Light Neutron-Rich Hypernuclei from the IT-NCSM

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Motivation

- Explore (broken) symmetries of strongly-interacting matter with strange baryons (hyperons).
- Apply χEFT ideas to general baryon-baryon interaction, treating π, K, η as pseudo-Goldstone bosons.
- Few scattering data, determination of LECs challenging.
- But: structure of hypernuclei experimentally accessible through multiple reaction channels
  ⇒ Hyperon separation energies.
  ⇒ Excited levels via decay γ rays.
- Baryon-baryon interaction has impact on appearance of hyperons in neutron-star matter
  ⇒ Influence on mass-radius relation and maximum mass.
  ⇒ Connection to and constraints from astrophysics.
- Use *ab initio* framework as link between data and interactions to select and improve models.
- Leading-order χEFT hyperon-nucleon interaction provides surprisingly good description of observables. But: need explicit YNN terms for SRG-evolved YN.
- Explore experimentally inaccessible parts of the hypernuclear landscape
  ⇒ Go neutron-rich.

Including Induced *YNN* Forces

- Similarity Renormalization Group (SRG) transformation of the Hamiltonian induces strong repulsive YNN terms $\tilde{V}_{YNN}$ [1]:

$$T_{\text{int}} + V_{NN} + V_{YN} + V_{3N}$$
$$\downarrow \text{SRG}$$
$$\tilde{T}_{\text{int}} + \tilde{V}_{NN} + \tilde{V}_{YN} + \tilde{V}_{3N} + \tilde{V}_{YNN}.$$

- Include terms in IT-NCSM calculation explicitly.
  ⇒ Solve SRG flow equation in three-body space:

$$\partial_\alpha H_\alpha = (2m_N)^2 [[T_{\text{int}}, H_\alpha], H_\alpha], \quad H_{\alpha=0} = H.$$

- Use Jacobi HO basis to separate center-of-mass d.o.f. and keep basis sizes manageable, truncate total energy $E \leq E_{3,\max}$.
- Isolate genuine three-body part by subtracting two-body interaction evolved *in two-body space*.
- Adapt HO basis parameter $\hbar\Omega$ from value optimal for SRG evolution to value providing optimal $N_{\max}$ convergence of target observables.
- Convert to single-particle coordinates.
- Decouple to m scheme during many-body calculation.

Hypernuclear Importance-Truncated NCSM [2]

- Starting point: SRG-evolved Hamiltonian with NN+3N interaction [3, 4], YN interaction [5, $\Lambda_Y = 700\,\text{MeV/c}$]:

$$H = T_{\text{int}} + M + V^{[2]} + V^{[3]}.$$

- Expand Hamiltonian on finite Slater Determinant basis.
- Single-particle basis $|n(ls)jm, \mathscr{S} t m_t\rangle$: harmonic oscillator ($\hbar\Omega = 20\,\text{MeV}$), additional strangeness quantum number $\mathscr{S}$ in isospin part.
- Include all particle species combinations with correct charge and strangeness, e.g. $np\Lambda$, $pp\Sigma^-$, $np\Sigma^0$, $nn\Sigma^+$.
- Limit number of HO excitation quanta to $N_{\max}$
- Compute matrix representation of H, diagonalize.

