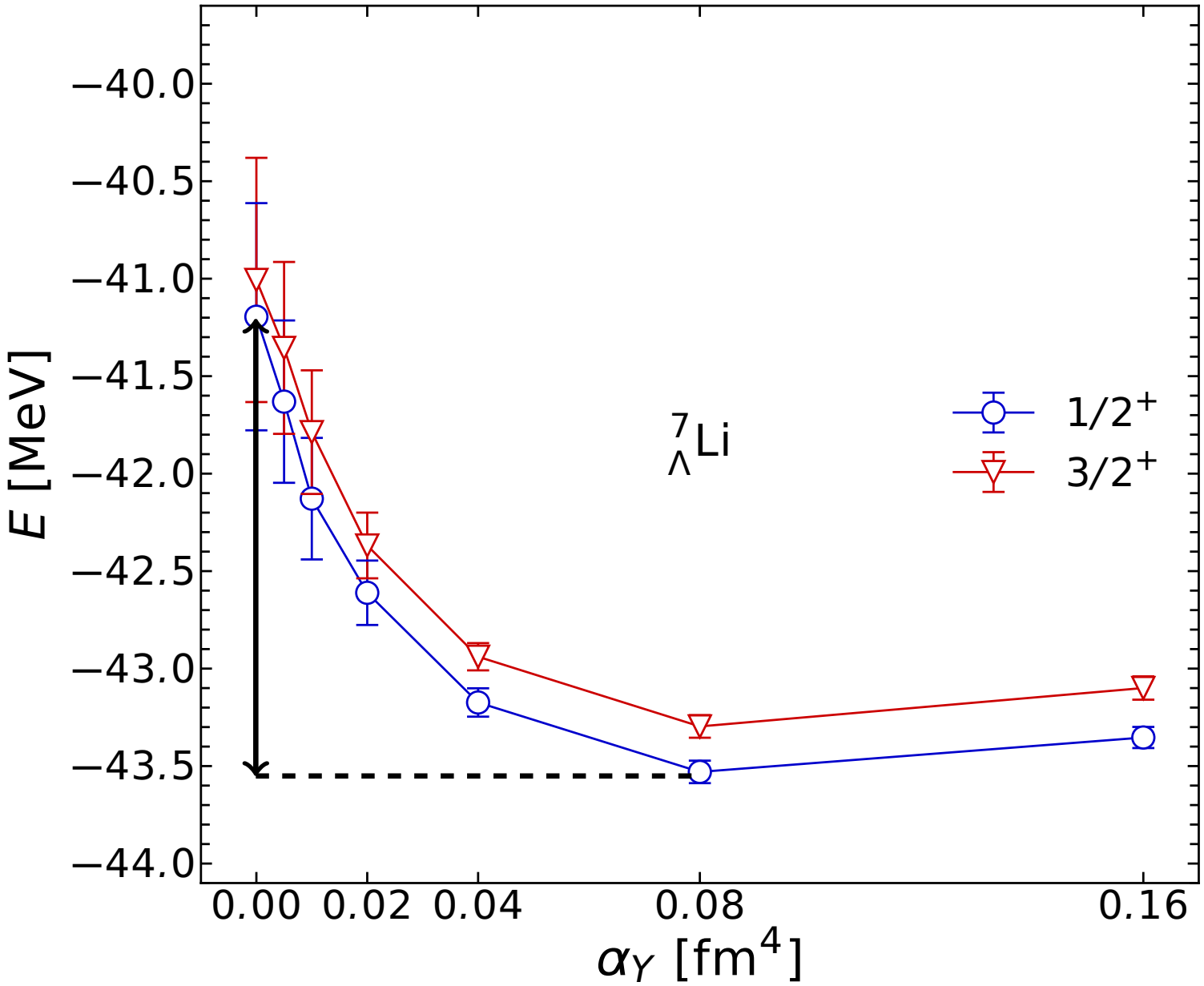

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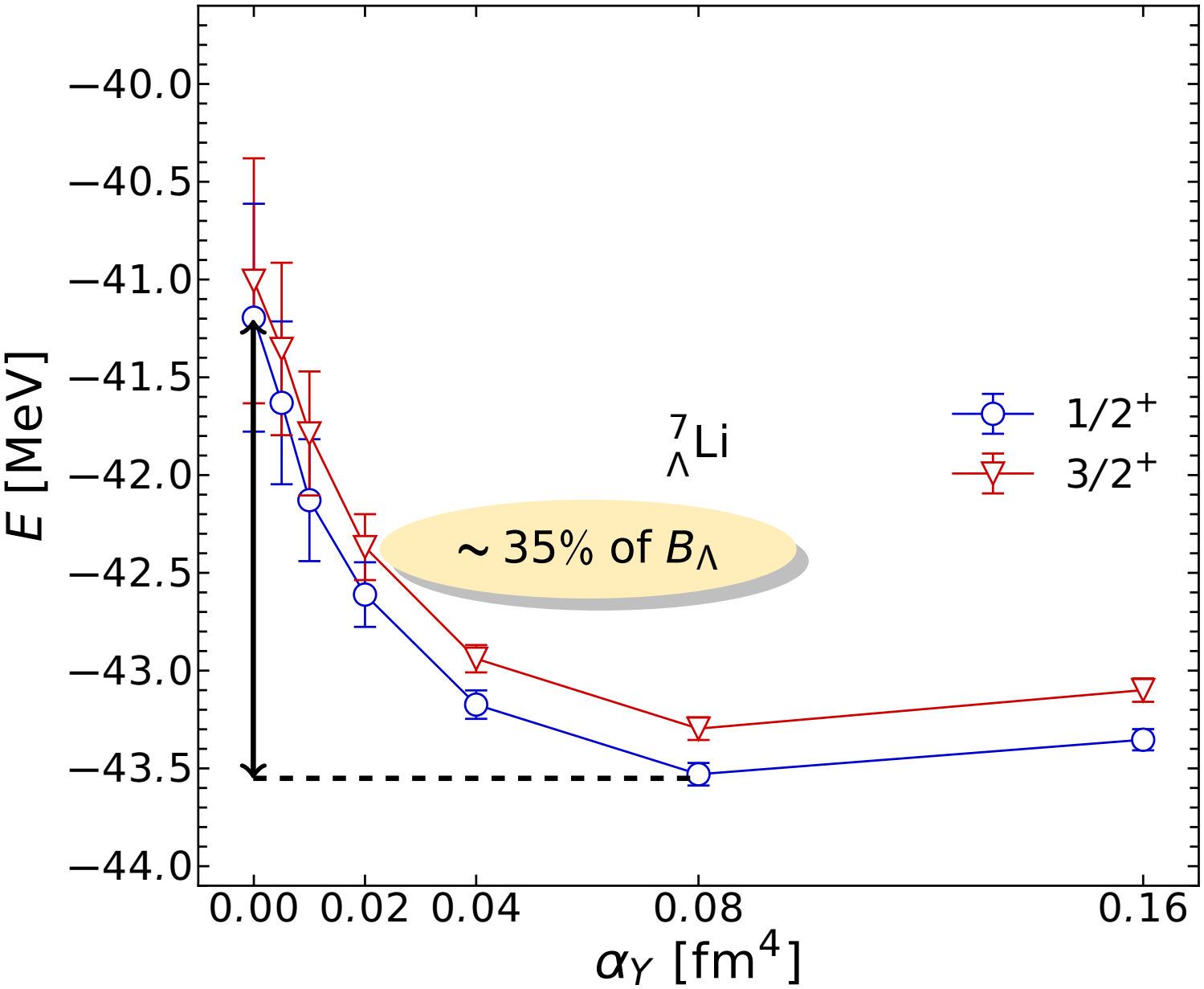

