# Single- & Double-strangeness Hypernuclei in the frame work of the NCSM and $\chi$EFT

Hoai Le, Forschungszentrum Jülich

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collaborators: Dr. Johann Haidenbauer, Prof. Ulf-G Meißner, Dr. Andreas Nogga

# Outline

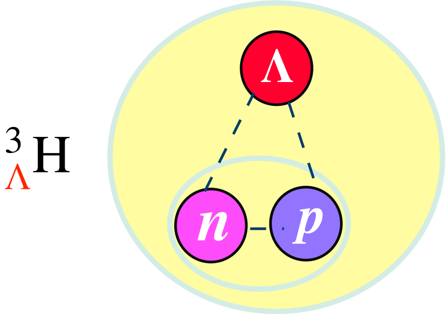
- Introduction:
  - Motivations
  - Baryon-Baryon (BB) interactions within chiral EFT theory

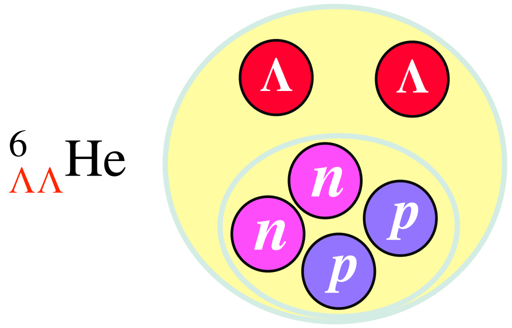
- Numerical approach:
  - Jacobi NCSM for nuclear systems with $S = -1, -2$
  - Similarity Renormalization Group (SRG) in two- & three-body space

- Results:
  - Separation energies and CSB in A=4-8 $\Lambda$ hypernuclei: ${}^{4}_{\Lambda}\mathrm{He}$, ${}^{5}_{\Lambda}\mathrm{He}$, ${}^{7}_{\Lambda}\mathrm{Li}$, ${}^{8}_{\Lambda}\mathrm{Li}$
  - Double-strangeness systems: ${}^{4}_{\Lambda\Lambda}\mathrm{He}$, ${}^{5}_{\Lambda\Lambda}\mathrm{He}$, ${}^{6}_{\Lambda\Lambda}\mathrm{He}$; ${}^{4}_{\Xi}\mathrm{H}$, ${}^{5}_{\Xi}\mathrm{H}$, ${}^{7}_{\Xi}\mathrm{H}$

- Summary & Outlook

# Why is hypernuclear physics interesting?




$\sim 40$ $\Lambda$-hypernuclei

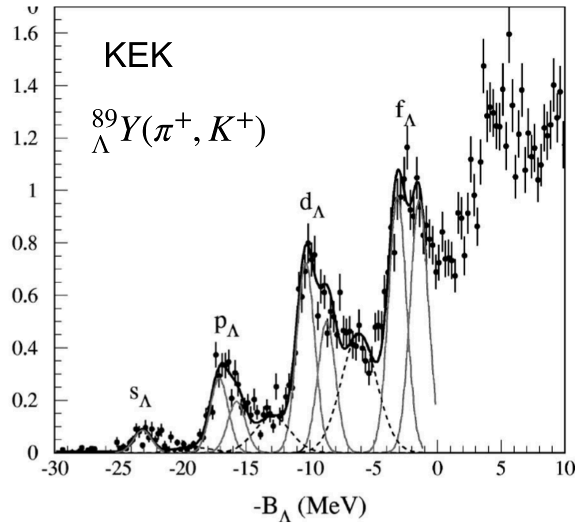
$^{3}_{\Lambda}\mathbf{H},\ ^{4}_{\Lambda}\mathbf{He},\cdots,^{208}_{\Lambda}\mathbf{Pb}$

$\Lambda\Lambda$ ($\Xi$)-hypernuclei

$^{6}_{\Lambda\Lambda}\mathbf{He},\ ^{10}_{\Lambda\Lambda}\mathbf{Be},\ ^{11}_{\Lambda\Lambda}\mathbf{Be};\ ^{15}_{\Xi}\mathbf{C}$

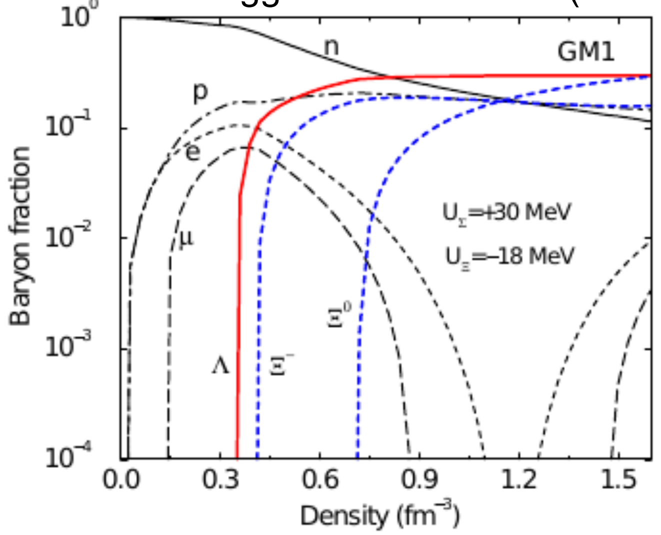
- unique laboratory to explore the MB aspect of 3-flavour BB interaction

H. Hotchi et al. PRC 64(2001)

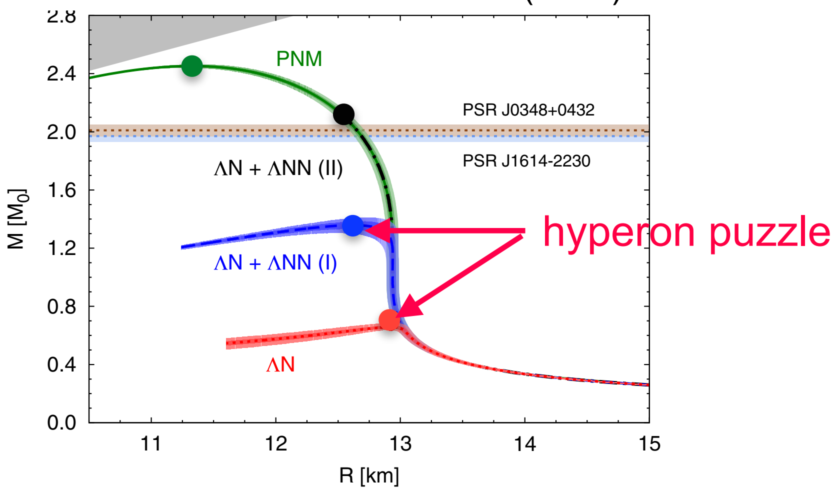



- probe of nuclear interior

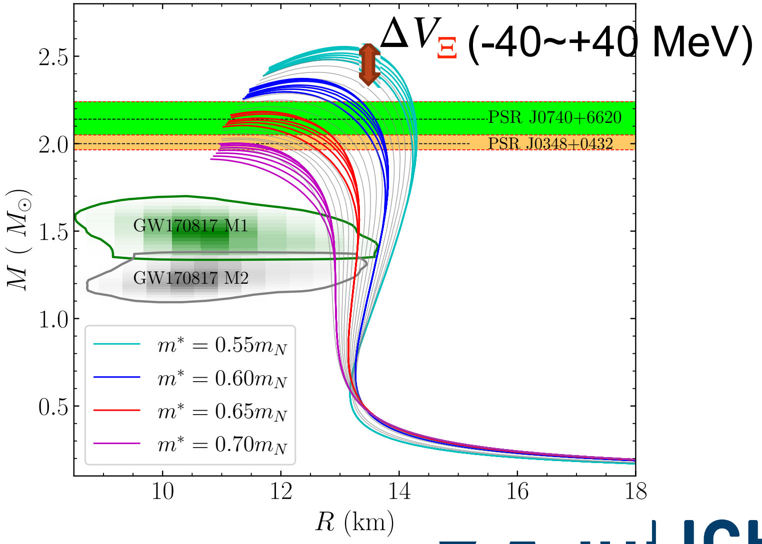
J. Schaggner et al. PRC 53(1995)




D. Lonardoni et al. PRL 114(2015)

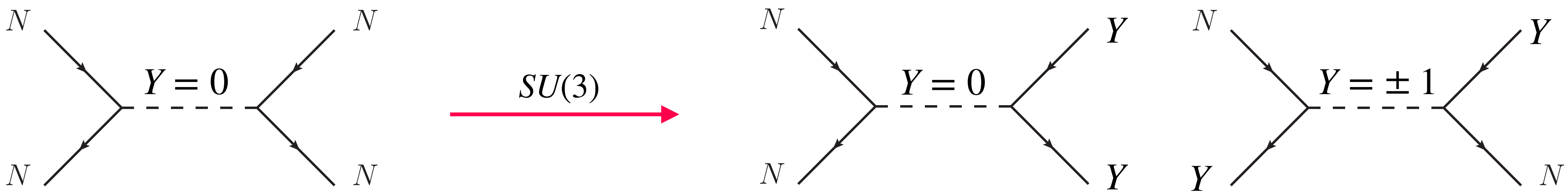



B. K. Pradhan et al. PRC 103(2021)




- contribute to NS at $\rho = 2 - 3\rho_0$
- **can 3BFs ($\Xi$ -hyperon) solve the puzzle?**

# Erkelenz’ work and modern BB interactions




- OBE model: **NN Bonn-potential**

**K. Erkelenz, Phys. Rept. 3 (1974) 191**

OBE model for YN interaction

**(R. Bottgen, K. Holinde, T. A. Rijken,…)**

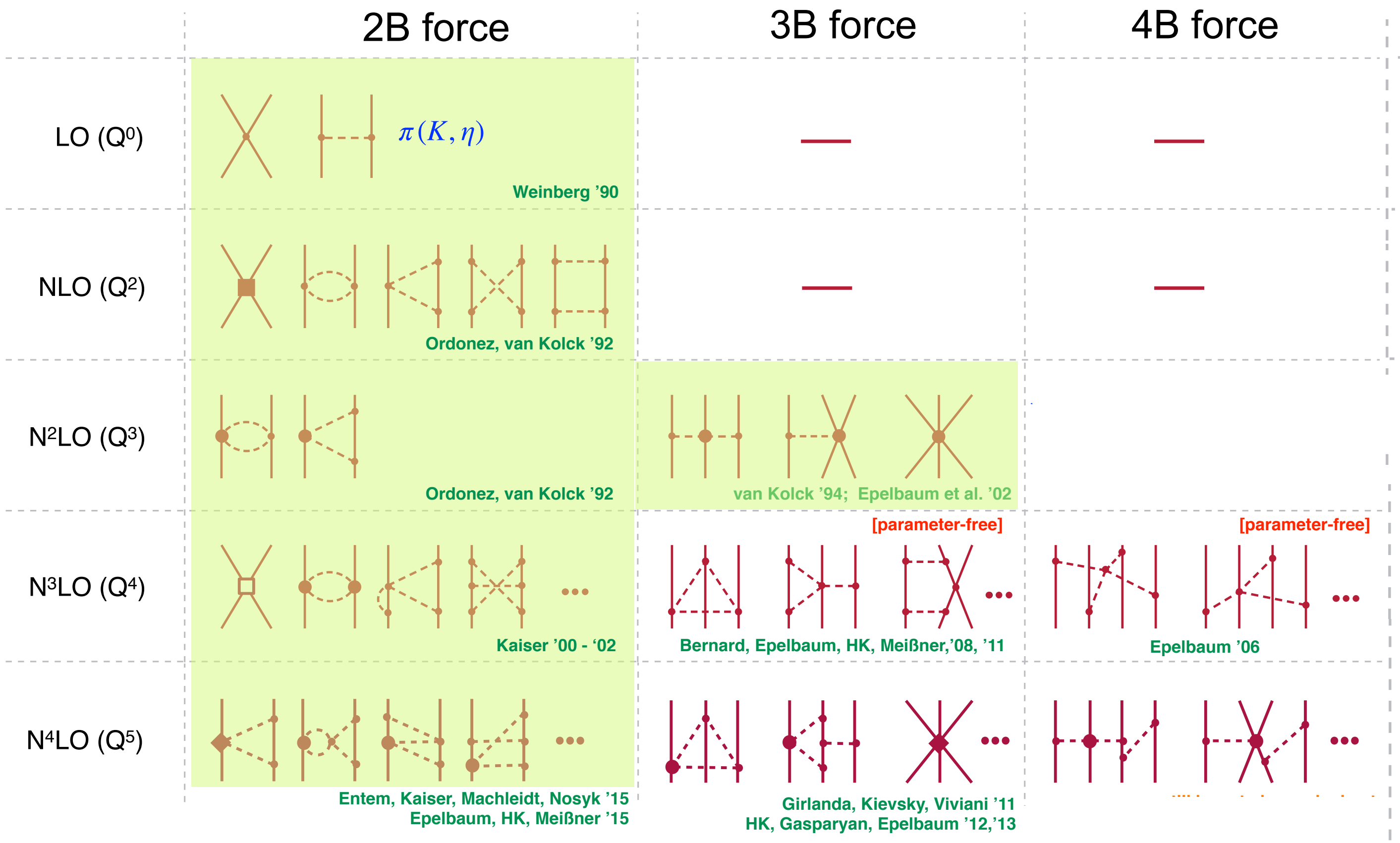
- Semi-phenomenological (meson-exchange) potentials:

**(CD-Bonn, Argonne V18, Nijmegen, $\chi^2$/datum $\sim 1$)** **(Nijmegen, Quark model, Bonn-Jülich)**

- Chiral EFT approach:

**(Weinberg, Ordonez, Ray and Van Kolck, Munich, Bonn-Jülich-Bochum, Idaho, Bochum, …)** **(Bonn-Jülich, Jülich-Bonn-Munich)**

# BB interactions in $\chi$EFT




2 NN, 5 YN LECs (short range parameters)

+7 NN, +23 YN LECs

+2 NNN LECs, +5 $\Lambda$NN LECs

+15 NN LECs

+5 NN LECs

(adapted from H. Krebs CD workshop Nov. 2021)

- LECs are determined via a fit to experiment:
  - ~5000 NN + Nd scattering data + $^2\mathrm{H}, {}^3\mathrm{H}/{}^3\mathrm{He}$ $\longrightarrow$ NN forces up to $\mathrm{N^4LO+}$, 3NF up to $\mathrm{N^2LO}$

    **(P. Reinert et al EPJA (2018), P. Maris et al PRC 103(2021))**
  - ~36 YN scattering data + $^3_\Lambda\mathbf{H}$ $\longrightarrow$ YN forces up to NLO **(NLO13, NLO19)** and $\mathrm{N^2LO}$

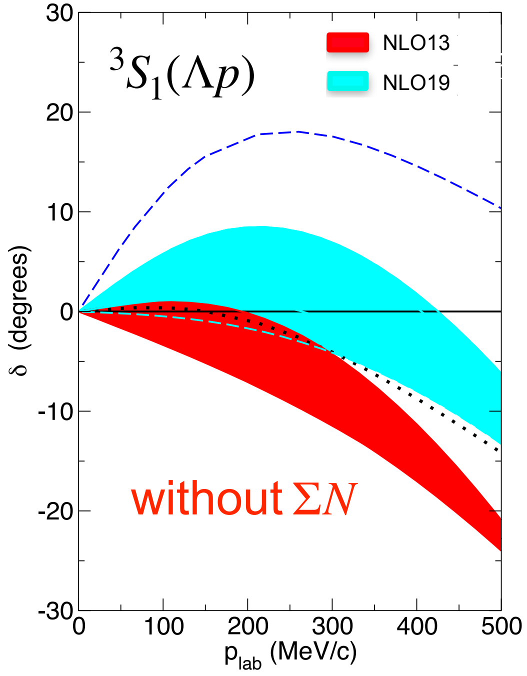
    **(J. Haidenbauer et al NPA 915(2013), EPJA 56(2019), EPJ Web of Conferences 271(2022))**

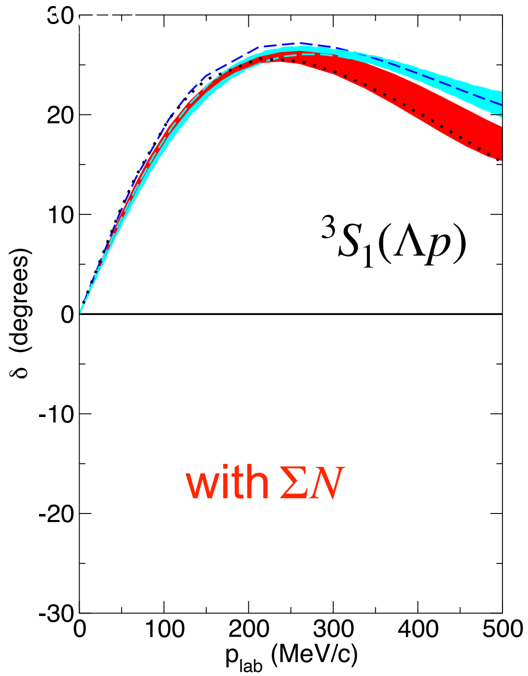
# YN interactions at NLO

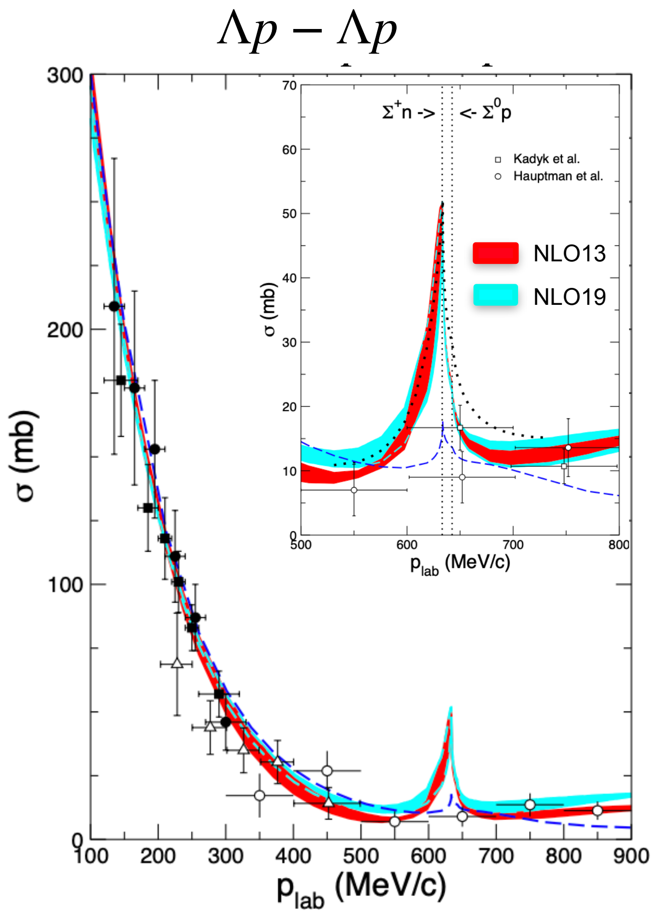
**NLO13: J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W. Weise, NPA 915 (2013) 24**

**NLO19: J. Haidenbauer, U.-G. Meißner, A. Nogga, EPJ A 56 (2019) 91**

- two realisation at NLO: NLO13 and NLO19
  - almost phase equivalent
  - NLO13 leads to a **larger transition potential** $\underbrace{V_{\Lambda N-\Sigma N}}_{\text{not a two-body observable}}$




→ NLO13 and NLO19 as a tool to estimate effect of **3BF in many-body systems**

(J. Haidenbauer, U.-G. Meißner, A. Nogga, EPJA 56 (2019) 91)

# How to further constrain YN interactions?

- $\Lambda$-separation energies are known with high accuracy

**realistic BB interactions:**

**(Chiral EFT)**

input

**ab initio** calculations:

**FY:** A =3,4 (A. Nogga)

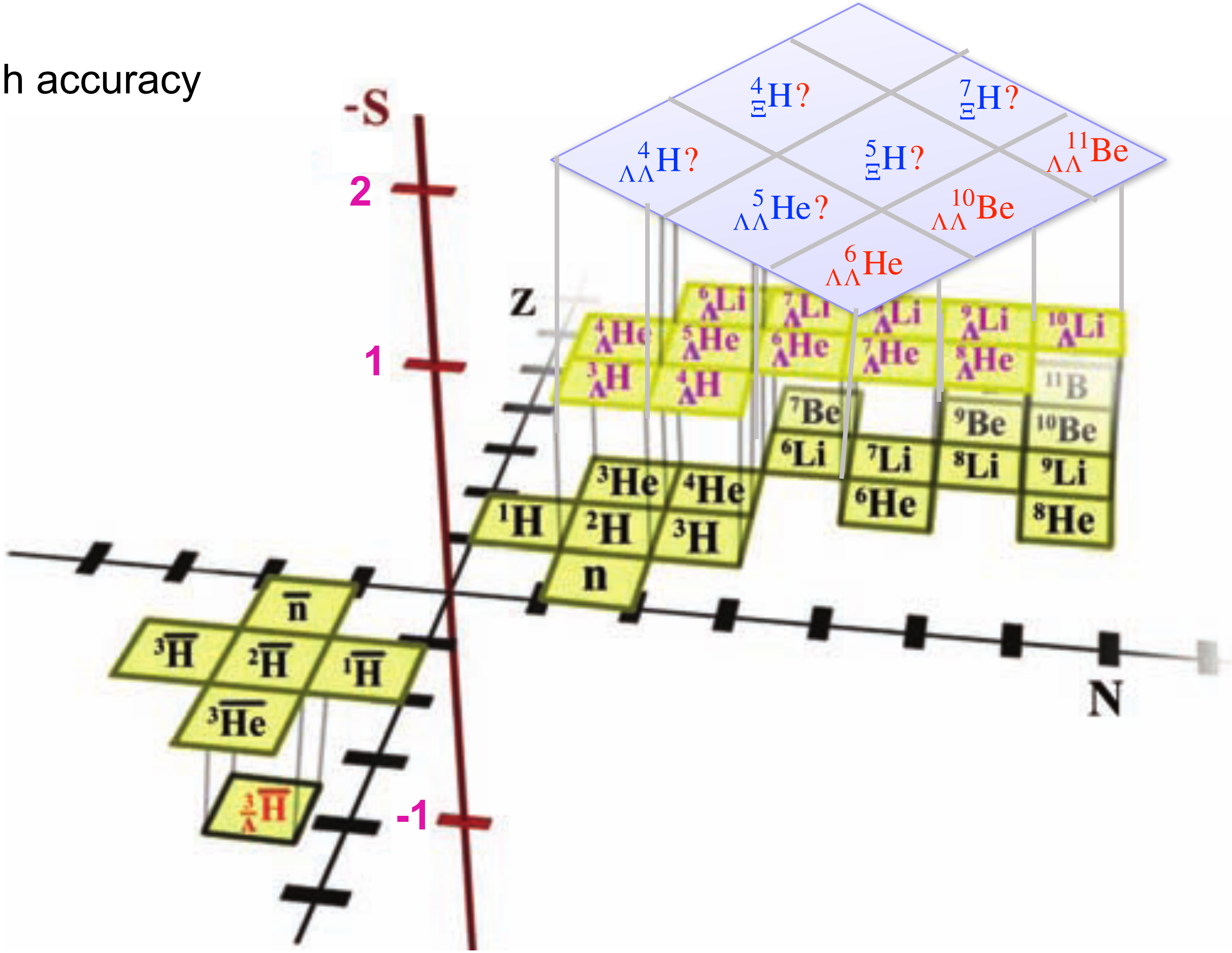
**J-NCSM:** $A \leq 9$

compare to exp.

**experiments:** $B_\Lambda, B_{\Lambda\Lambda}, E_{ex}$

No direct information

Improve interactions




(adapted from 10.1126/science.1183980 )

# Jacobi-NCSM approach

- **Idea:** represent the A-body translationally invariant hypernuclear Hamiltonian:

$$\begin{aligned}\mathrm{H} &= \mathrm{T}_{rel} + \mathrm{V}^{\mathrm{NN}} + \mathrm{V}^{\mathrm{YN}} + \mathrm{V}^{\mathrm{NNN}} + \mathrm{V}^{\mathrm{YNN}} + \underbrace{\Delta M}_{\Lambda\mathrm{N} \leftrightarrow \Sigma\mathrm{N}} + \cdots \\ &= \sum_{i<j=1}^{A-1} h_{ij}^{NN} + \sum_{i<j<k=1}^{A-1} \mathrm{V}_{ijk}^{3N} + \sum_{i=1}^{A-1} h_{iY}^{YN} + \sum_{i<j}^{A-1} \mathrm{V}_{ijY}^{YNN} + \cdots\end{aligned}$$

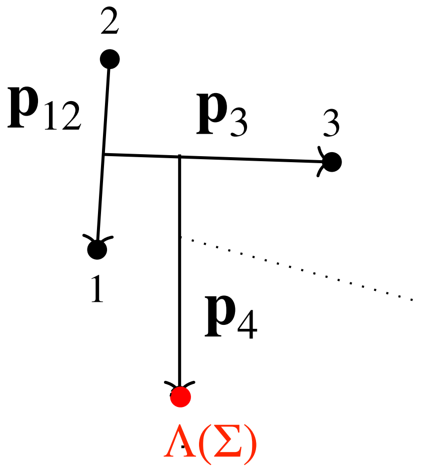
  in a basis constructed from HO functions

- Jacobi basis: **depends on relative Jacobi coordinates of all particles**

(A-1)N

$$| \;\rangle = |\mathcal{N}JT, \underbrace{\mathcal{N}_{A-1}J_{A-1}T_{A-1},}_{antisym.(A-1)N} \underbrace{n_Y l_Y I_Y\, t_Y;}_{\Lambda(\Sigma)\ state} (J_{A-1}(l_Y s_Y)I_Y)\,J, (T_{A-1}t_Y)T\rangle$$

Λ(Σ)