Importance Truncation

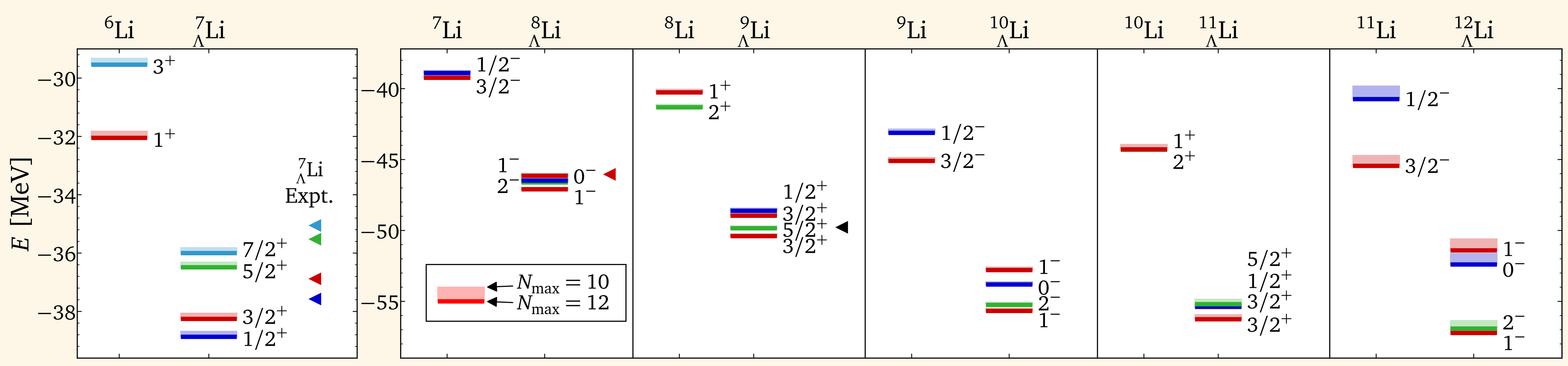
- Many basis states contribute very little to low-lying states.
  ⇒ Neglecting introduces only small error.
- Estimate contribution for basis state $|\phi_i\rangle$ from 1st-order perturbation theory

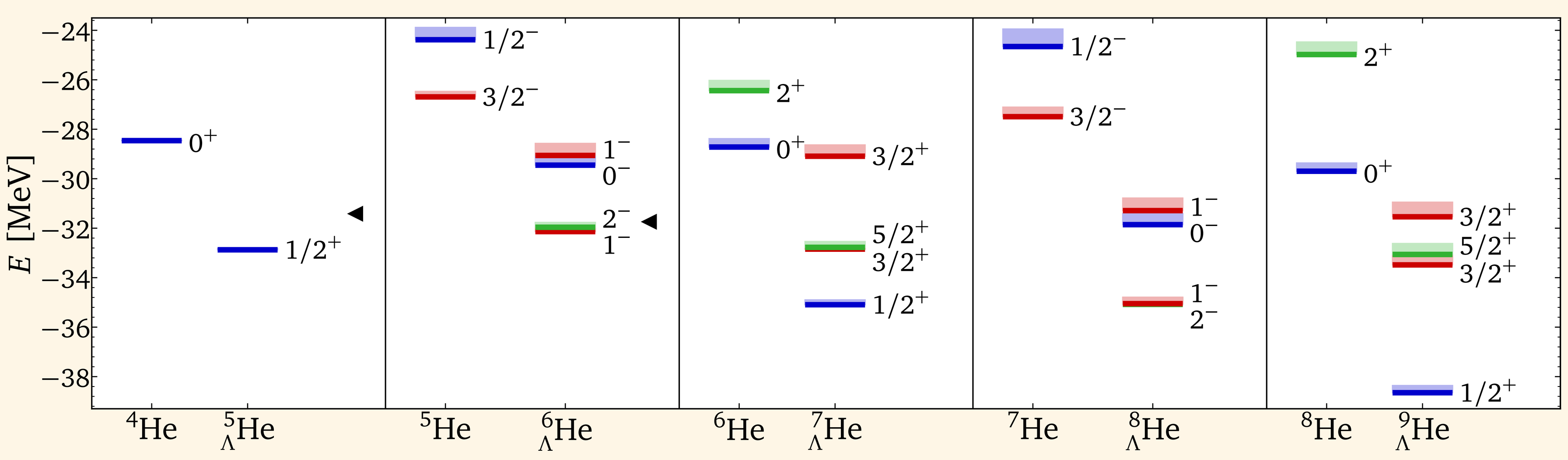
$$\kappa(|\phi_i\rangle) = -\frac{\langle\phi_i|H|\psi_{\text{ref}}\rangle}{\Delta\epsilon_i}.$$

State $|\psi_{\text{ref}}\rangle$: approximation to target state from smaller model space. Unperturbed energy difference $\Delta\epsilon_i$ contains Λ-Σ mass difference.

