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Avraham Gal, HU, Jerusalem, Israel

Remarks on the elusive H dibaryon

triggered by G. Farar's idea to make it
a long-lived Dark-Matter candidate

followed by

Update on ΛNN content of V_Λ

fitting all ($1s_\Lambda$, $1p_\Lambda$) pairs, $12 \leq A \leq 208$:

(i) OVERBOUND ΛN poential depth $D_\Lambda^{(2)}$.
(ii) REPULSIVE ΛNN potential depth,

$$D_\Lambda^{(3)} = 11.3 \pm 1.4 \text{ MeV at } \rho_0 = 0.17 \text{ fm}^{-3},$$

constraining the 'hyperon puzzle'.

E. Friedman, A. Gal, PLB 837 (2023) 137669
& NEW arXiv:2306.06973

Elusive H Dibaryon

The elusive H dibaryon

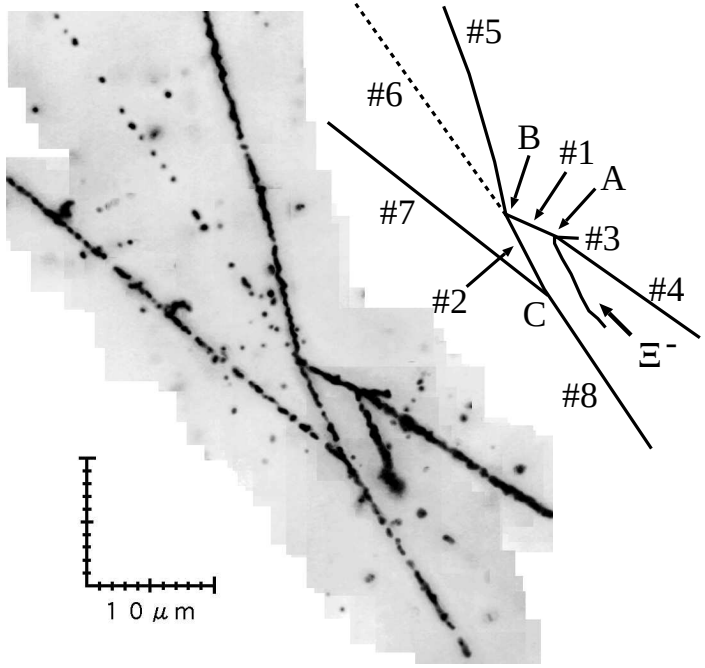
Jaffe's H(uuddss) [PRL 38 (1977) 195] predicted stable

$$\mathbf{H} \sim \mathcal{A}[\sqrt{\mathbf{1/8}}\ \Lambda\Lambda + \sqrt{\mathbf{1/2}}\ N\Xi - \sqrt{\mathbf{3/8}}\ \Sigma\Sigma,]_{I=S=0}$$

- **No H signal in past (K^-, K^+) experiments at AGS-BNL & PS-KEK. Awaiting J-PARC E42.**
- **Bound H ruled out by STAR study of $\Lambda\Lambda$ correlation femtoscopy [PRL 114 (2015) 022301].**
- **Bound H not ruled out by ALICE study of $\Lambda\Lambda$ correlation femto [PLB 797 (2019) 134822].**
- **Bound H above $\Lambda p \pi^-$, ~37 MeV below $\Lambda\Lambda$, ruled out by ALICE search for a weakly decaying $\Lambda\Lambda$ bound state [PLB 752 (2016) 267].**

- **Bound H above $\Lambda p \pi^-$ ruled out in Belle study of Υ(1S,2S) decays** [PRL 110 (2013) 222002].
- **Deeply bound H below Λn, $m_H \leq 2.05$ GeV, ruled out in BaBar's Υ(2S,3S)$\rightarrow$H$\bar{\Lambda}\bar{\Lambda}$ search** [PRL 122 (2019) 072002].
- **H is weakly bound in LQCD calculations, e.g., PRL 127 (2021) 242003, see Wittig's talk. $SU(3)_f$ breaking might push it to $\approx$26 MeV in the $\Lambda\Lambda$ continuum, near NΞ threshold: HALQCD Collaboration** [NPA 881 (2012) 28] **& Haidenbauer-Meißner** [NPA 881 (2012) 44].