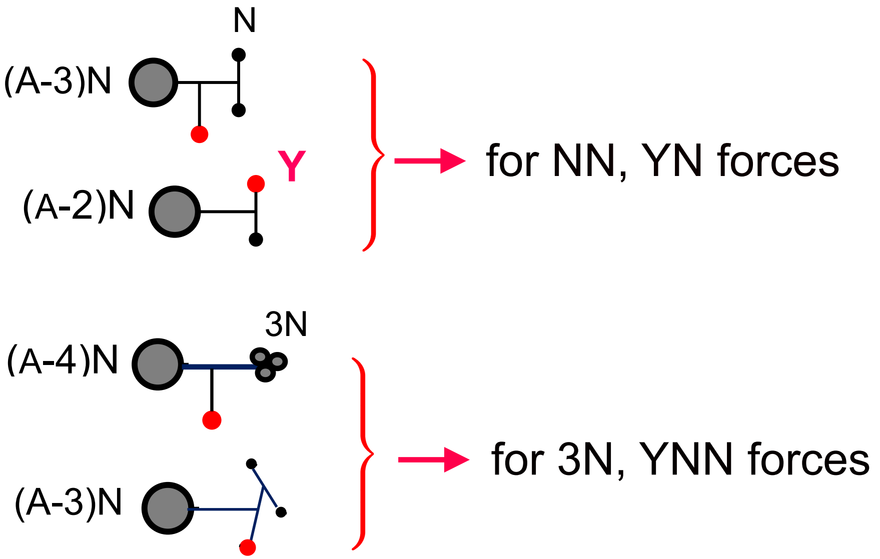

- anti-symmetrized (A-1)N states are constructed iteratively:
  - 2N states: $|\alpha_{12}\rangle \equiv |N_{12}(l_{12}S_{12})J_{12}, (t_1 t_2)t_{12}\rangle \xrightarrow{\text{antisymmetric}} \boxed{(-1)^{l_{12}+s_{12}+t_{12}} = -1}$
  - 3N Jacobi states: $|\alpha_3^{*(1)}\rangle \equiv |N_3 J_3 T_3\, \alpha_{12}\, n_3(l_3 s_3)I_3, t_3;\, (J_{12}I_3)J_3\,, (t_{12}t_3)T_3\rangle$ **antisymmetric w.t. r.** $(1) \leftrightarrow (2)$

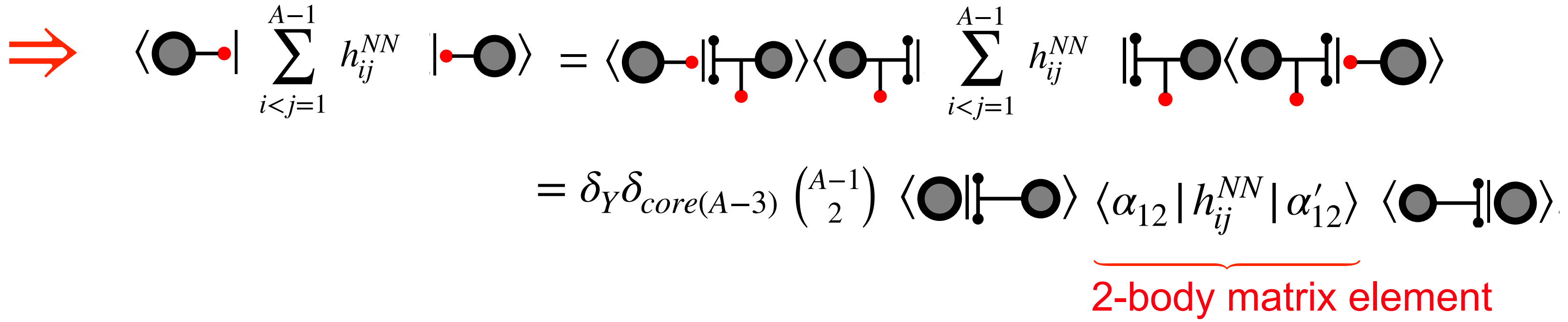
→ idea: use antisymmetrizer to project out the (non)antrisymmetric states:

$$\langle \alpha_3^{\prime *(1)} | \frac{1}{3}(1 - 2\mathscr{P}_{23}) | \alpha_3^{*(1)} \rangle \langle \alpha_3^{*(1)} | \alpha_3 \rangle = \lambda \langle \alpha_3^{*(1)} | \alpha_3 \rangle \qquad \lambda = (0)1$$

# Jacobi-NCSM approach

- intermediate bases for evaluating Hamiltonian:

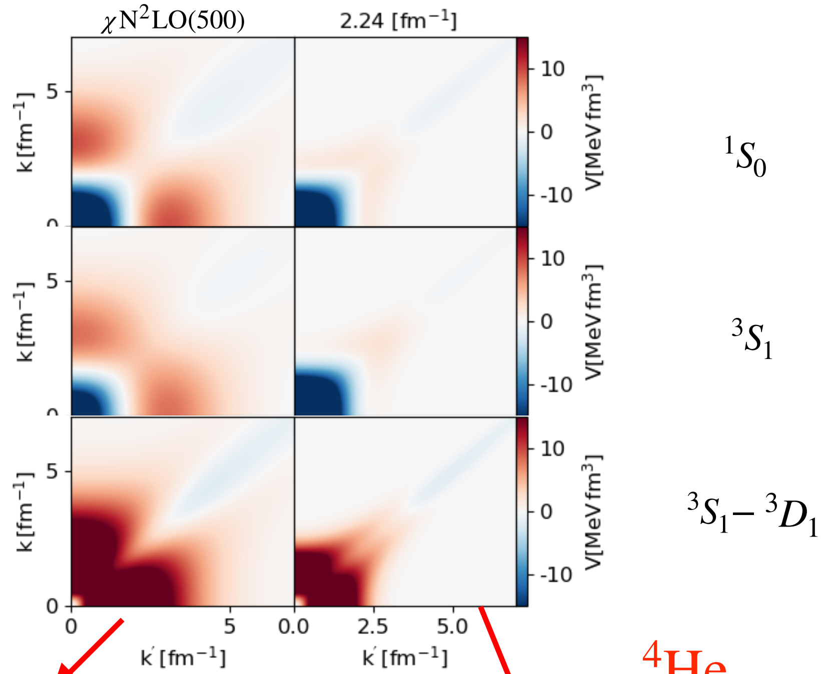

- basis truncation: $\mathcal{N} = \mathcal{N}_{A-1} + 2n_\lambda + \lambda \leq \mathcal{N}_{max}$ $\Rightarrow E_b = E_b(\omega, \mathcal{N}_{max})$

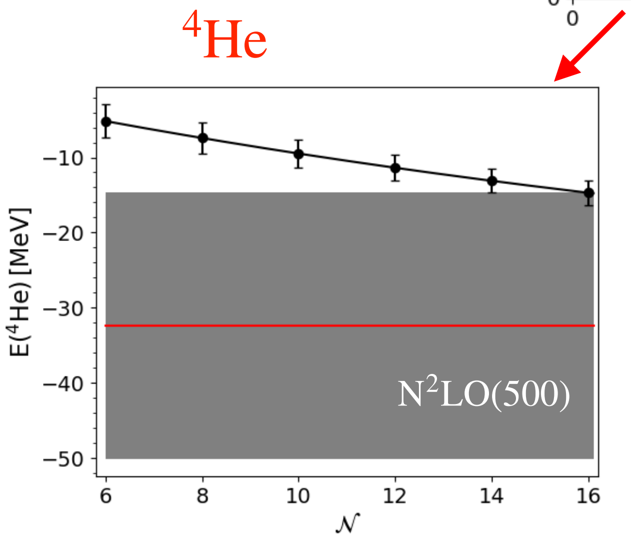
→ extrapolate in $\omega$- and $\mathcal{N}$-spaces to obtain converged results

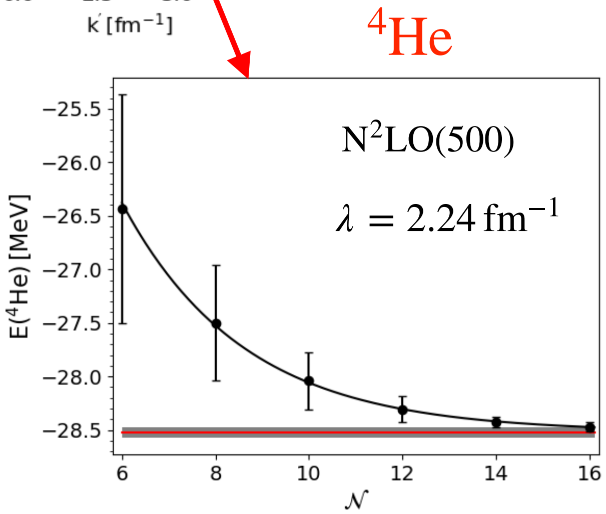
**HL, J. Haidenbauer, U.-G. Meißner, A. Nogga EPJA (2020)**

# Convergence of $E$ with respect to $\mathcal{N}$

- BB interactions contain **short-range and tensor** correlations that couple low- and high-momentum states → **NCSM calculations converge slowly**



# Similarity Renormalization Group (SRG)

**Idea: continuously apply unitary transformation to H to suppress off-diagonal matrix elements**

→ observables (binding energies) are conserved due to unitarity of transformation

F.J. Wegner NPB 90 (2000). S.K. Bogner, R.J. Furnstahl, R.J. Perry PRC 75 (2007)

$$\frac{dV(s)}{ds} = \left[\left[T_{rel}, V(s)\right], H(s)\right], \qquad H(s) = T_{rel} + V(s) + \Delta M$$

$$s = 0 \to \infty \qquad V(s) = V_{12}(s) + V_{13}(s) + V_{23}(s) + V_{123}(s), \quad V_{123,s=0} \equiv V^{bare}_{NNN}; \; (V^{bare}_{YNN} = 0)$$

- separate SRG flow equations for 2-body and 3-body interactions:

**(S.K. Bogner et al PRC75 (2007), K. Hebeler PRC85 (2012))**

$$\frac{dV^{NN}(s)}{ds} = \left[\left[T^{NN}, V^{NN}\right], T^{NN} + V^{NN}\right]$$

$$\frac{dV^{YN}(s)}{ds} = \left[\left[T^{YN}, V^{YN}\right], T^{YN} + V^{YN} + \Delta M\right]$$

$$\begin{aligned}\frac{dV_{123}}{ds} &= \left[\left[T_{12}, V_{12}\right], V_{31} + V_{23} + V_{123}\right] \\ &+ \left[\left[T_{31}, V_{31}\right], V_{12} + V_{23} + V_{123}\right] \\ &+ \left[\left[T_{23}, V_{23}\right], V_{12} + V_{31} + V_{123}\right] + \left[\left[T_{rel}, V_{123}\right], H_s\right]\end{aligned}$$

Eqs.(1)

→ **SRG-induced 3BFs are generated even if $V^{\text{bare}}_{123} = 0$**

- Eqs.(1) are solved by projecting on a 3N (YNN) Jacobi-momentum basis

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# SRG evolution of NN, YN

- $\lambda = (4\mu^2/s)^{1/4}$, $[\lambda] = [p]$: $\lambda \sim$ width of the band-diagonal structure of $V$ in p-space

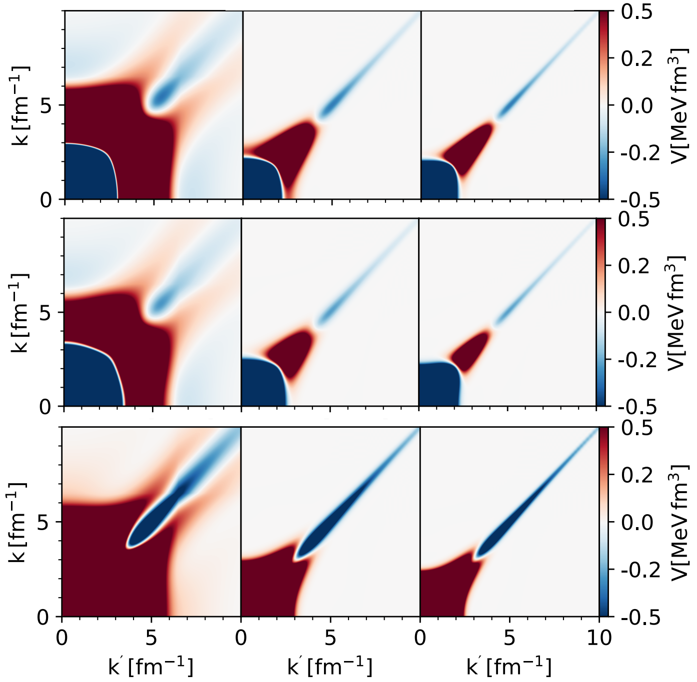
**(S.K. Bogner et al., PRC 75 (2007))**

bare $\lambda = 2.236$ $\lambda = 1.88$

$^1S_0$

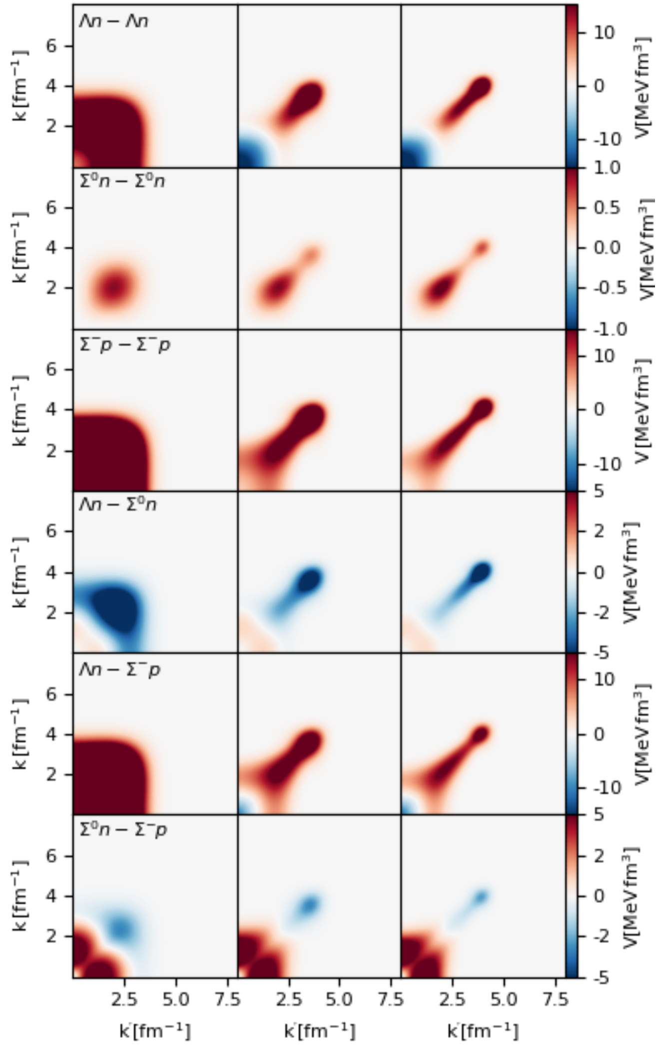
$^3S_1$

$^3S_1 - {}^3D_1$




NN: $\mathrm{N^4LO+}$ (450)