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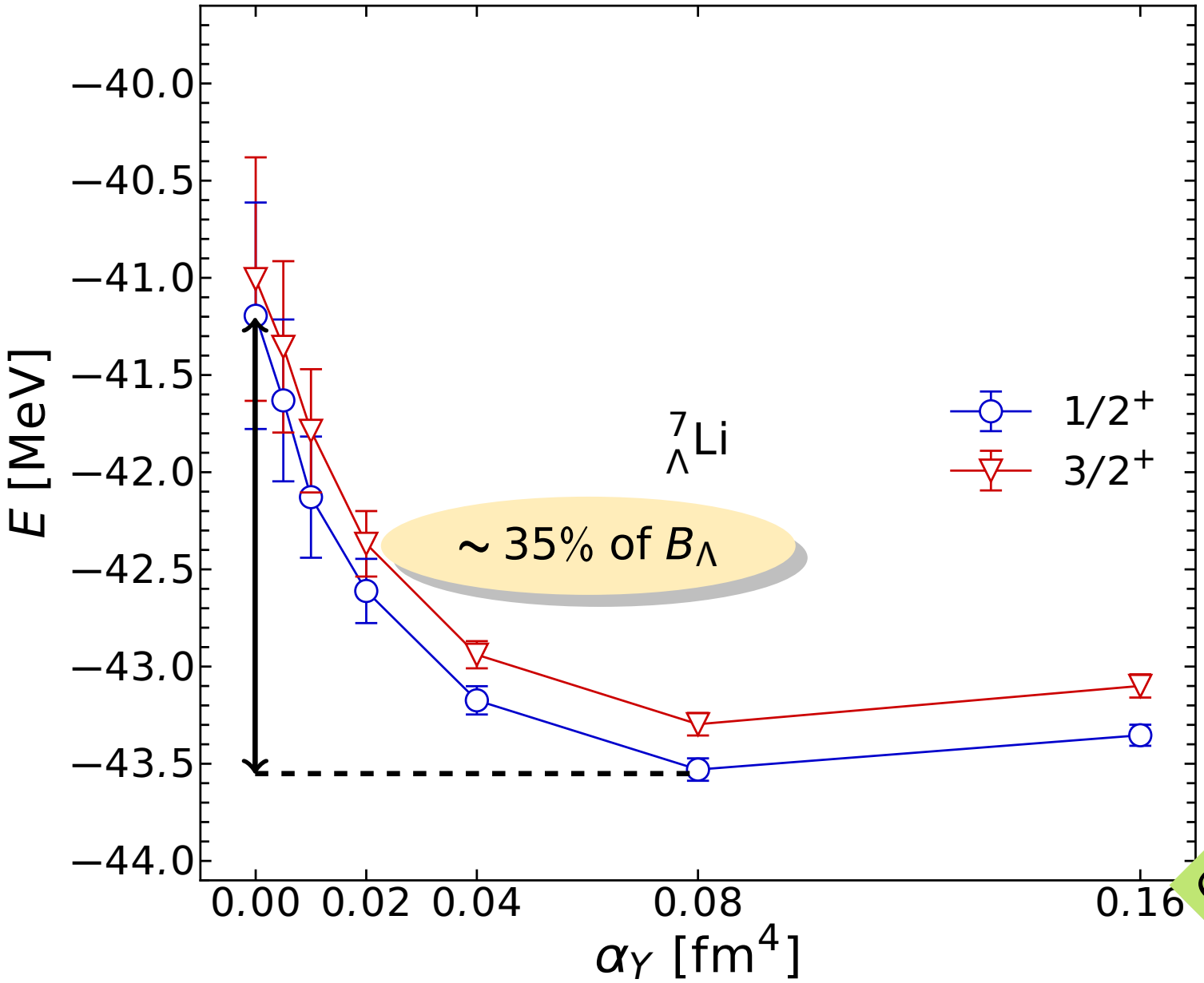

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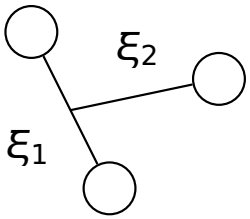
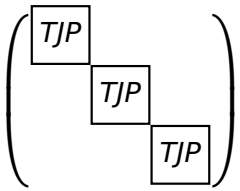
Capture induced YNN terms!

Evolution in Three-Body Space

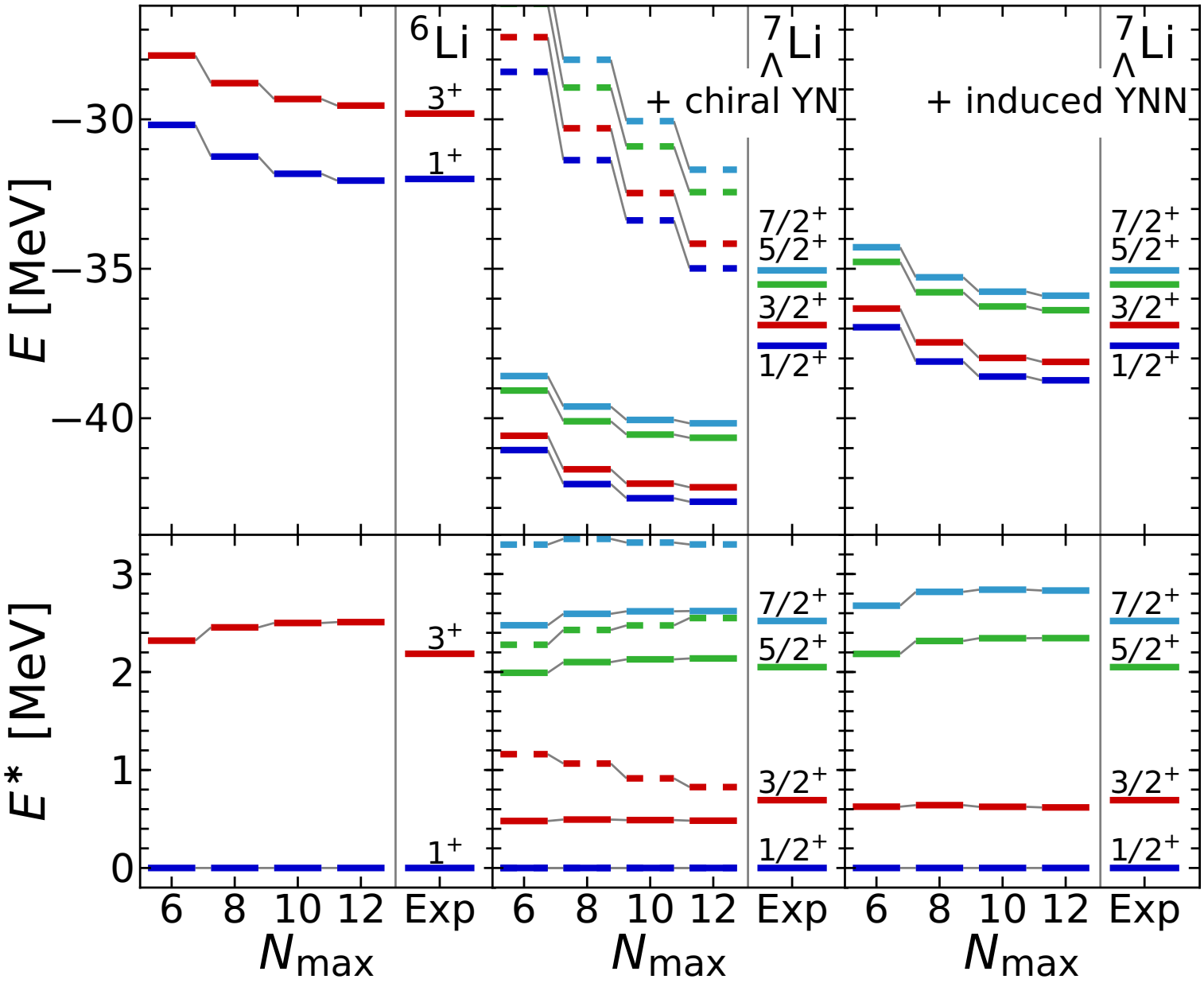




- Introduce Jacobi coordinates and partially antisymmetrized states $|\alpha\rangle$
- Diagonalize antisymmetrizer $\langle\alpha|\mathcal{A}|\alpha'\rangle$
  $\Rightarrow$ Basis $|EiXJT\rangle_a$ (X = ΛNN, ΣNN)
- Hamiltonian decouples into *TJP* blocks
- For each block: Compute matrix elements and solve SRG flow equation
- Transform back to single-particle coordinates (*JT*-coupled matrix elements)

Like 3N, but 3 isospin channels and 2 particle combinations

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



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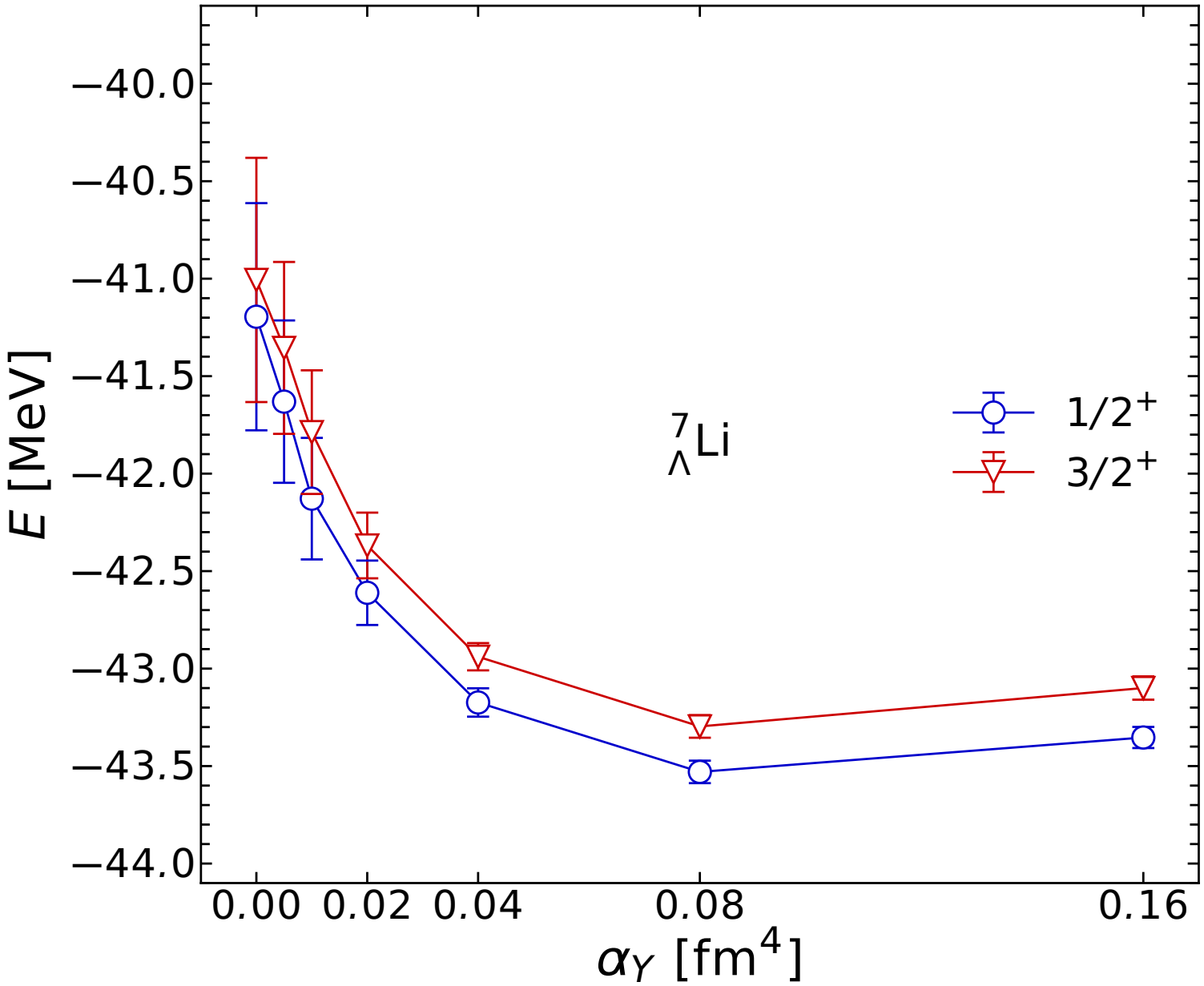
Evolved YN overbinds