- Build IT model space $\mathscr{M}(\kappa_{\min}) = \{|\phi_i\rangle : |\kappa(|\phi_i\rangle)| \geq \kappa_{\min}\}$.
- Diagonalize for multiple thresholds $\kappa_{\min}$, extrapolate $\kappa_{\min} \to 0$ to recover full-space result.
- Raise $N_{\max}$ until convergence, use eigenstate $|\psi\rangle$ from $N_{\max}$ as $|\psi_{\text{ref}}\rangle$ for $N_{\max}+2$.

Ground- and Excited-State Energies

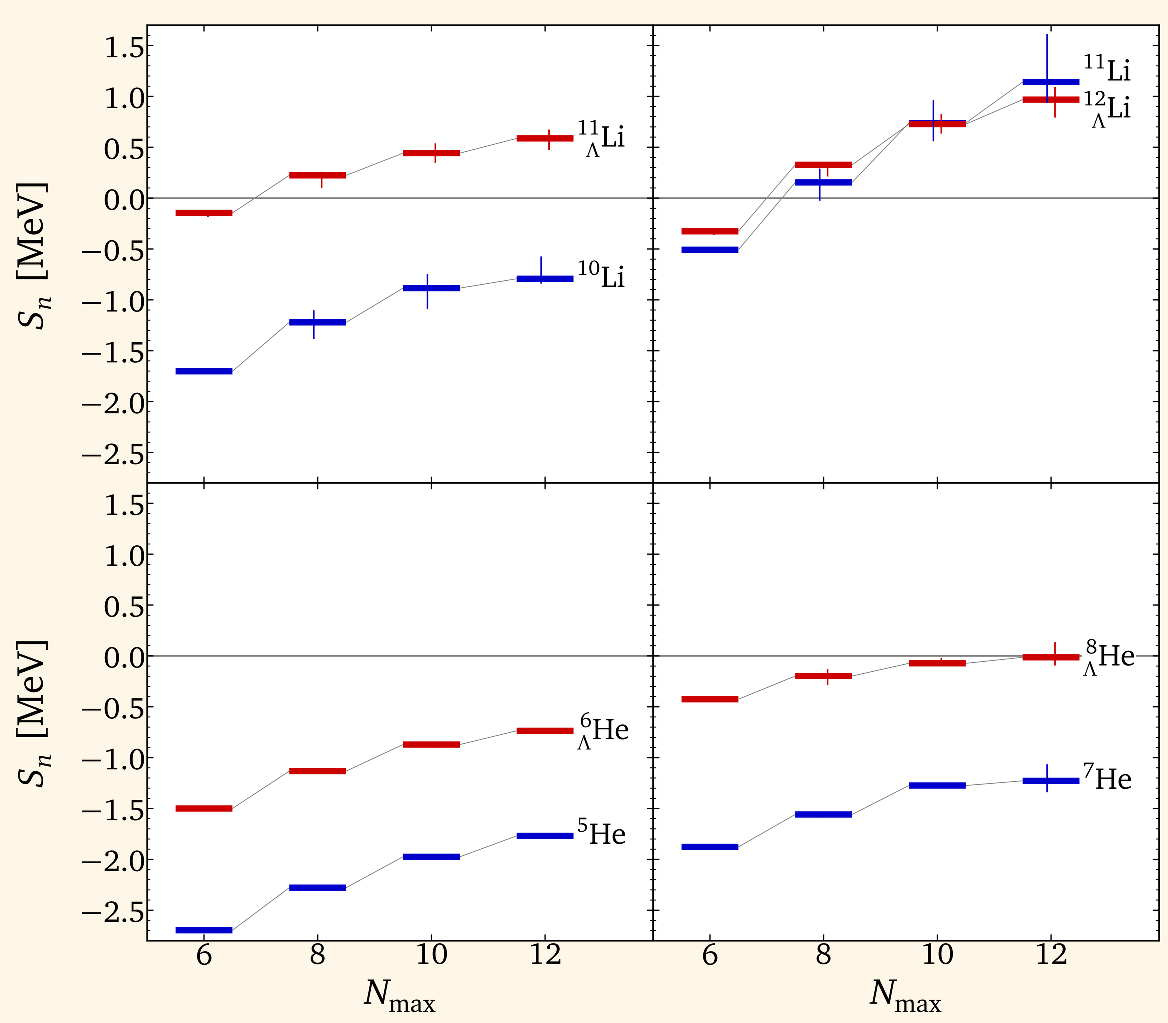




- Good reproduction of experimental data [6, 7].
- Strong odd-even staggering in helium chain, not present in lithium.
- Data suggests $^6_\Lambda$He is particle stable, calculation predicts it unstable.