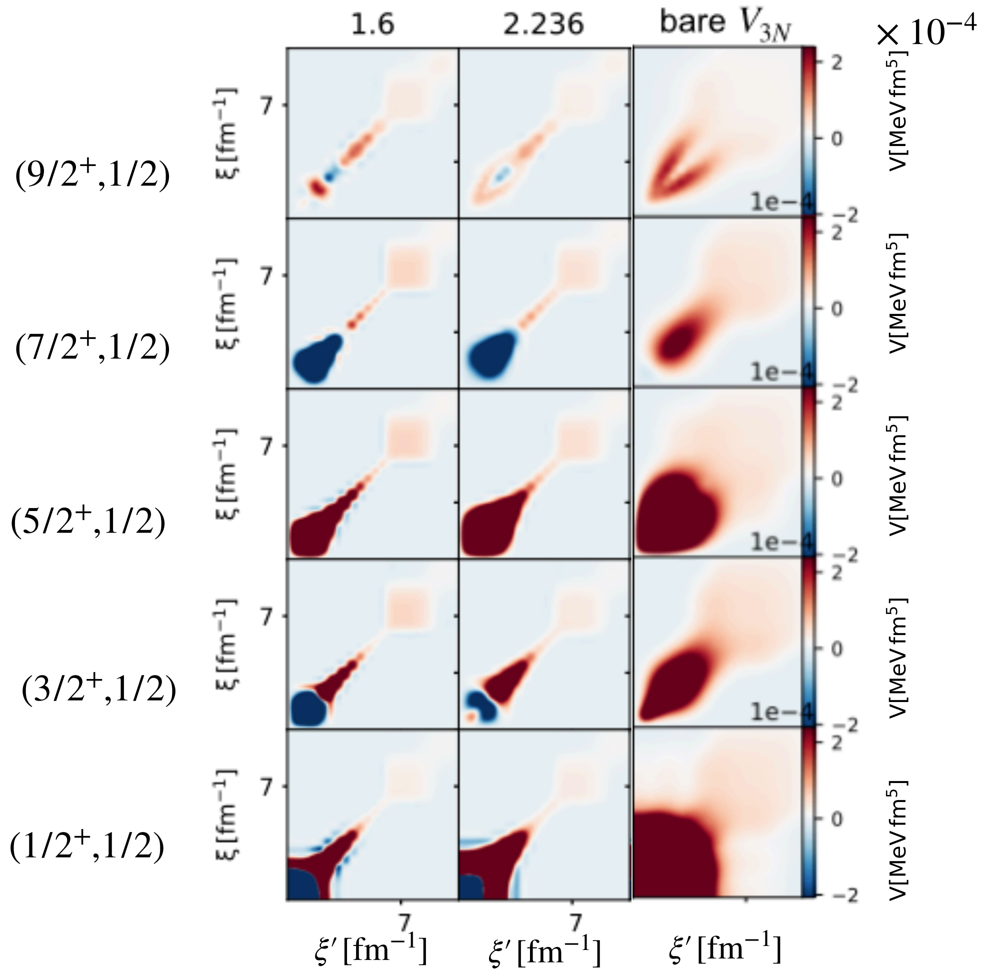
bare $\lambda = 2.236$ $\lambda = 1.88$




YN: NLO19(500)

# SRG evolution of 3N, YNN: $V(pq\alpha, p'q'\alpha')$

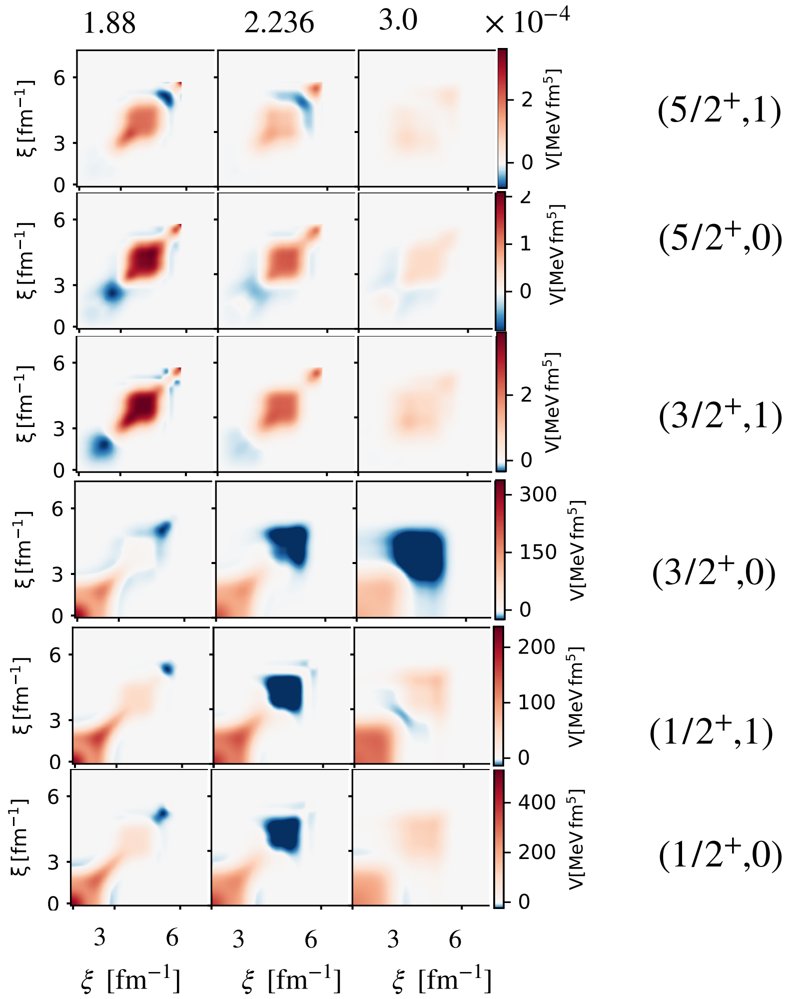
- hyperradius $\xi^2 = p^2 + \frac{3}{4}q^2$; $\tan\theta = 2p/\sqrt{3}q$ $(\theta = \pi/12)$; $\alpha = \alpha' = 1 \Rightarrow$ $V_{123} = V_{123}(\xi', \xi)$ **(K. Hebeler PRC85 (2012))**




**2N+3N:** $\chi$N$^2$LO(550)

**(evolve in 3N space)**

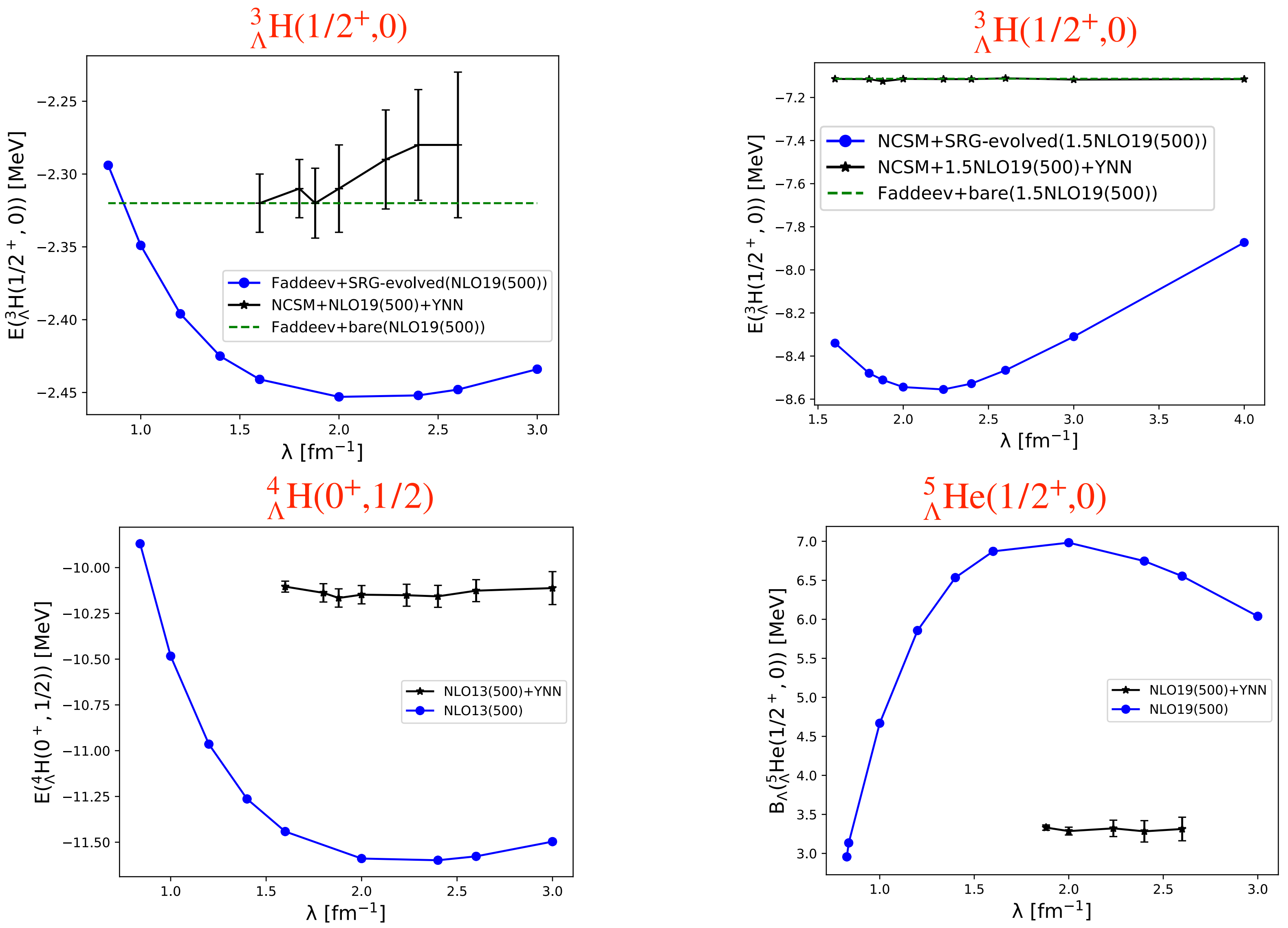
**SRG-induced** $V_{\Lambda NN-\Lambda NN}$