Induced YNN improves agreement

Flow Parameter Dependence



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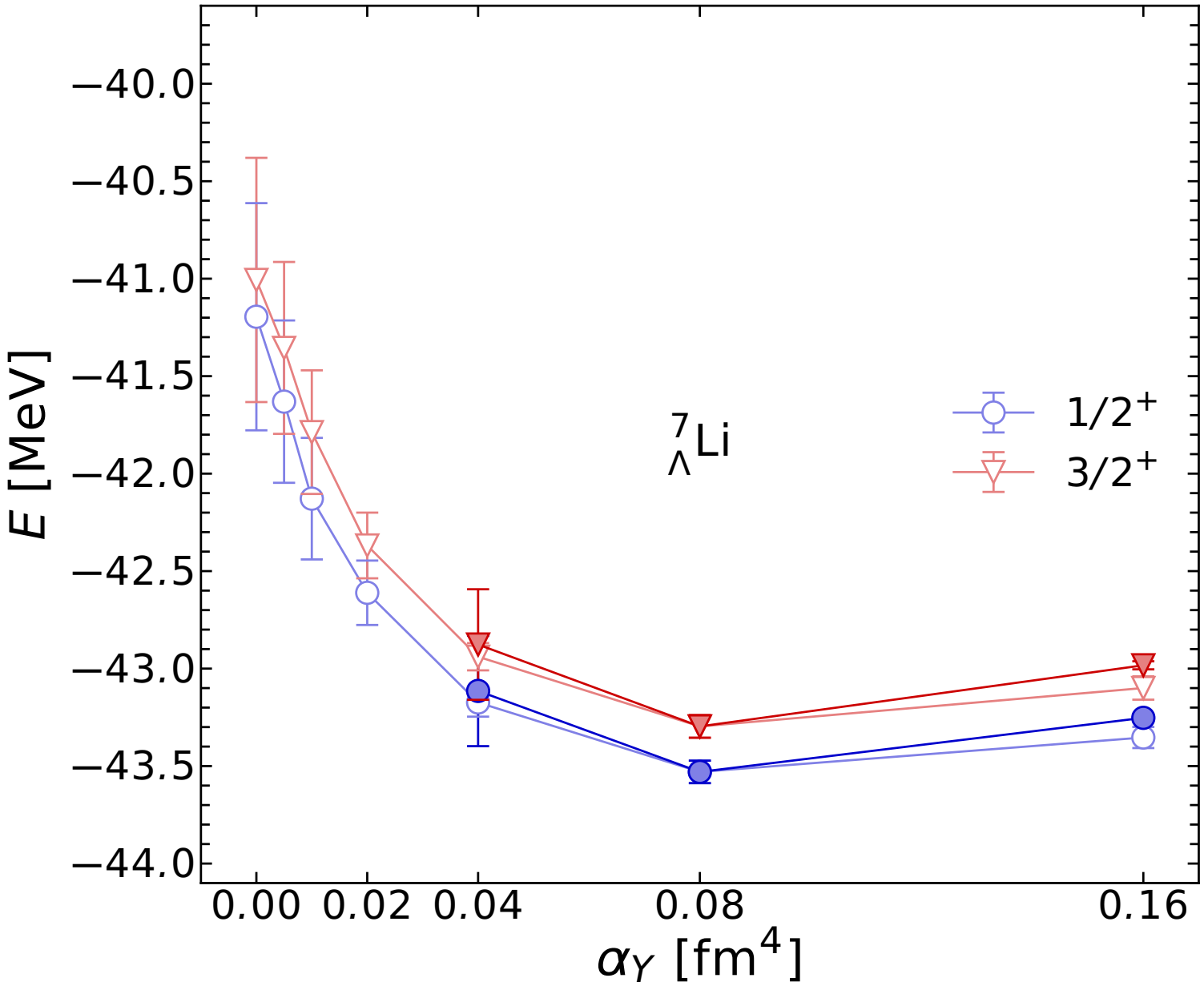

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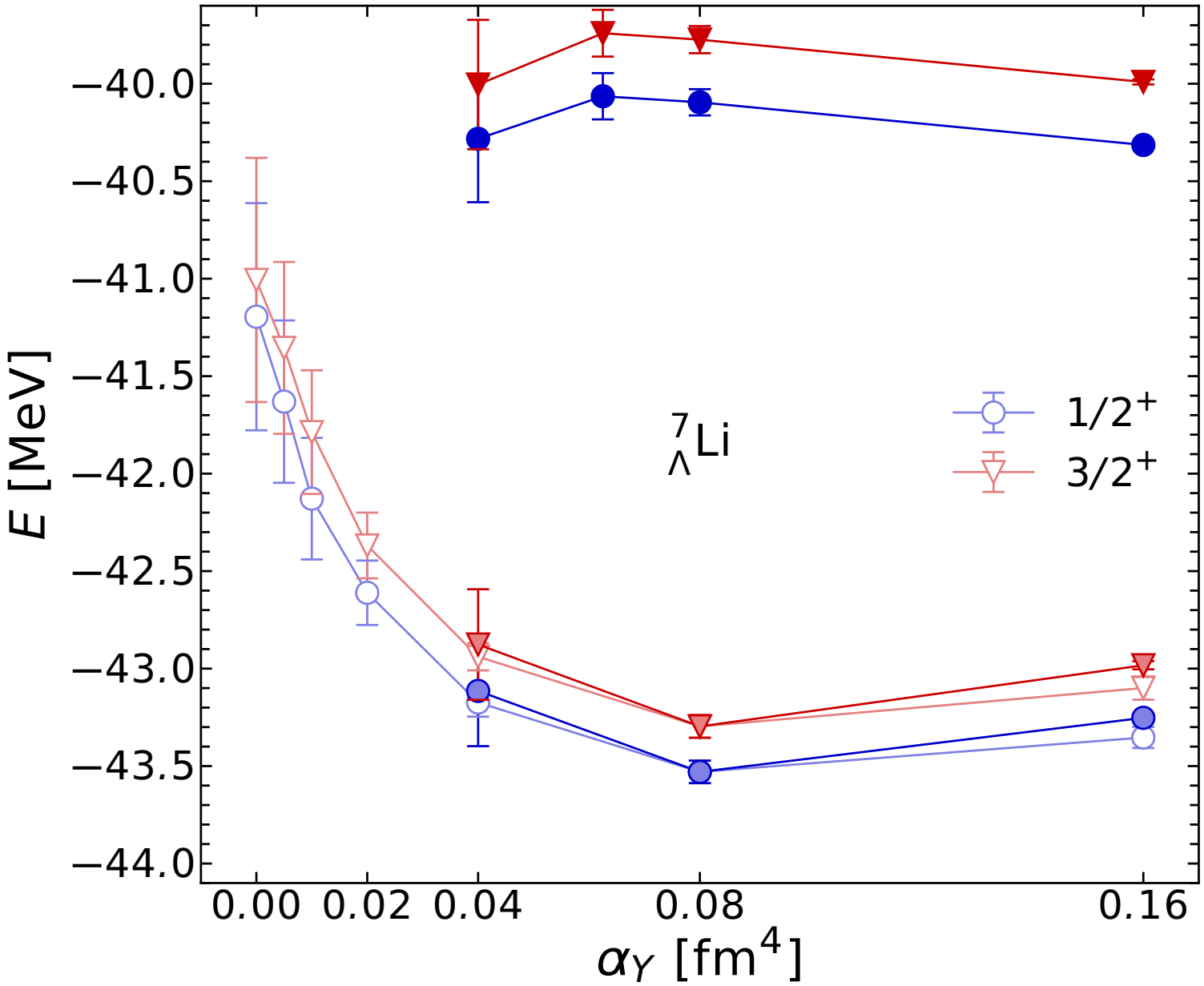