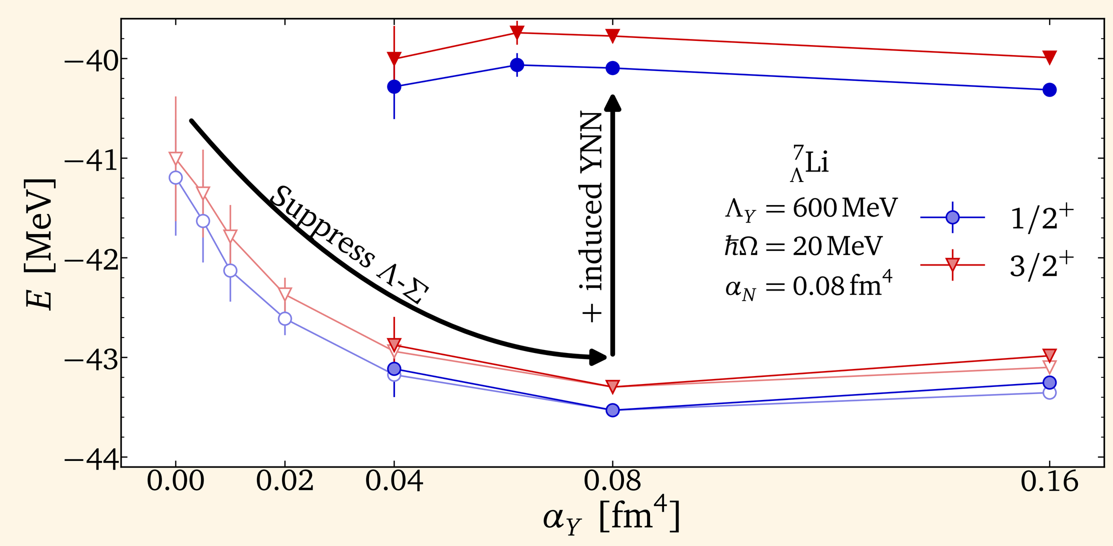
Shifting the Neutron Dripline with Hyperons

- Presence of a hyperon can strongly modify properties of hypernucleus compared to nucleonic parent.
- Additional attraction provided by hyperon-nucleon interaction can stabilize particle-unstable cores.
- Hyperon separation energy increases by approx. 1 MeV per additional nucleon; effect more pronounced in heavier hypernuclei.
- Sample cases:
  - $^6_\Lambda$He: not enough to stabilize.
  - $^6_\Lambda$He & $^{11}_\Lambda$Li: hyperon provides additional binding to stabilize nucleonic cores.
  - $^{12}_\Lambda$Li: No additional neutron binding. Indication of proximity to neutron drip line?
- Caveat: YN force overbinds $^5_\Lambda$He ⇒ S_n of $^6_\Lambda$He too small



The Hyperon Puzzle

- Nuclear matter at high tends to favor conversion of nucleons to hyperons: less energy needed to add low-momentum hyperon than for a nucleon at k_F.
- Hyperon-nucleon interaction can enhance or suppress conversion, also modifies compressibility.
- Conventional calculations: conversion causes softening of matter EoS, very small maximum neutron-star masses (*hyperon puzzle*).
- Often solved by adding strongly-repulsive YNN terms.
- But: calculations either use schemes without Σ hyperons or with Σ hyperons, but with G-matrix renormalized two-body interactions.
  ⇒ Conversion between Λ and Σ treated incompletely.
  ⇒ Three-body terms neglected.
- Use SRG to suppress Σ: ground-state energies drop.
- Adding induced YNN terms recovers original result.
  ⇒ Interaction with Λ-Σ conversion is unitary equivalent to Λ-only theory with strongly-repulsive ΛNN terms.



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