**NN+YN:** N$^4$LO$^+$(450) + NLO19(500)

**(evolve in YNN space)**

# A=3-5 hypernuclei with SRG-induced YNN




**NN:SMS N$^4$LO+(450)**

**3N: N$^2$LO(450)**

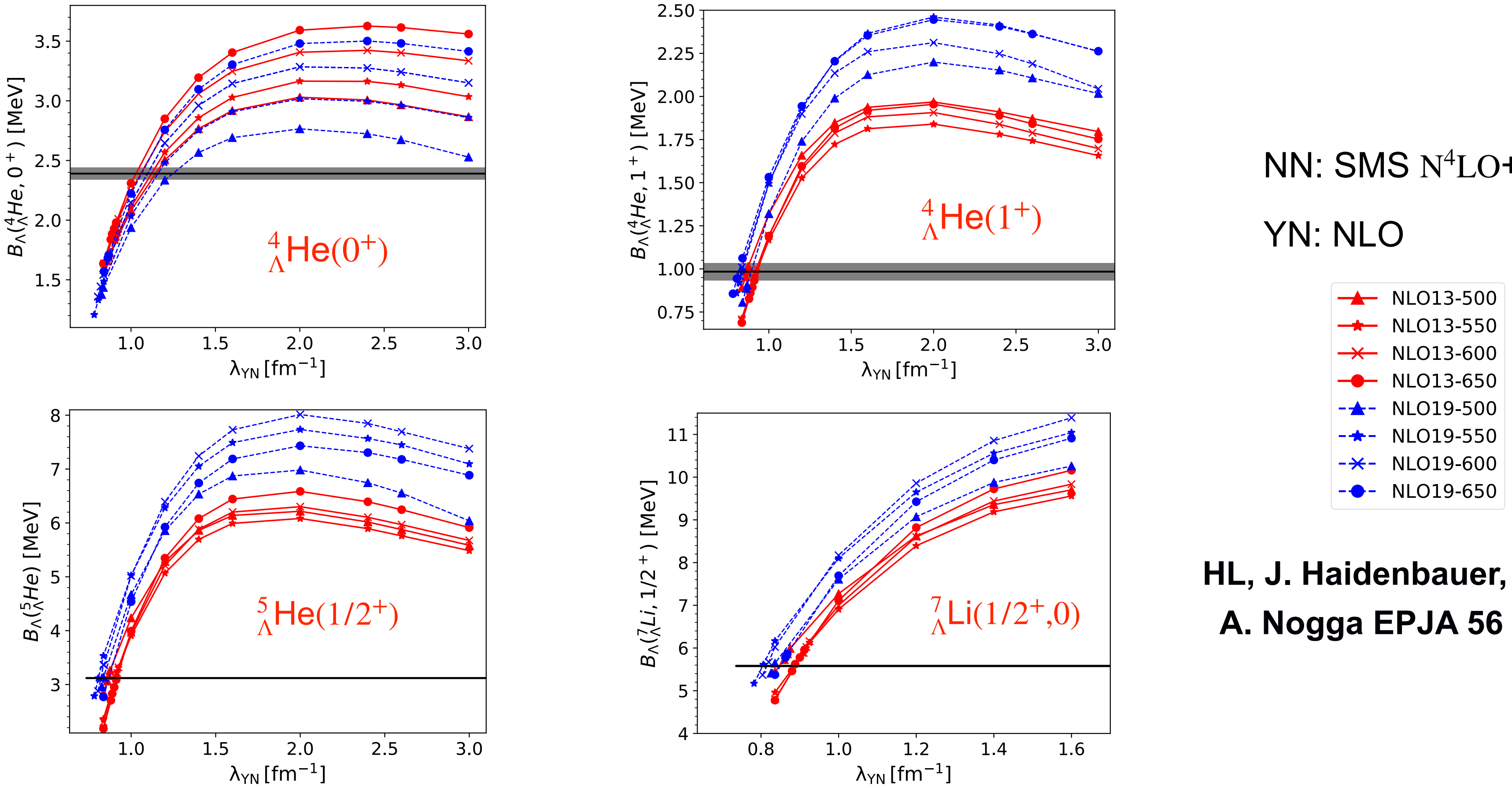
→ **contributions of SRG-induced YNNN forces to $B_\Lambda({}^4_\Lambda\mathrm{H},\,{}^5_\Lambda\mathrm{He})$ are negligible**

R. Wirth, R. Roth PRL117 (2016), PRC100 (2019)

# Impact of YN interactions on $B_\Lambda(A \leq 7)$

- NLO13 and NLO19 are almost **phase equivalent** in the 2-body sector
- NLO13 characterised by a stronger $\Lambda N - \Sigma N$ transition potential (especially in $^3S_1$)

  → **manifest in higher-body observables** **(J.Haidenbauer et al., NPA 915 (2019))**




NN: SMS N$^4$LO+(450)

YN: NLO

**HL, J. Haidenbauer, U.-G. Meißner, A. Nogga EPJA 56 12(2020)**

- $B_\Lambda$(NLO19) > $B_\Lambda$(NLO13) → **contribution of chiral YNN force**



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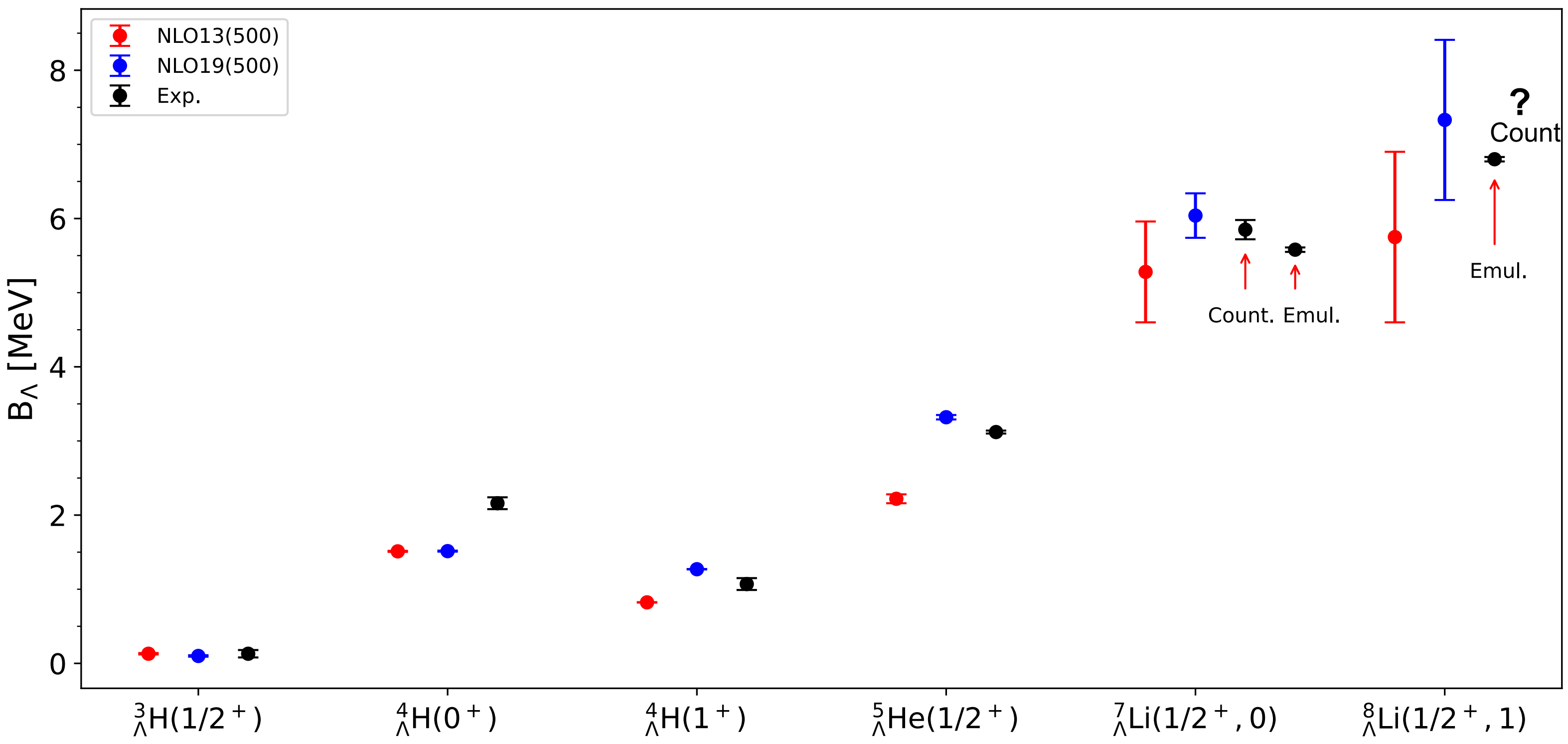
# Impact of YN interactions on $B_\Lambda(A \leq 8)$

- NLO13 and NLO19 are almost **phase equivalent** in the 2-body sector
- NLO13 characterised by a stronger $\Lambda N - \Sigma N$ transition potential (especially in ${}^3S_1$)

→ **manifest in higher-body observables** **(J.Haidenbauer et al., NPA 915 (2019))**




NN:SMS N$^4$LO+(450)

+3N: N$^2$LO(450)

+SRG-induced YNN

Experiment:

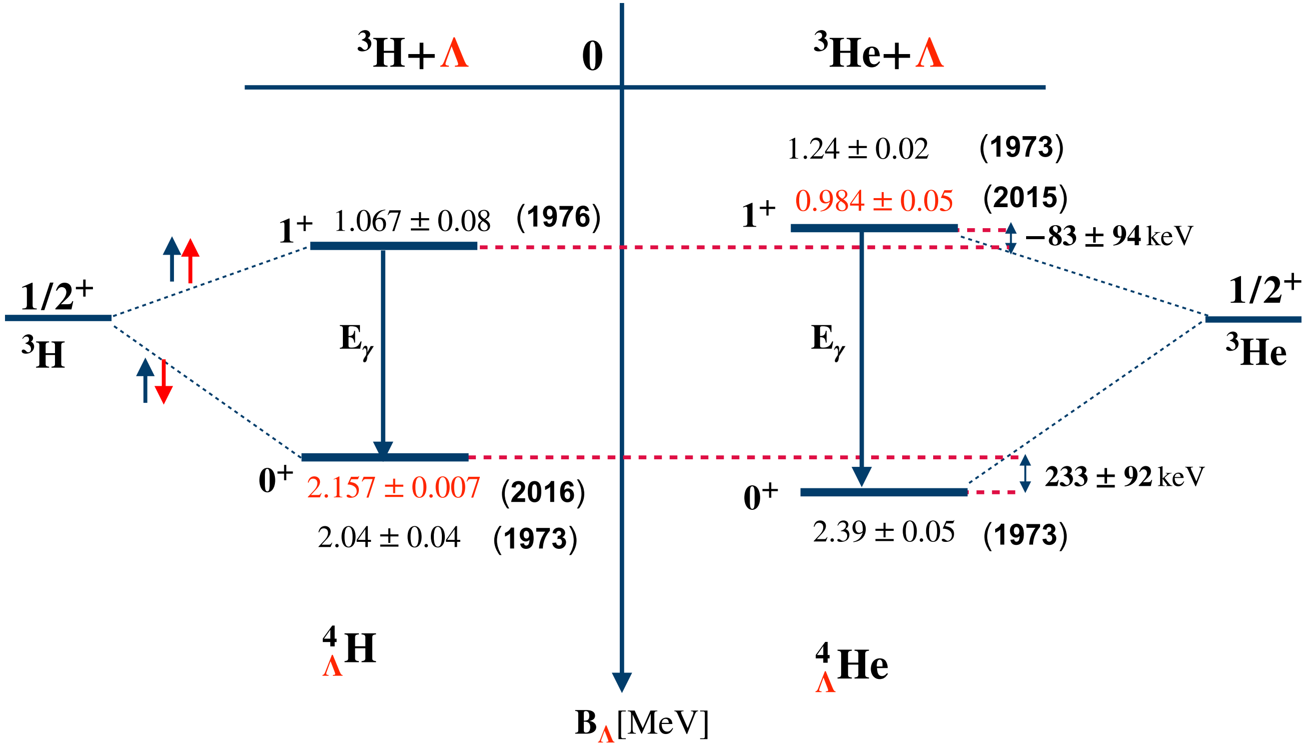
**M. Agnello et al. PLB 681(2009)**

**M. Juric NPB 52(1973)**

→ ${}^4_\Lambda$H(1$^+$), ${}^5_\Lambda$He, ${}^7_\Lambda$Li, ${}^8_\Lambda$Li are fairly well described by **NLO19**; **NLO13** underestimates these systems

**HL, J. Haidenbauer, U.-G. Meißner, Andreas Nogga, arXiv:2210.03387**

# Charge symmetry breaking (CSB) in A=4




- **Schulz et al.(2016); Yamamoto et al. (2015); Juric et al. (1973); Bedjidian et al (1976,1979)**

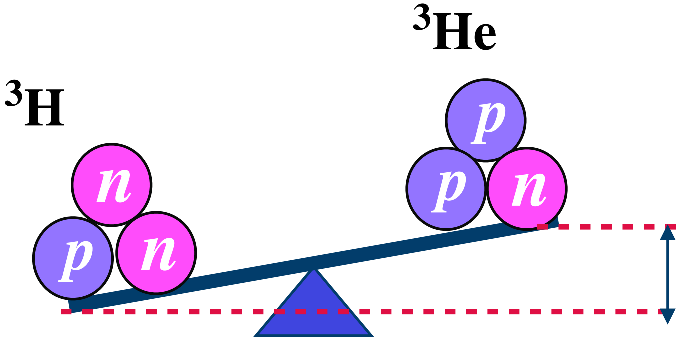
$$\Delta E(1^+) = B_\Lambda(^4_\Lambda\mathrm{He}, 1^+) - B_\Lambda(^4_\Lambda\mathrm{H}, 1^+) = -83 \pm 94\ \mathrm{keV}$$

$$\Delta E(0^+) = B_\Lambda(^4_\Lambda\mathrm{He}, 0^+) - B_\Lambda(^4_\Lambda\mathrm{H}, 0^+) = 233 \pm 92\ \mathrm{keV}$$

- $^4_\Lambda\mathrm{He} - {}^4_\Lambda\mathrm{H}$ Coulomb corrections $\sim -50$ keV

**(A. R. Bodmer et al. PRC 31(1985))**

→ **CSB in ($^4_\Lambda$He, $^4_\Lambda$H) is due to strong interaction**




$764\ \mathrm{keV} \sim \underset{\text{Coulomb}}{683} + \underset{\Delta M(p,n)}{81}$

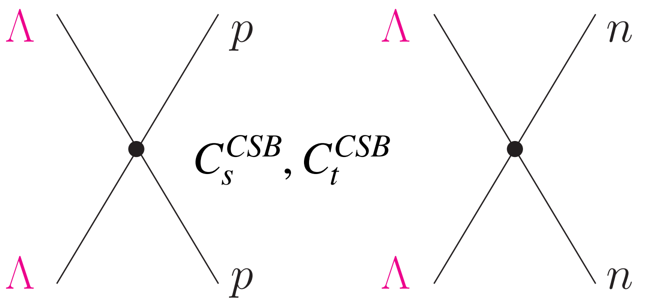
**(R. A. Brandenburg et al. NPA 294 (1978))**