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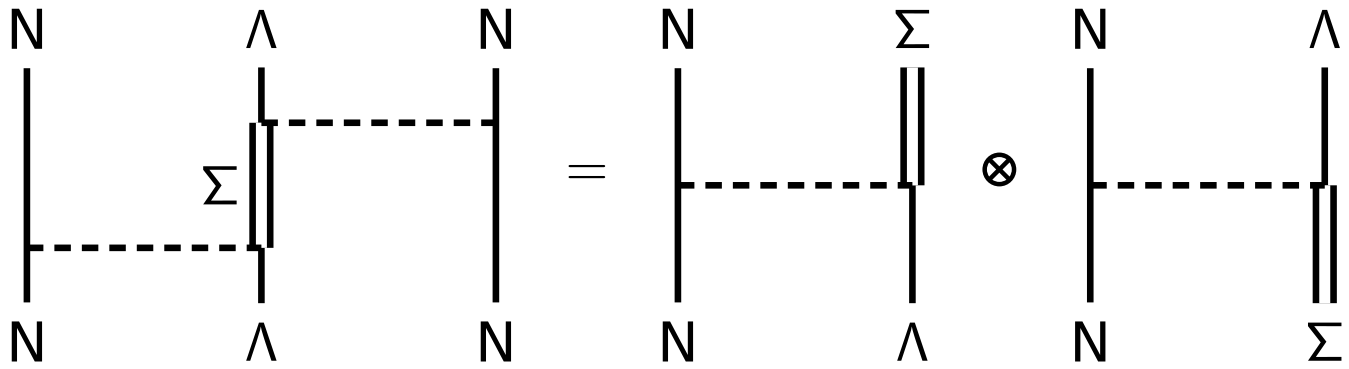
Induced YNN strongly repulsive

Induced YNN reduces α-dependence

Induced YNN Terms

Origin of the Induced Terms

- Two-body evolution suppresses Λ-Σ conversion
- Mechanism for inducing YNN?



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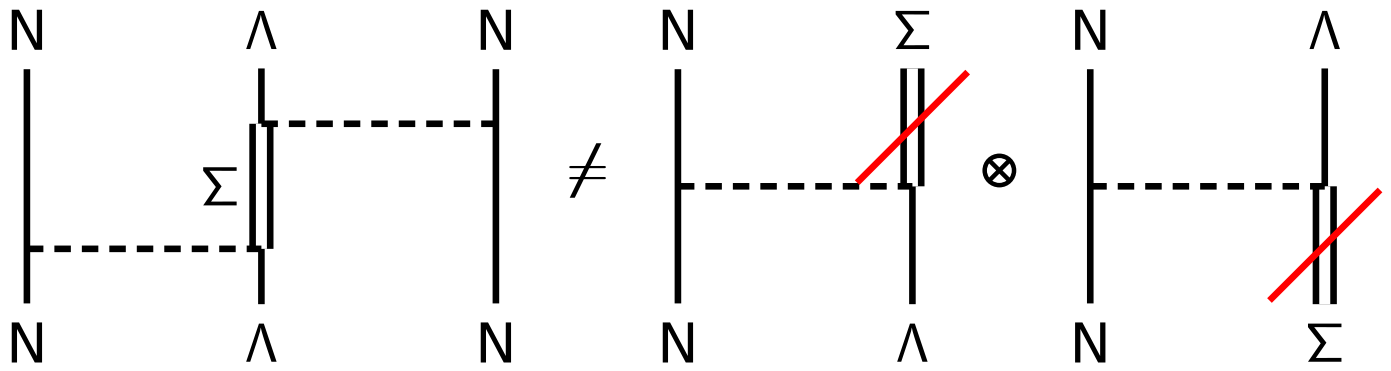


⇒ Induced YNN terms driven by suppression of Λ-Σ conversion?

Origin of the Induced Terms — Wegner SRG

- Explicitly suppress Λ-Σ conversion. **How?**

$$\boldsymbol{H} = \begin{pmatrix} \boldsymbol{H}_\Lambda & \boldsymbol{H}_{\Lambda\Sigma} \\ \boldsymbol{H}_{\Lambda\Sigma}^\dagger & \boldsymbol{H}_\Sigma \end{pmatrix}$$

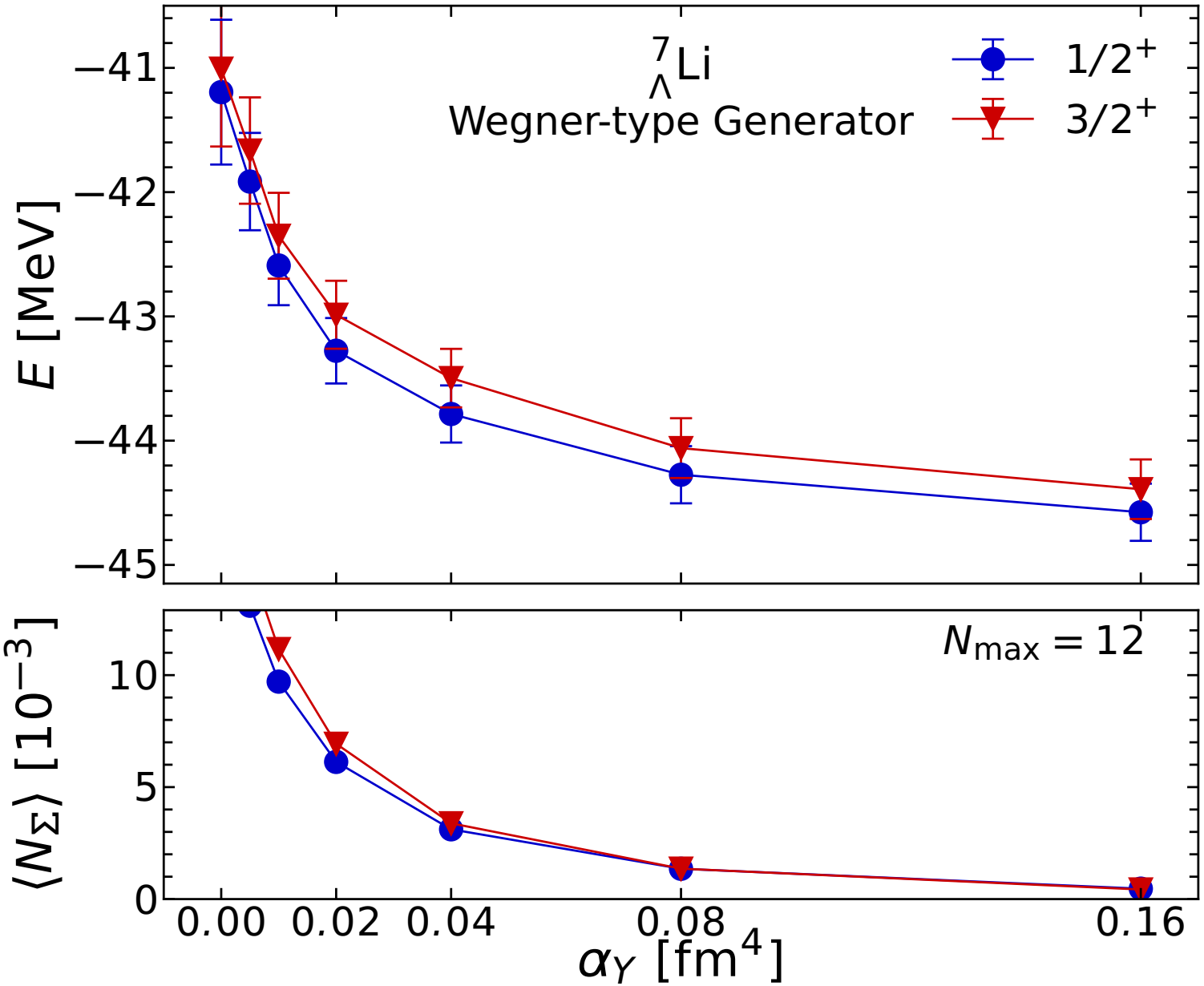
- Wegner SRG generator $\boldsymbol{\eta}_W(\alpha) = [\boldsymbol{H}_\mathrm{d}(\alpha), \boldsymbol{H}(\alpha)]$:

$$\boldsymbol{H}_\mathrm{d} = \begin{pmatrix} \boldsymbol{H}_\Lambda & 0 \\ 0 & \boldsymbol{H}_\Sigma \end{pmatrix}$$

$$\boldsymbol{H} = \begin{pmatrix} \boldsymbol{H}_\Lambda & \boldsymbol{H}_{\Lambda\Sigma} \\ \boldsymbol{H}_{\Lambda\Sigma}^\dagger & \boldsymbol{H}_\Sigma \end{pmatrix} \xrightarrow{\text{SRG}} \begin{pmatrix} \tilde{\boldsymbol{H}}_\Lambda & 0 \\ 0 & \tilde{\boldsymbol{H}}_\Sigma \end{pmatrix}$$

- Integrate out Σ d.o.f., controlled by SRG flow parameter.