# Charge symmetry breaking (CSB) in A=4

**(J. Haidenbauer, U-G. Meißner and A. Nogga FBS 62(2021))**

- **additional 2LECs (at LO)** contributing to CSB are adjusted to $\Delta E(0^+, 1^+)$

| (fm//keV) | $a_s^{\Lambda p}$ | $a_s^{\Lambda n}$ | $\delta a_s$ | $a_t^{\Lambda p}$ | $a_t^{\Lambda n}$ | $\delta a_t$ | $\Delta E(0^+)$ | $\Delta E(1^+)$ |
|---|---|---|---|---|---|---|---|---|
| NLO19(**500**) no CSB | **-2.91** | **-2.91** | **0** | **-1.42** | **-1.41** | **-0.01** | **34** | **10** |
| CSB1(**500**) | **-2.65** | **-3.20** | **0.55** | **-1.58** | **-1.47** | **-0.11** | **249** | **-75** |
| CSB1(550) | -2.64 | -3.21 | 0.57 | -1.52 | -1.41 | -0.11 | 252 | -72 |
| CSB1(600) | -2.63 | -3.23 | 0.6 | -1.47 | -1.36 | -0.09 | 243 | -67 |
| CSB1(650) | -2.62 | -3.23 | 0.61 | -1.46 | -1.37 | -0.09 | 250 | -69 |




$$\Delta E(1^+) = B_\Lambda({}^4_\Lambda\mathrm{He}, 1^+) - B_\Lambda({}^4_\Lambda\mathrm{H}, 1^+) = -83 \pm 94\ \mathrm{keV}$$

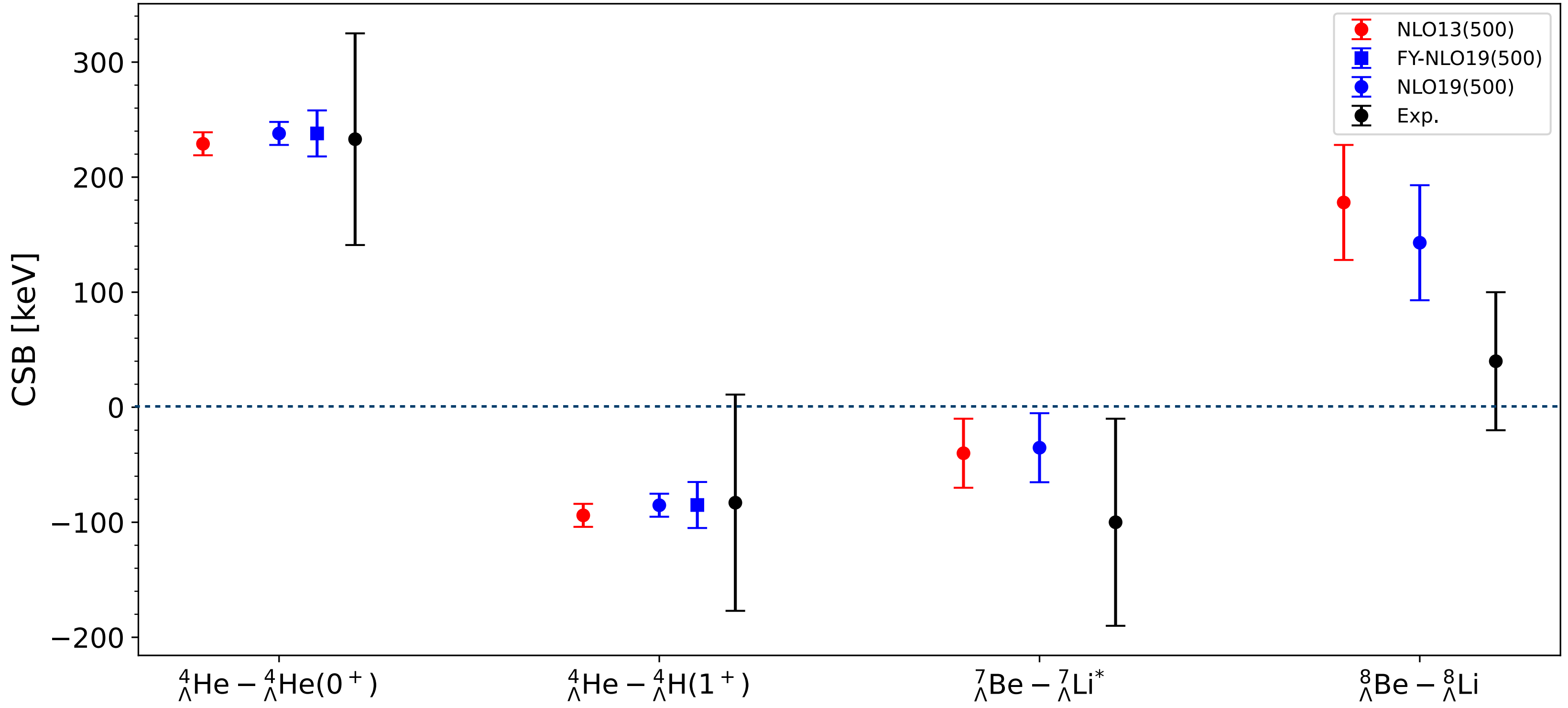
$$\Delta E(0^+) = B_\Lambda({}^4_\Lambda\mathrm{He}, 0^+) - B_\Lambda({}^4_\Lambda\mathrm{H}, 0^+) = 233 \pm 92\ \mathrm{keV}$$

→ ▸ **CSB in singlet ($^1S_0$) is much larger than in triplet ($^3S_1$)**

▸ predictions for A=4 are **independent of cutoff**, same results for NLO13

▸ **predictions for CSB in A=7,8 multiplets ?**

# Charge symmetry breaking (CSB) in A=4-8




NN:SMS $\mathrm{N^4LO}$+(450)

+3N: $\mathrm{N^2LO}$(450)

+SRG-induced YNN

**HL, J. Haidenbauer, U.-G. Meißner, A. Nogga, arXiv:2210.03387**

- NLO13 & NLO19 CSB results for A=7 **are comparable to experiment.**
- two potentials predict a somewhat **larger CSB in A=8 doublet as compared to experiment**
  - experimental CSB splitting for A=8 could be **larger than $40 \pm 60$ keV**?
  - CSB estimated for A=4 could **still be too large** or have **different spin-dependence**?



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# Fitting LECs to new Star measurement

**Recent Star measurement suggests somewhat different CSB in A=4:**

$$\Delta E(1^+) = B_\Lambda({}^4_\Lambda\mathrm{He}, 1^+) - B_\Lambda({}^4_\Lambda\mathrm{H}, 1^+)$$

$$= -83 \pm 94\ \mathrm{keV} \quad \Rightarrow \text{(CSB)}$$

$$= \mathbf{-160 \pm 140 \pm 100}\ \ \mathrm{keV}^* \quad \Rightarrow \text{(CSB*)}$$

$$\Delta E(0^+) = B_\Lambda({}^4_\Lambda\mathrm{He}, 0^+) - B_\Lambda({}^4_\Lambda\mathrm{H}, 0^+)$$

$$= 233 \pm 92\ \mathrm{keV} \quad \Rightarrow \text{(CSB1)}$$

$$= \mathbf{160 \pm 140 \pm 100}\ \ \mathrm{keV}^* \quad \Rightarrow \text{(CSB*)}$$

* STAR Collaboration PLB 834 (2022)

| | NLO19(500) | CSB | CSB* |
|---|---|---|---|
| $a_s^{\Lambda p}$ | -2.91 | -2.65 | -2.58 |
| $a_s^{\Lambda n}$ | -2.91 | -3.20 | -3.29 |
| $\boldsymbol{\delta a_s}$ | **0** | **0.55** | **0.71** |
| $a_t^{\Lambda p}$ | -1.42 | -1.57 | -1.52 |
| $a_t^{\Lambda n}$ | -1.41 | -1.45 | -1.49 |
| $\boldsymbol{\delta a_t}$ | **-0.01** | **-0.12** | **-0.03** |

**HL, J. Haidenbauer, U.-G. Meißner, A. Nogga arXiv:2210.03387**

→ **How does the STAR measurement affect the predictions of CSB in A=7,8 multiplets ?**



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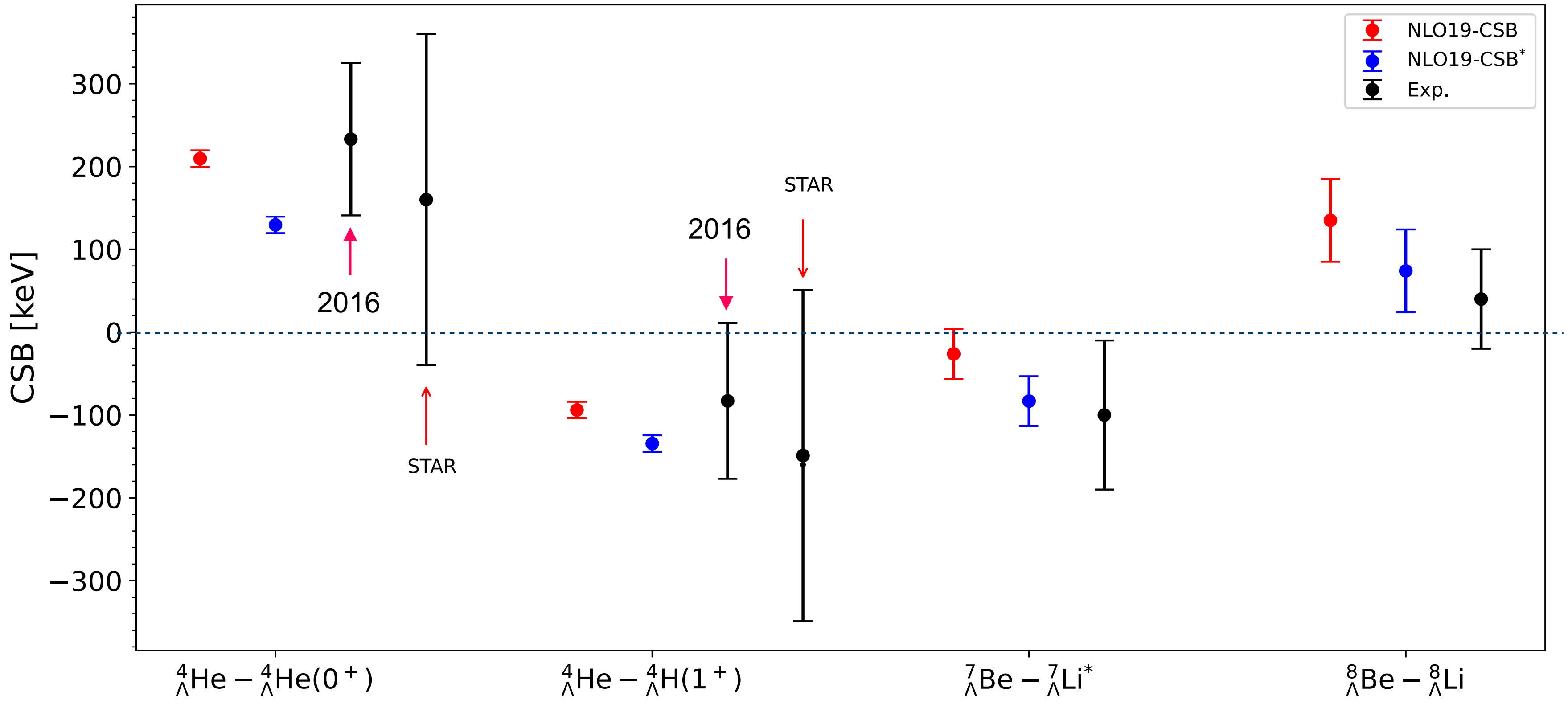
# Impact of Star measurement on CSB in A=7,8




NN:SMS $N^4LO+(450)$

$\lambda_{NN} = 1.6\,\text{fm}^{-1}$

$\lambda_{YN} = 0.823\,\text{fm}^{-1}$

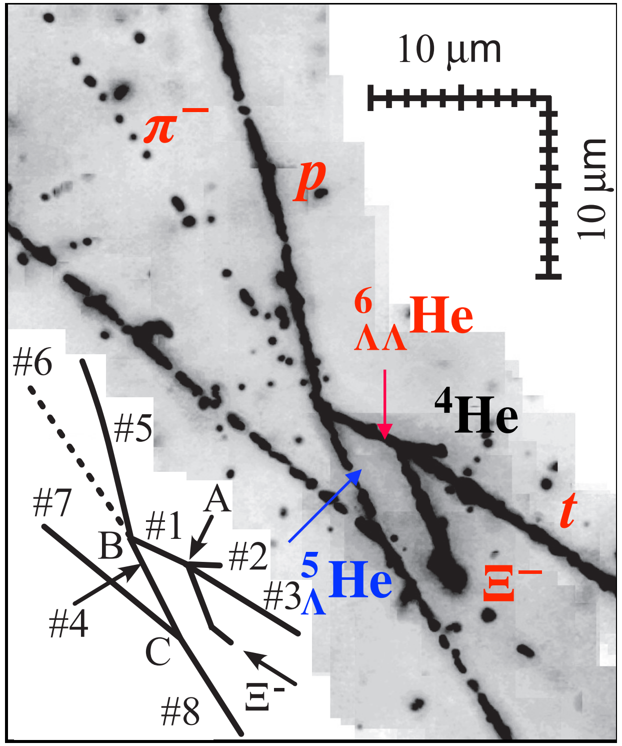
**HL, J. Haidenbauer, U.-G. Meißner, A. Nogga, arXiv:2210.03387**

**HL, J. Haidenbauer, U.-G. Meißner, A. Nogga, arXiv:2210.03387**

→ **CSB* fit predicts reasonable CSB in both A=7 and A=8 systems**

# S-shell $\Lambda\Lambda$ hypernuclei:

NAGARA Event ${}^{6}_{\Lambda\Lambda}\mathrm{He}$

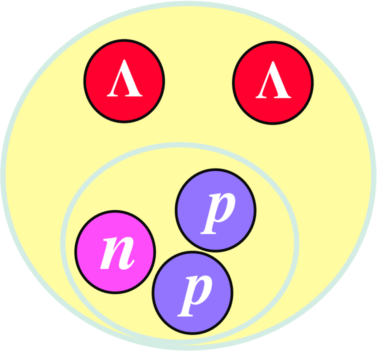



$$ {}^{12}\mathrm{C} + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t $$

$$ {}^{6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^- $$

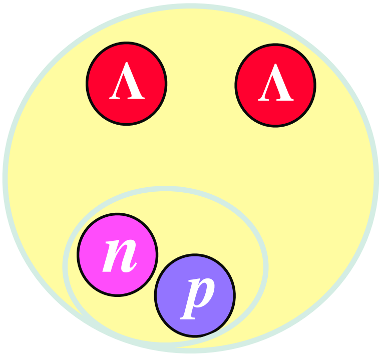
$$ \Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) - 2B_{\Lambda}({}^{5}_{\Lambda}\mathrm{He}) = 0.67 \pm 0.17\,\mathrm{MeV} $$

(K. Nakazawa et al., NPA 835 (2010))




${}^{5}_{\Lambda\Lambda}\mathrm{He}/{}^{5}_{\Lambda\Lambda}\mathrm{H}$?

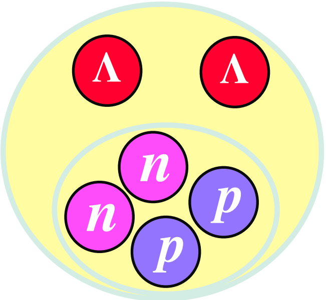
- bound in few-body calculations using phenomenological potentials
- predicted $\Delta B_{\Lambda\Lambda}$ is model-dependence
- experimental searching is on going at J-PARC E75




${}^{4}_{\Lambda\Lambda}\mathrm{H}$?

- only loosely bound ($B_{\Lambda\Lambda} \approx 2\,\mathrm{keV}$) in H. Nemura calculation

(H.Nemura et al., PRL 94 (2005))

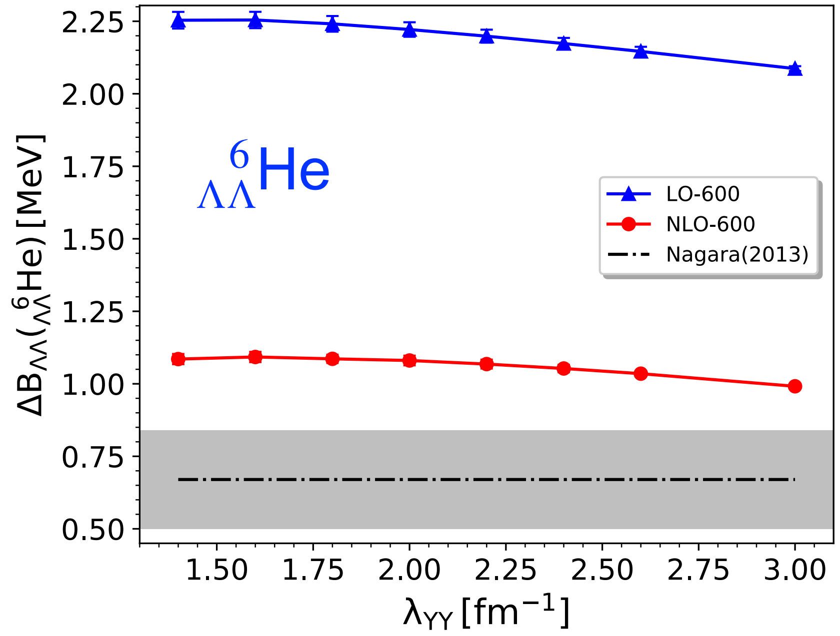


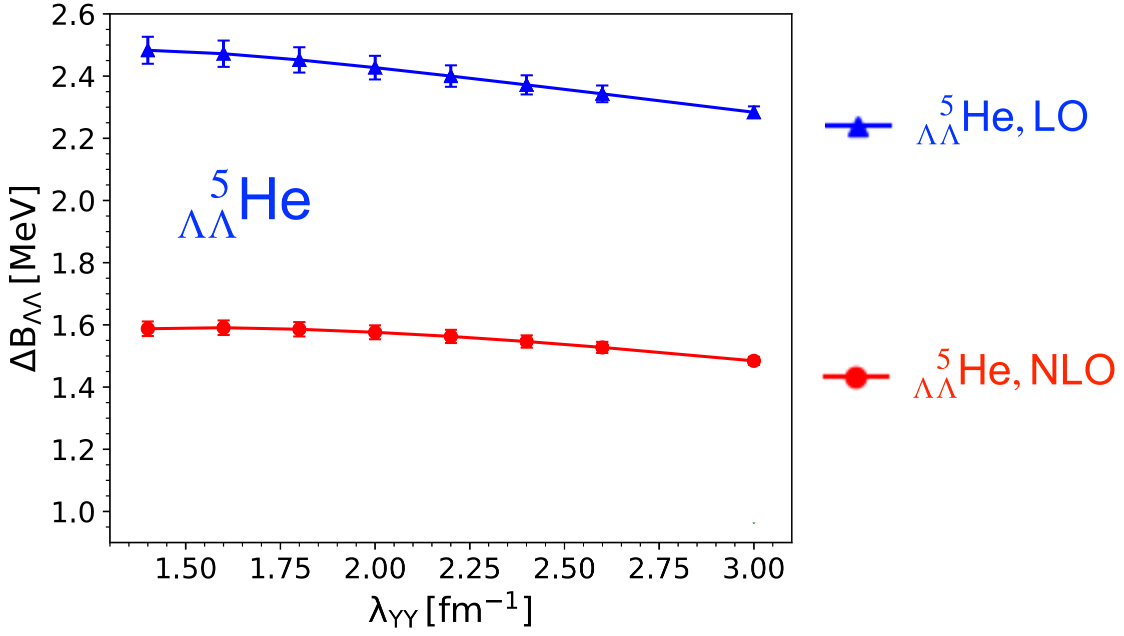

${}^{6}_{\Lambda\Lambda}\mathrm{He}$

**Predictions of chiral YY potentials?**

# Results for ${}^{6}_{\Lambda\Lambda}$He, ${}^{5}_{\Lambda\Lambda}$He

(HL, J. Haidenbauer, U.-G. Meißner, A. Nogga EPJA 57 7(2021))



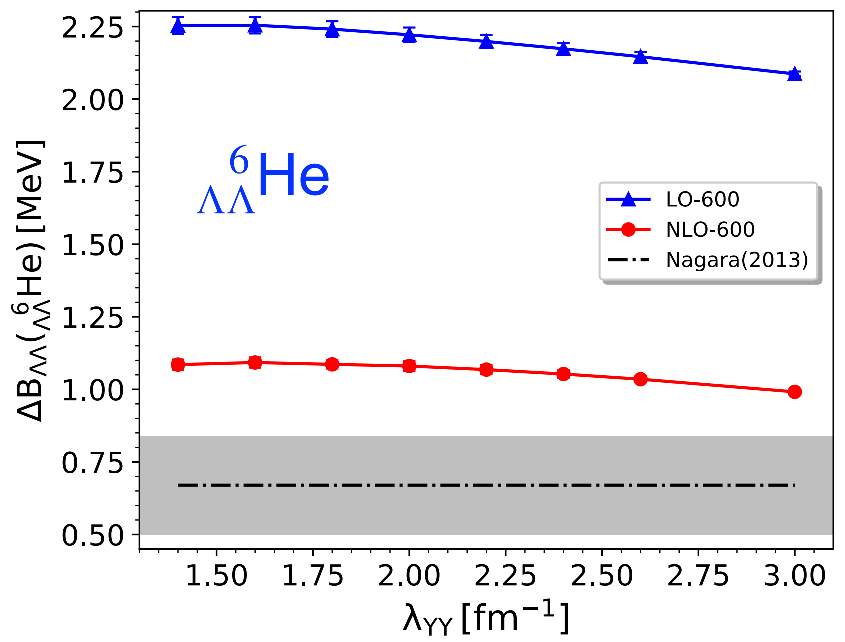

- Effect of SRG-induced YYN forces is negligible
- NLO results are comparable to the Nagara, LO potential overestimates ${}^{6}_{\Lambda\Lambda}$He
- Large difference between $\Delta B_{\Lambda\Lambda}$: $\Delta B_{\Lambda\Lambda}({}^{5}_{\Lambda\Lambda}\mathrm{He}) > \Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He})$ **(K. S. Myint et al EPJ (2003))**

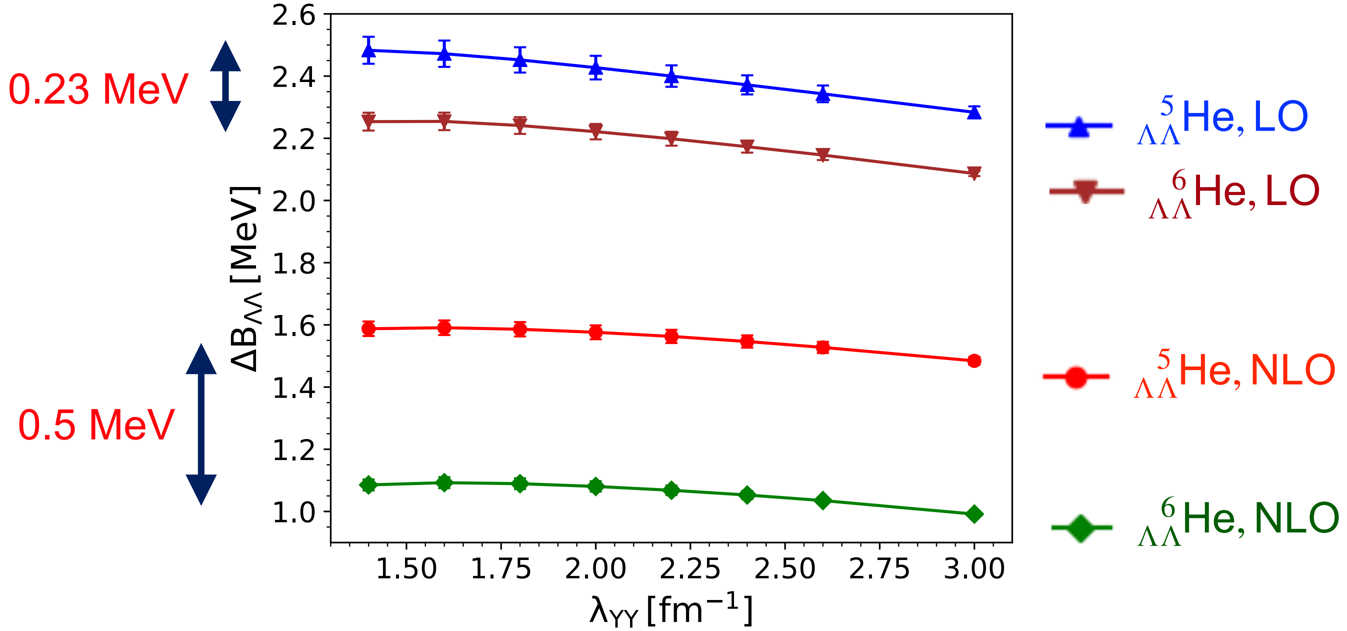
FY calculation: $\Delta B_{\Lambda\Lambda}({}^{5}_{\Lambda\Lambda}\mathrm{He}) < \Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He})$ **(I. Filikhin, A. Gal NPA 707 (2002))**

**Suppression of $\Lambda\Lambda \leftrightarrow \Xi N$ in ${}^{6}_{\Lambda\Lambda}$He ?**

# Results for ${}^{6}_{\Lambda\Lambda}$He, ${}^{5}_{\Lambda\Lambda}$He

(HL, J. Haidenbauer, U.-G. Meißner, A. Nogga EPJA 57 7(2021))

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**Suppression of $\Lambda\Lambda \leftrightarrow \Xi N$ in ${}^{6}_{\Lambda\Lambda}$He ?**