Origin of the Induced Terms — Wegner SRG



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Energy and $\langle N_\Sigma \rangle$: same behavior

$\langle N_\Sigma \rangle$ of both states become equal

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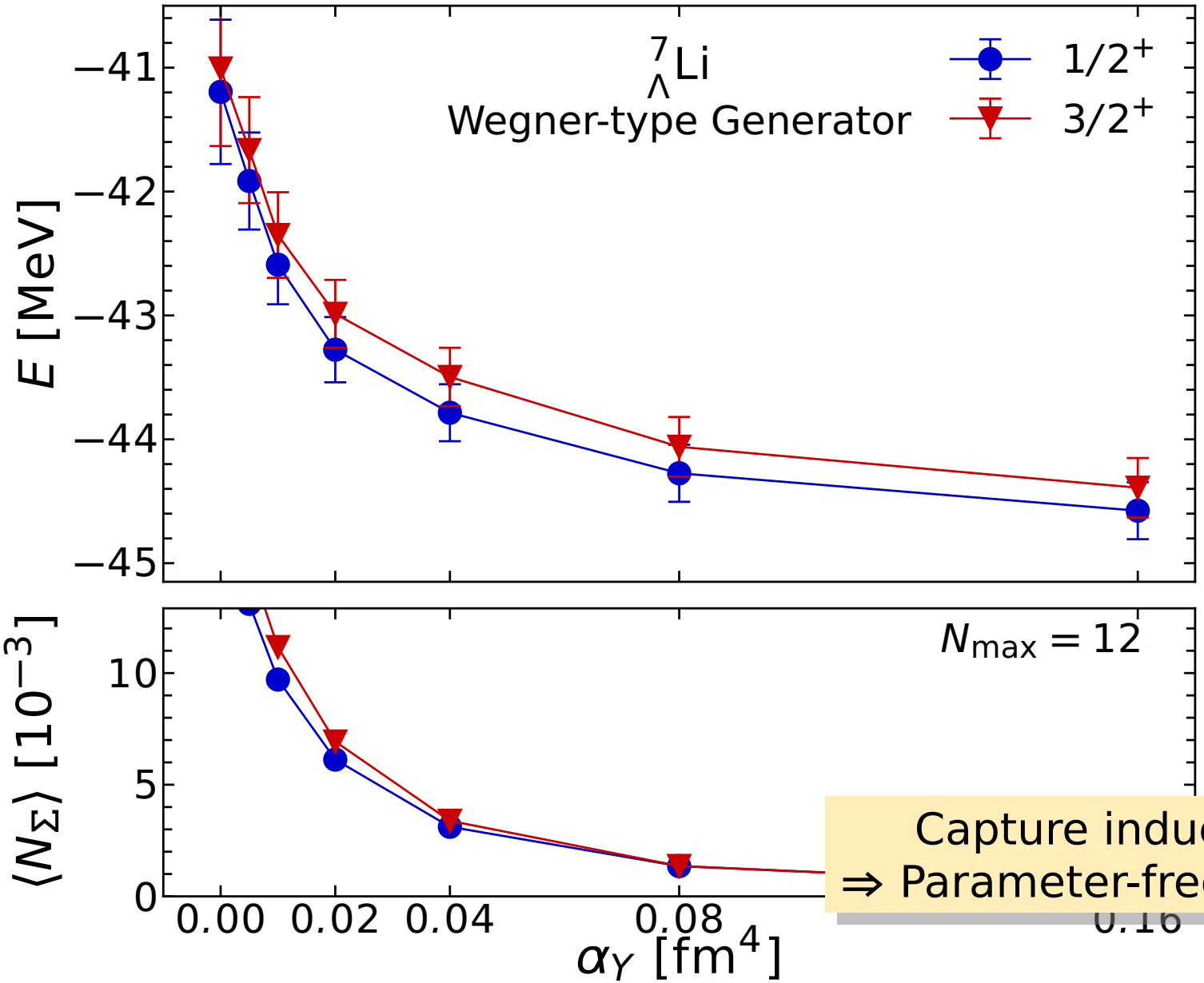

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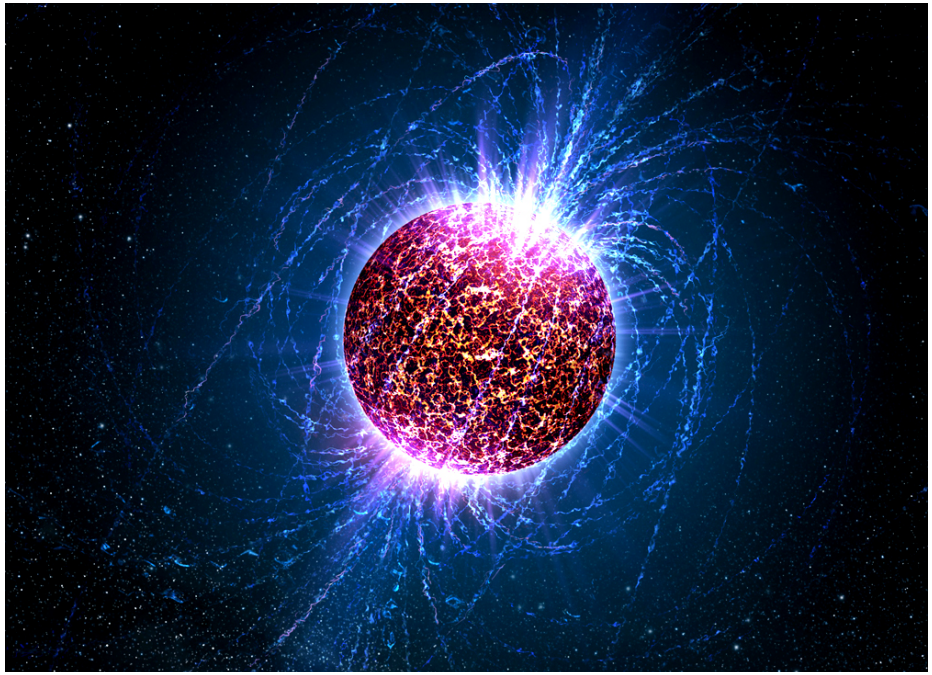
Capture induced YNN
⇒ Parameter-free ΛNN force

Implications for Neutron Star Structure

Neutron Stars — The Hyperon Puzzle



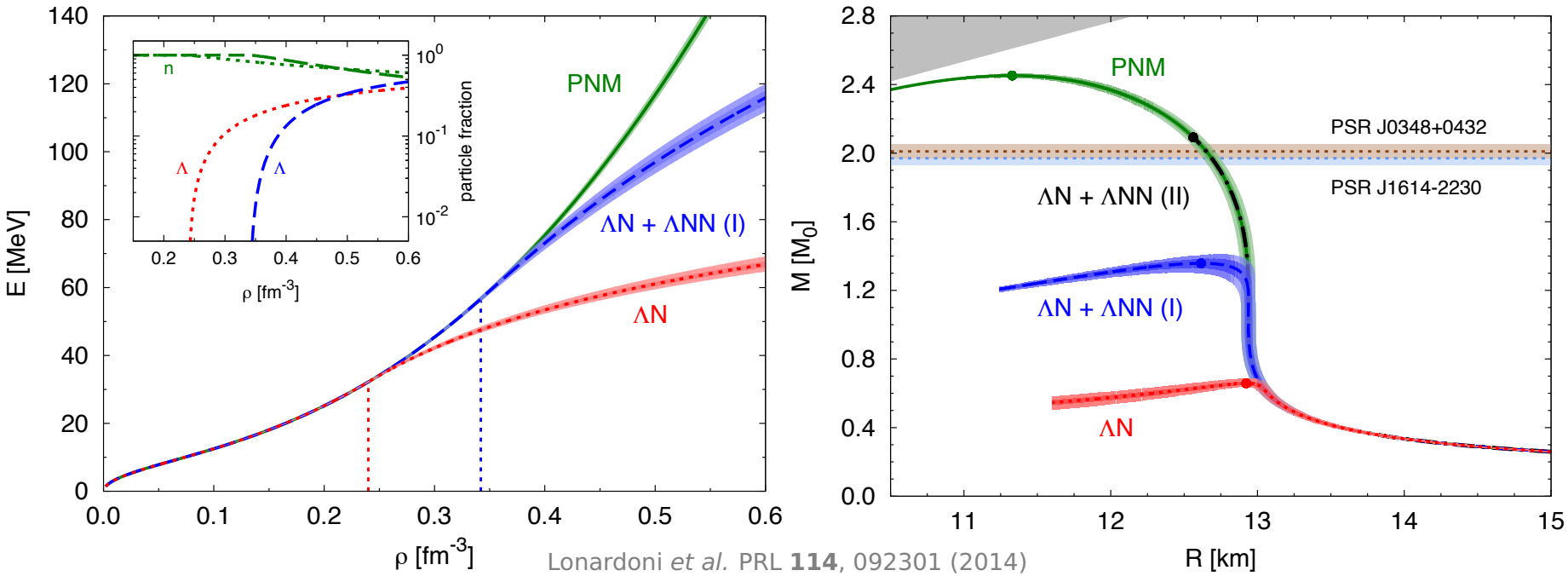
- Expect hyperon production at high densities
- Neutron matter → Strange matter: Add Λ and ΛN interaction
- But: EoS softens too much ⇒ Excluded by $2M_\odot$ NS
- One solution: Add **surprisingly strong** repulsive ΛNN force. **Why?**

Neutron Stars — Calculating Strange Matter

Auxiliary Field Diffusion Monte Carlo

Lonardoni *et al.* PRL **114**, 092301 (2014)
Lonardoni *et al.* PRC **89**, 014314 (2013)

- Simple Hamiltonian in operator form: AV8’ + UIX + ΛN + ΛNN
- Heavy hypernuclei and matter accessible in same framework
- Two fits for ΛNN:
  ΛNN(I) fits B_Λ of ${}^{5}_{\Lambda}$He and ${}^{17}_{\Lambda}$O in **Variational MC**,
  ΛNN(II) reproduces both in **AFDMC**



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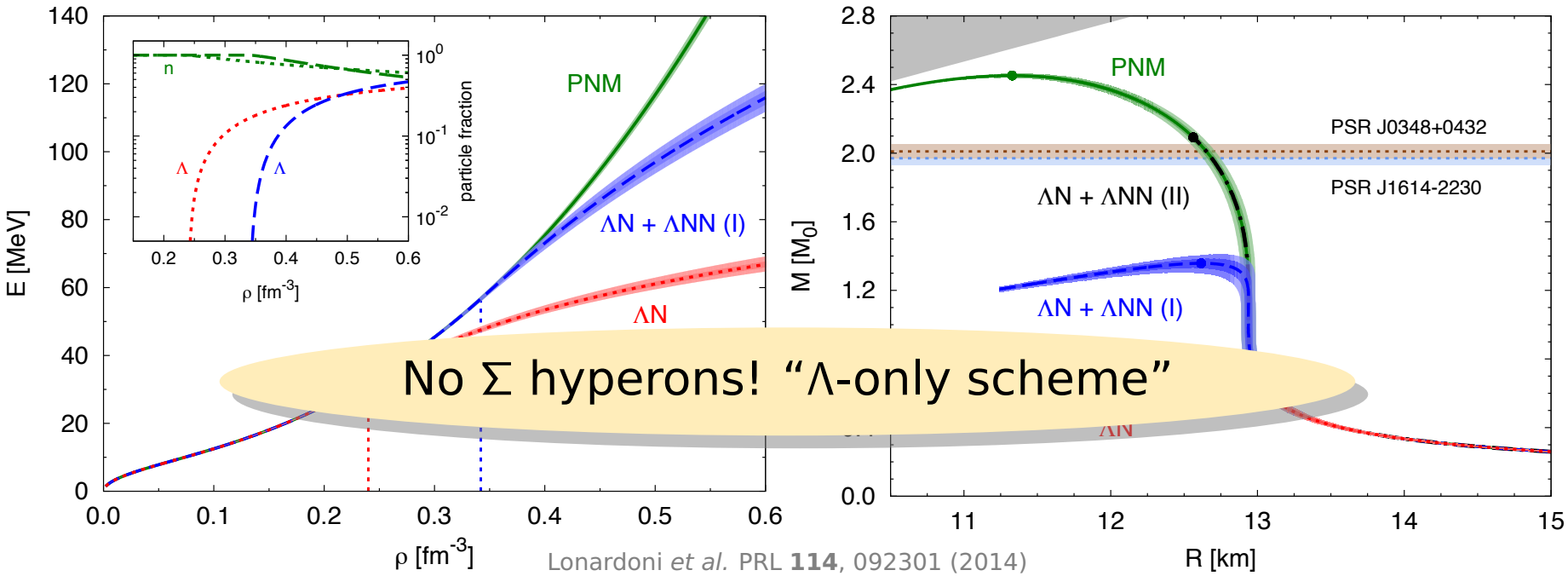

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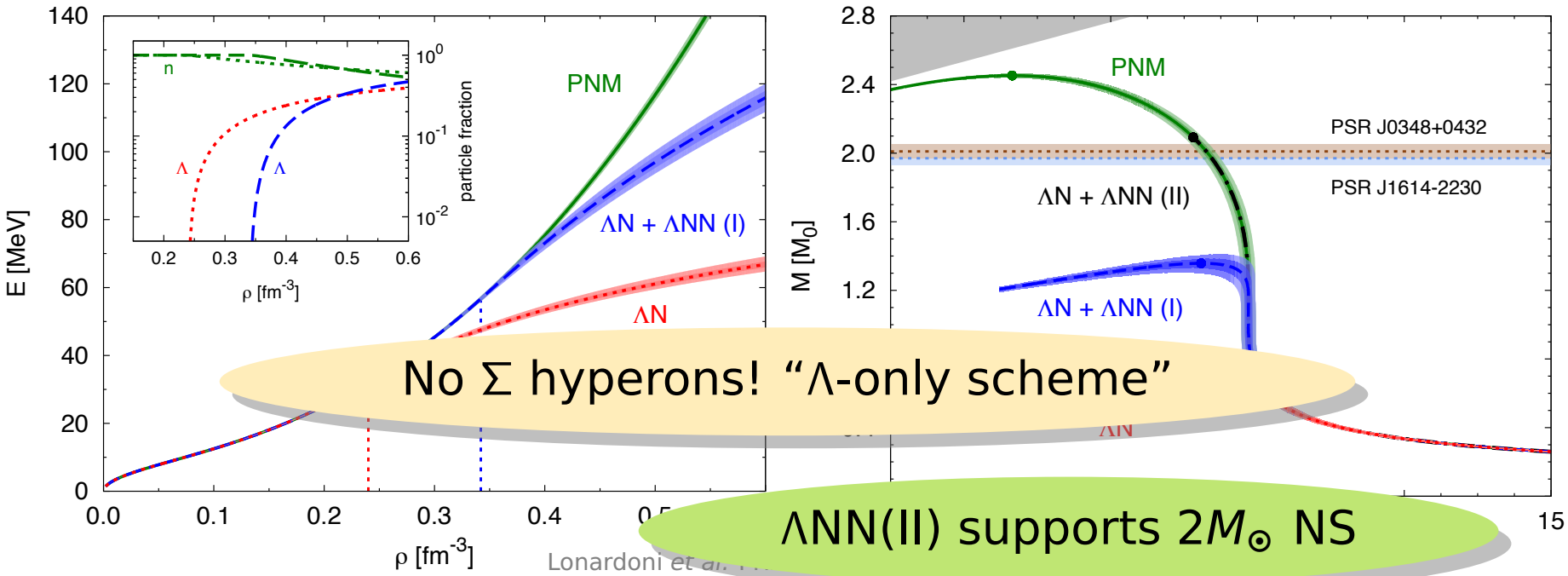
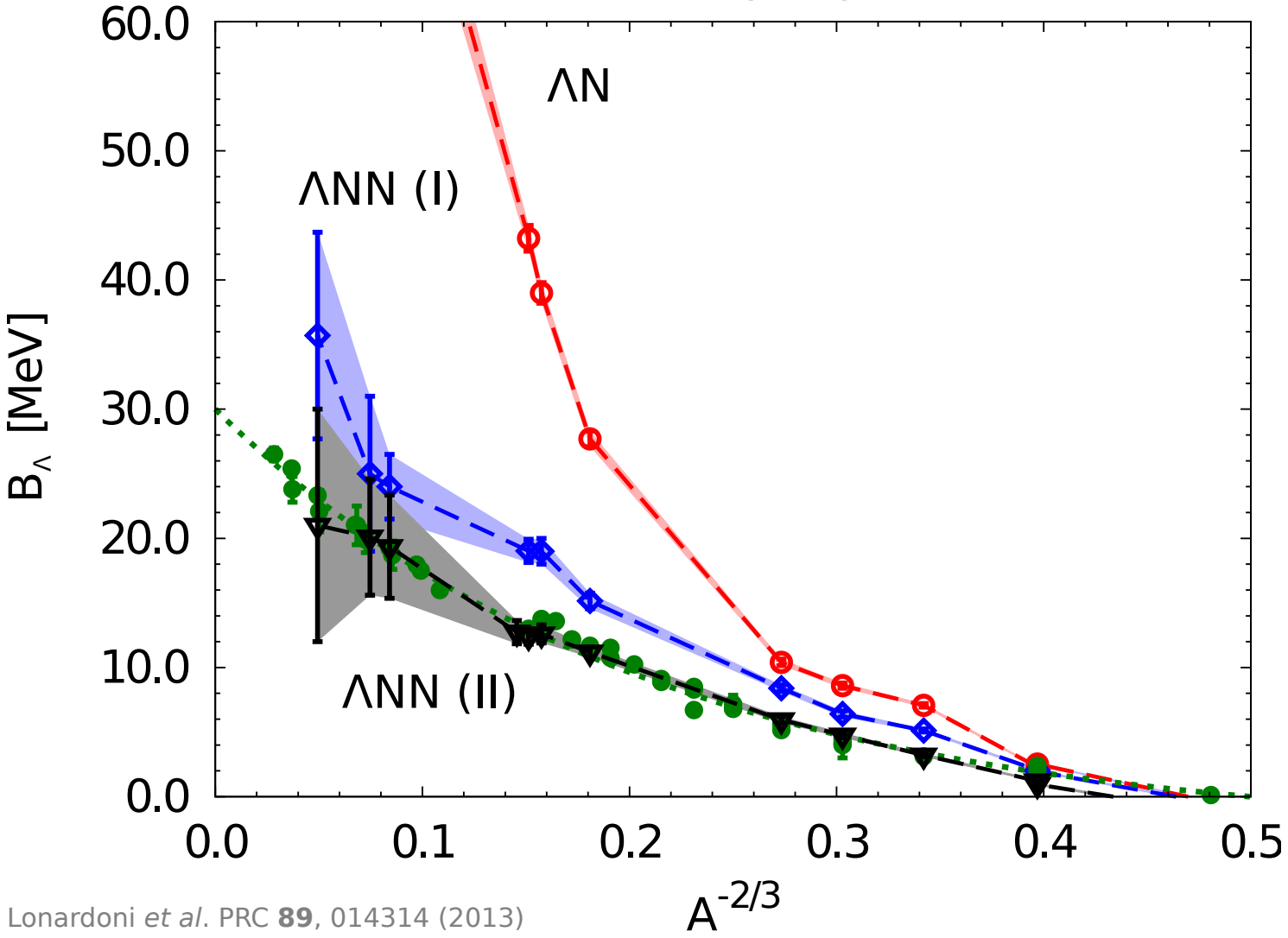