# Is ${}^{4}_{\Lambda\Lambda}$H stable against the breakup to ${}^{3}_{\Lambda}$H $+ \ \Lambda$?

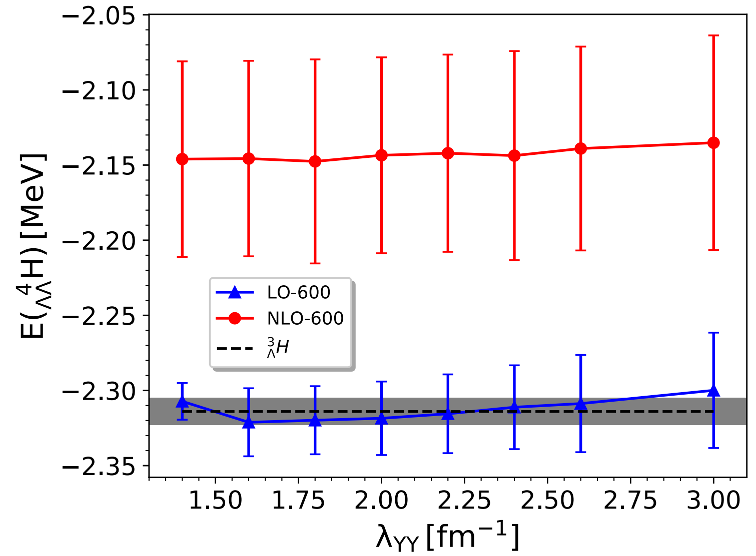
- H. Nemura et al., PRL 94 (2005) employ an effective YY potentials

  → ${}^{6}_{\Lambda\Lambda}$He, ${}^{5}_{\Lambda\Lambda}$H/He are strongly bound, $B_{\Lambda\Lambda}({}^{4}_{\Lambda\Lambda}\mathrm{H}) \approx 2$ keV

- L. Contessi et al., PLB 797 (2019) use pointless EFT interactions at LO

  → the existence of ${}^{4}_{\Lambda\Lambda}$H is incompatible with the Nagara result for ${}^{6}_{\Lambda\Lambda}$He

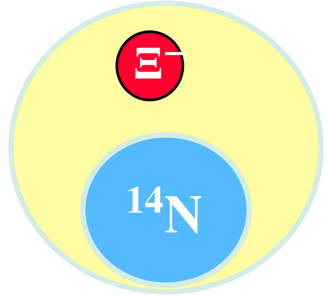
- Chiral YY interactions at LO & NLO: **(HL, J. Haidenbauer, U.-G. Meißner, A. Nogga, EPJA 57 7(2021))**



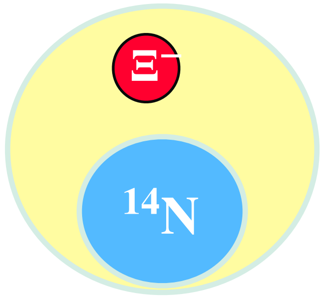

${}^{4}_{\Lambda\Lambda}$H$(1^{+},0)$

→ NLO leads to a particle unstable ${}^{4}_{\Lambda\Lambda}$H. Existence of $A = 4\ \Lambda\Lambda$ hypernucleus is very unlikely

# Ξ hypernuclei:




$^{15}_{\Xi^-}\mathrm{C}$




$^{12}_{\Xi^-}\mathrm{Be}$?

**T. Fukuda et al. PRC 58 (1998)**

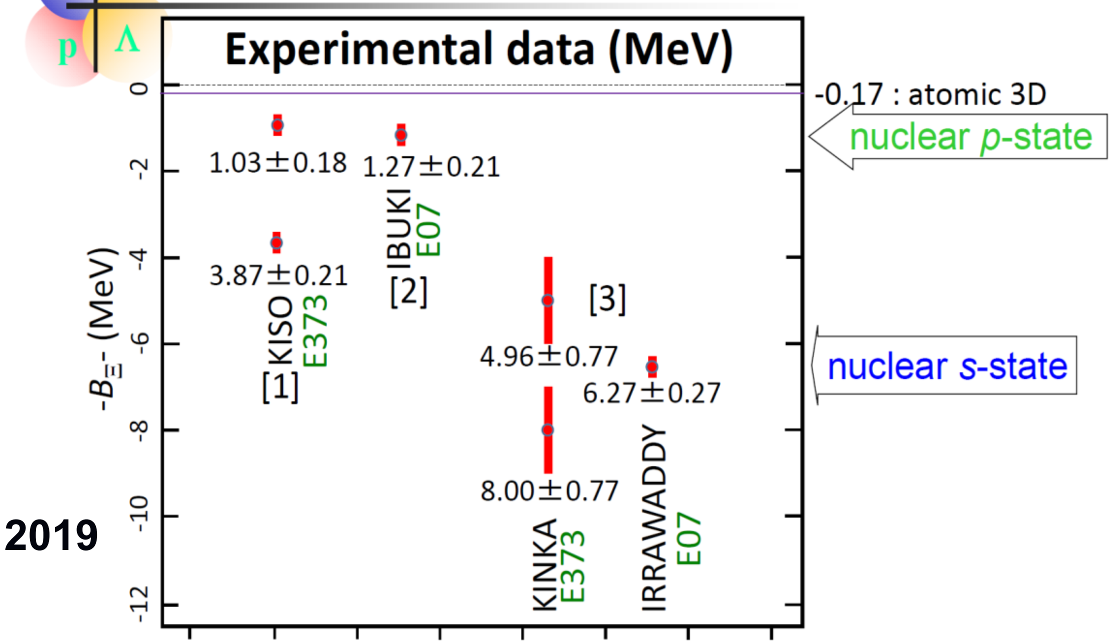
**T. Nagar et al. Pos (INPC2016); AIP Conf. proc 2019**

$$\Rightarrow \quad U_\Xi(k=0) \approx -14 \ \ \mathrm{MeV}$$

$$U_\Xi(k=0, \chi\mathrm{EFT}) \approx -9 \ \ \mathrm{MeV}$$

**M. Kohno, PRC 024313 (2019)**

Level scheme of Ξ hypernucleus ($^{15}_{\Xi}\mathrm{C}$ [$\Xi^-$-$^{14}\mathrm{N}$])



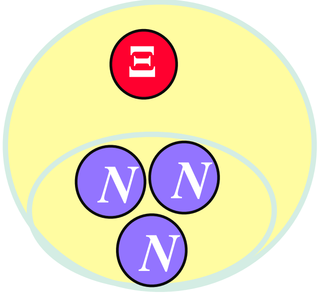

**[1] K. Nakazała et al. PTEP 033D02 (2015)**
**[2] S. Hayakawa et al. PTL 062501 (2021)**
**[3] M. Yoshimoto PTEP 073D02 (2021)**

(adapted from Y. Tanimura HYP2022 (2022))

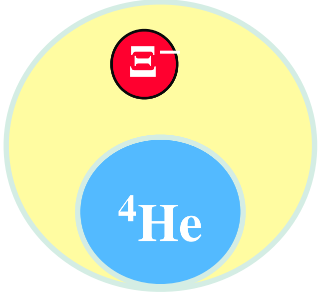
# lighter systems?

**using $\Xi N$ NLO potential we predict the existence of A=4-7 Ξ hypernuclei:**

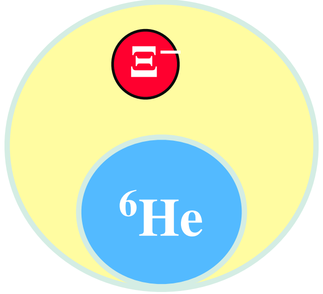
$NNN\Xi$ ?




$^{5}_{\Xi^-}\mathrm{H}$ ?




$^{7}_{\Xi^-}\mathrm{H}$ ?

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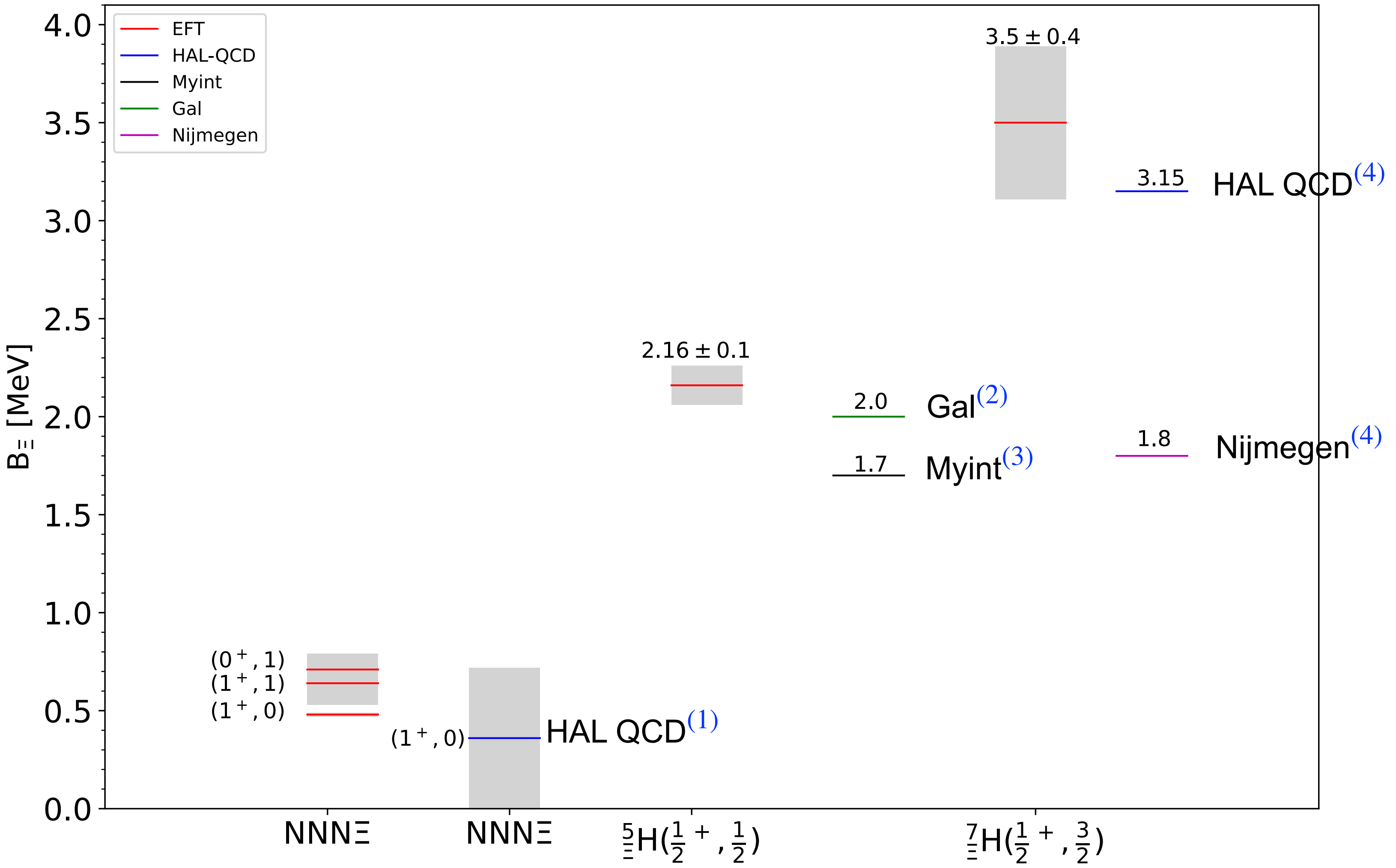
# Results for $A = 4-7$ $\Xi$-hypernuclei

**HL, J. Haidenbauer, U.-G. Meißner, A. Nogga, EPJA 57 12(2021)**




NN:SMS $\mathrm{N^4LO}$+(450)

$\Xi$N: NLO(500)

$\lambda_{NN} = \lambda_{YY} = 1.6\ [\mathrm{fm}^{-1}]$

(1) E.Hiyama et al. PRL 124 (2020)

(2) E. Friedman, A. Gal PLB(2021)

(3) K. Myint et al PTPS 117 (1994)

(4) H. Fujioko APFB2021, 3(2021)

- Coulomb interaction contributes ~ 200, 600 and 400 keV to $NNN\Xi$, $^5_\Xi\mathrm{H}$, $^7_\Xi\mathrm{H}$
- $^7_\Xi\mathbf{H}$ is expected to be produced and studied in $^7\mathrm{Li}(K^-, K^+)$ at J-PARC **(H. Fujioka et al., FBS 69(2021))**

# Summary & outlook

**At our disposal we have 2 tools to tackle light (hyper)nuclear systems:**

- s-shell (hyper)nuclei: Faddeev-Yakubovsky method (**Andreas Nogga**)
- s-shell & light p-shell: Jacobi No-core Shell Model approach

→ establish direct link between underlying YN (YY) interactions and observables (A<9)

**YN at NLO yields reasonable predictions for $A = 3 - 8$ hypernuclei:**

- include chiral YNN forces in order to properly describe light hypernuclei
- use neural network to perform extrapolation to infinite model space for A=7,8 systems

**Chiral YY ($\Xi N$) potentials predict the existence of $^{5}_{\Lambda\Lambda}\mathrm{He}/^{5}_{\Lambda\Lambda}\mathrm{H}$, $NNN\Xi$, $^{5}_{\Xi}\mathrm{H}$ and $^{7}_{\Xi}\mathrm{H}$:**

- include SRG-induce ΞNN forces to obtain more quantitive estimates

# Thank you!

- production of ${}^{5}_{\Xi}\mathrm{H}$?

$$\bar{p}\,p \to \Xi^{-}\ \bar{\Xi}^{+}$$

$$\Xi^{-} \longrightarrow {}^{4}\mathrm{He} \to {}^{5}_{\Xi}\mathrm{H}$$

PANDA **(J.I. Pütz PhD Thesis (2020))**

$$\to \bar{\Xi}^{+}\ \Xi^{*}(1530),$$ then $$\Xi^{*}(1530) \to \Xi^{-} + \pi^{+}$$

$$\Xi^{-} \longrightarrow {}^{4}\mathrm{He} \to {}^{5}_{\Xi}\mathrm{H}$$