The Hyperon Puzzle — Three-Body Forces

What if we take full Λ-Σ coupling into account?



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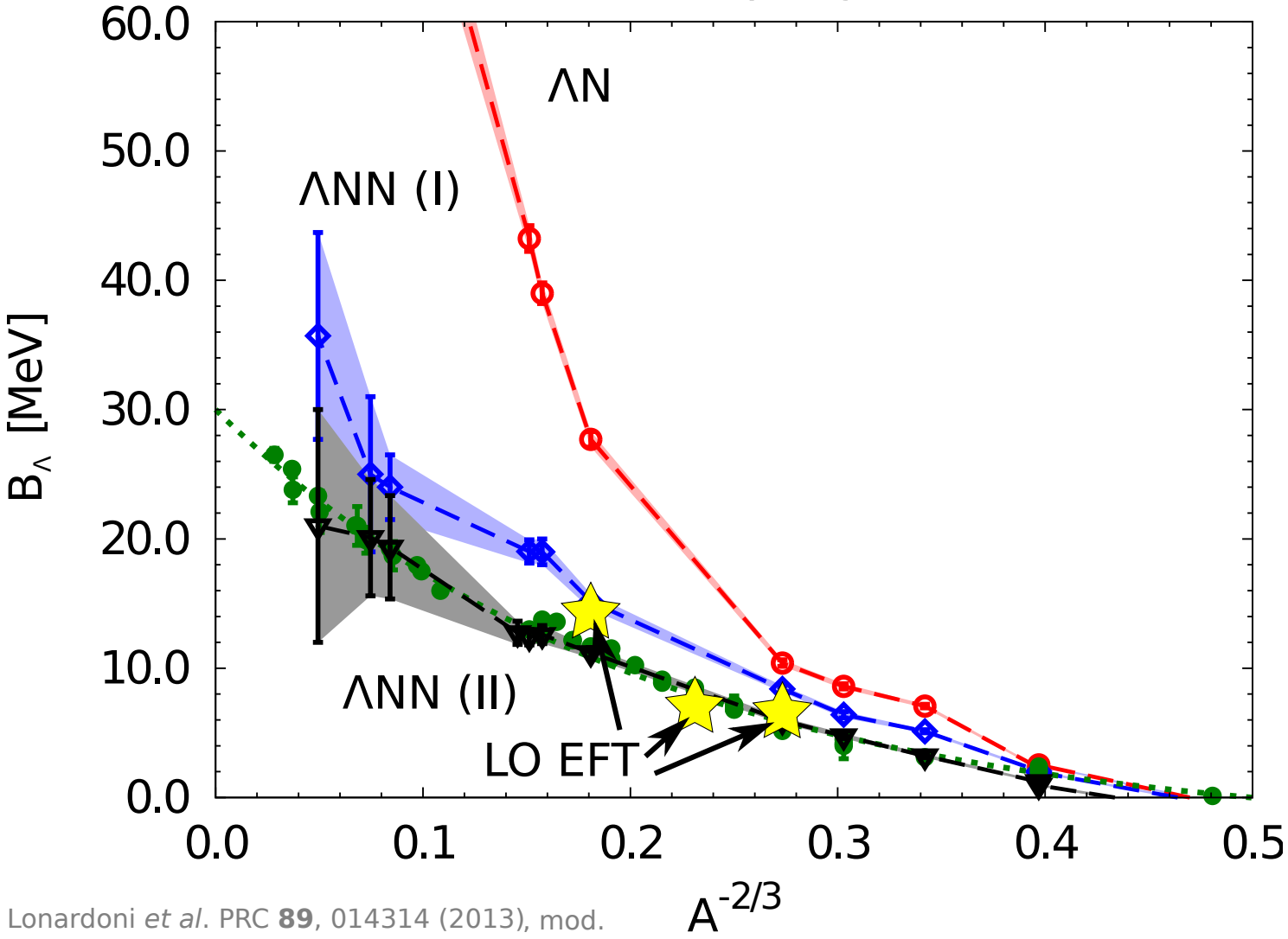

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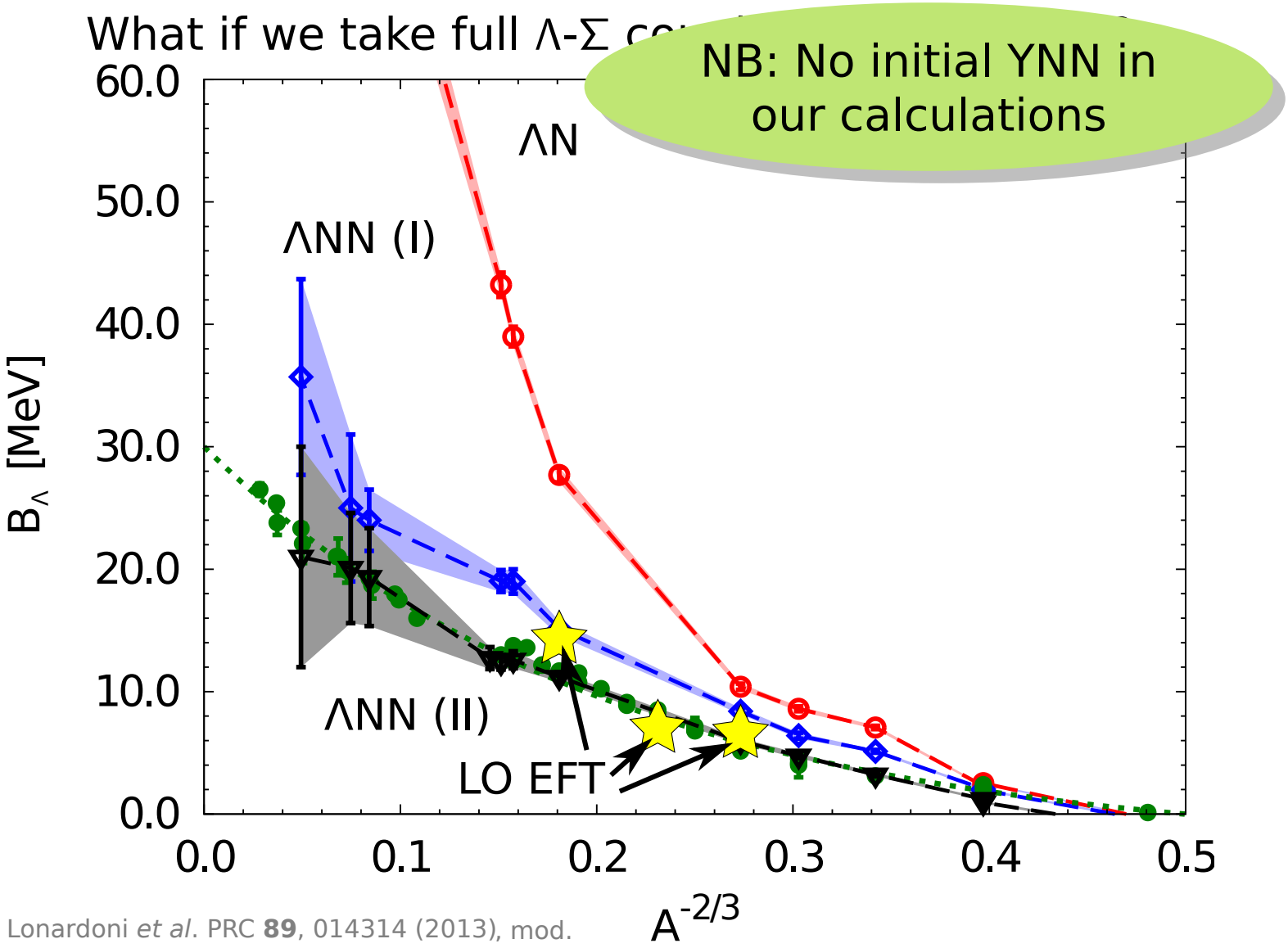

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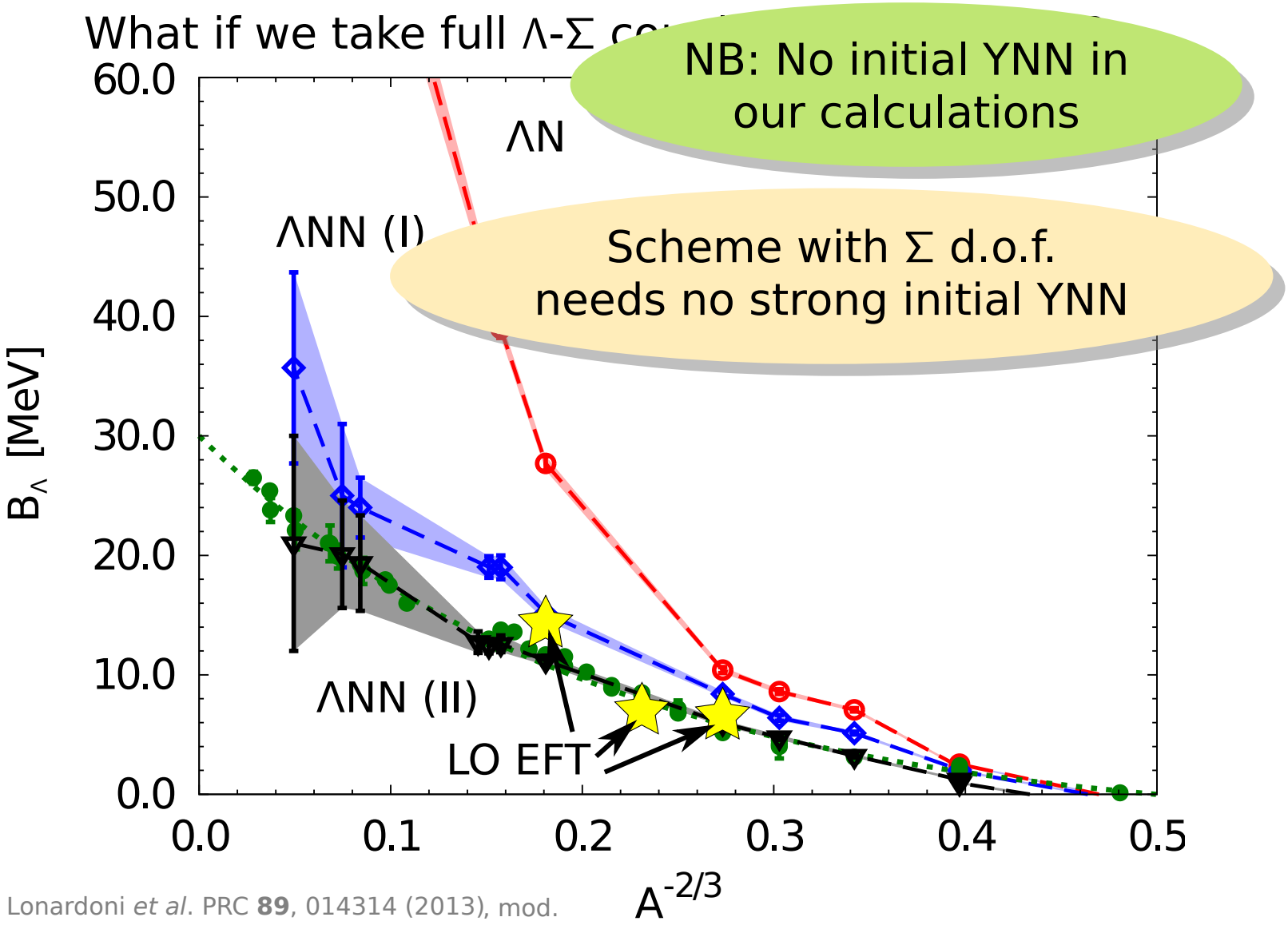

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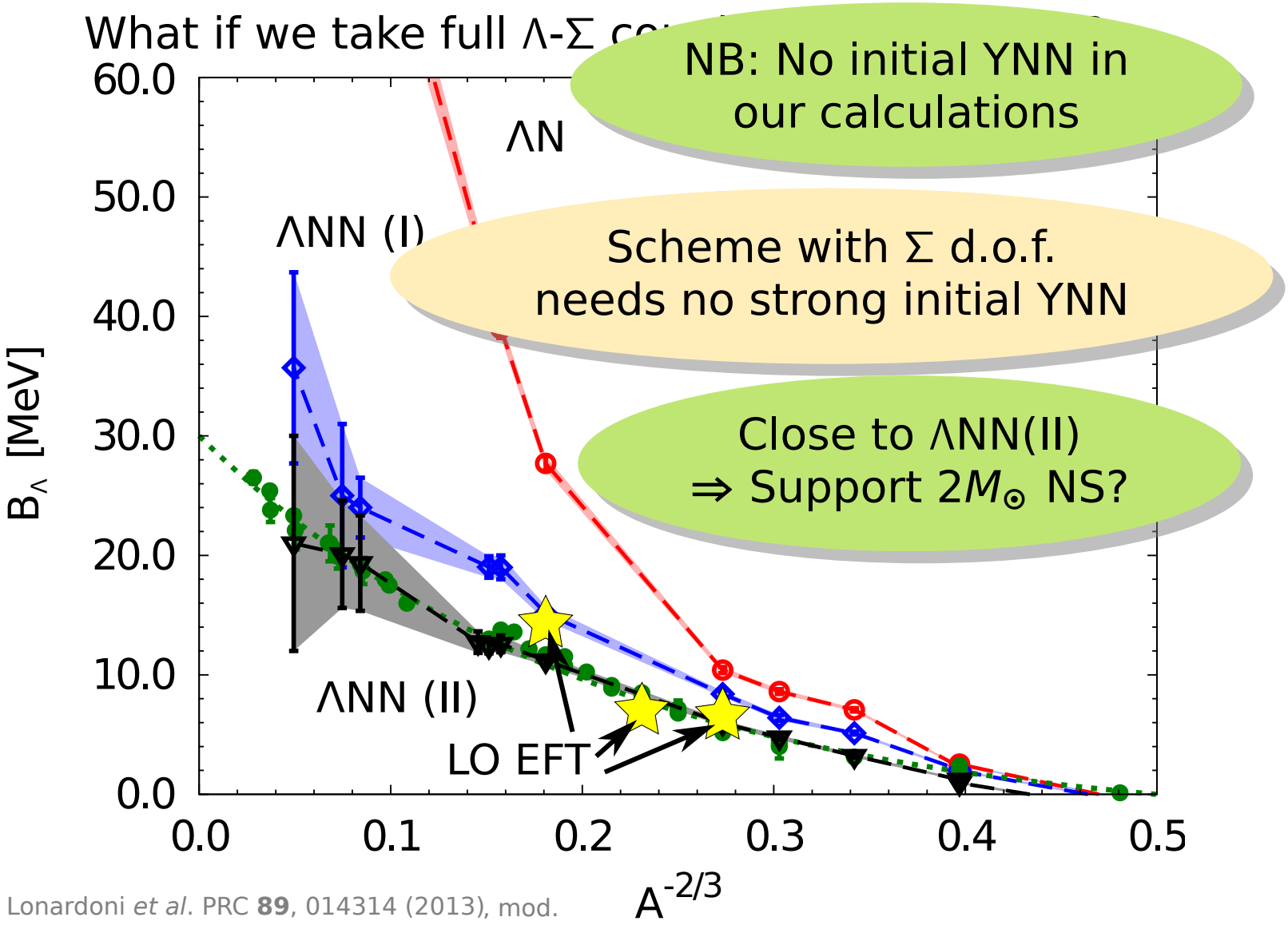

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Summary & Outlook

- SRG-induced YNN must be accounted for
  ⇒ Good reproduction of data
- Induced YNN driven by suppression of Λ-Σ conversion
  ⇒ Integrating out (high-energy) Σ d.o.f. generates many-body forces
- Scheme-dependence of the Hyperon Puzzle
  ⇒ Size of three-body forces depends on choice of d.o.f.
  ⇒ SRG as a tool to transform between schemes

- Analyze interaction: NLO, LEC variation at LO
- Build systematics: more *p*-shell hypernuclei
- Calculate matter with induced three-body terms

Epilog

- **Thanks to my group**
  - S. Alexa, S. Dentinger, E. Gebrerufael, T. Hüther, L. Kreher, L. Mertes, **R. Roth**, S. Schulz, H. Spiess, C. Stumpf, A. Tichai, R. Trippel, K. Vobig

    Institut für Kernphysik, TU Darmstadt

- **Thank you for your attention!**

JURECA JÜLICH FORSCHUNGSZENTRUM

LOEWE-CSC Center for Scientific Computing Frankfurt

LICHTENBERG HRZ Hochschulrechenzentrum

COMPUTING TIME

SFB 1245

Deutsche Forschungsgemeinschaft DFG

HIC for FAIR Helmholtz International Center

LOEWE Exzellente Forschung für Hessens Zukunft

HELMHOLTZ GEMEINSCHAFT

Bundesministerium für Bildung und Forschung