Constraints from Hypernuclei



Nagara event, ${}_{\Lambda\Lambda}^{\ 6}\mathrm{He}$, (KEK-E373) PRL 87 (2001) 212502

$B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{\ 6}\mathrm{He}_{\mathrm{g.s.}})$**=6.91±0.16 MeV, uniquely identified.**

- **A:** Ξ^- **capture** $\Xi^- + {}^{12}\mathrm{C} \rightarrow {}_{\Lambda\Lambda}^{\ 6}\mathrm{He} + t + \alpha$
- **B: weak decay** ${}_{\Lambda\Lambda}^{\ 6}\mathrm{He} \rightarrow {}_{\Lambda}^{5}\mathrm{He} + p + \pi^-$ **(no** ${}_{\Lambda\Lambda}^{\ 6}\mathrm{He} \rightarrow {}^{4}\mathrm{He}$ **+ H)**
- **C:** ${}_{\Lambda}^{5}\mathrm{He}$ **nonmesic weak decay to two** Z**=1 recoils + n.**

Few other weakly decaying ${}_{\Lambda\Lambda}^{\ A}\mathrm{Z}$ **hypernuclei identified.**

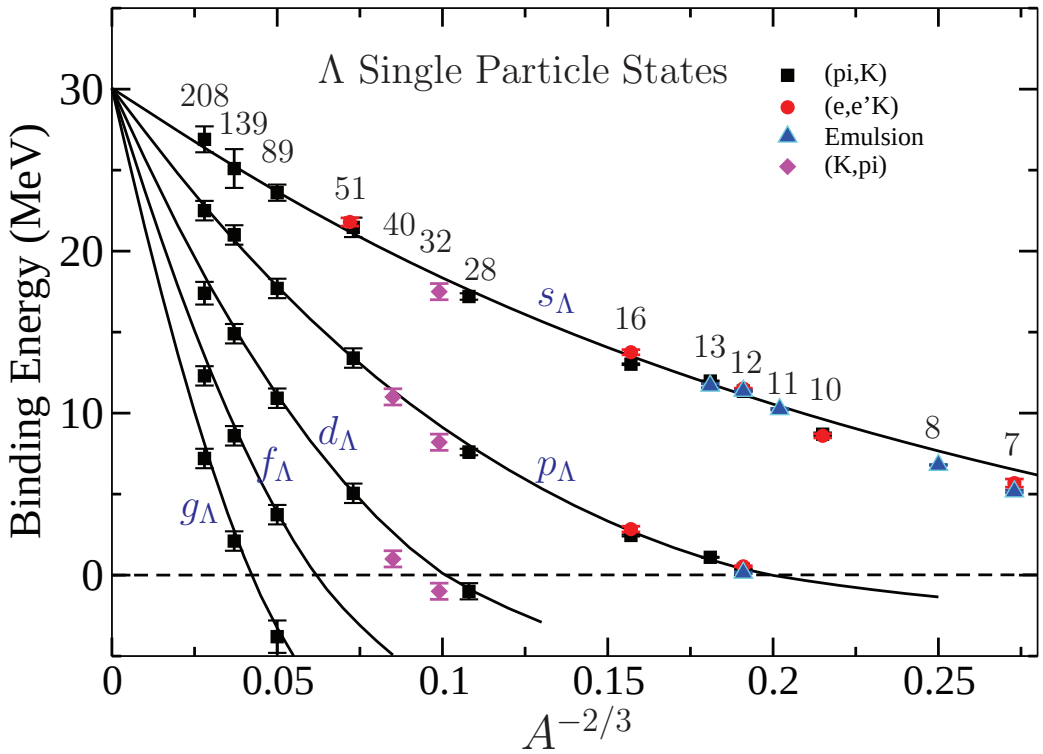
Constraints from Hypernuclei

- To forbid ${}^{6}_{\Lambda\Lambda}$He$\rightarrow$H+^{4}He, set B(H)$\leq$7 MeV. However, ${}^{6}_{\Lambda\Lambda}$He comes out then overbound [Gal, PRL 110 (2013) 179201].
- A correlated $\Lambda\Lambda$ pair in a given ${}^{A}_{\Lambda\Lambda}$Z would decay strongly to a bound H, contrary to observing ${}^{A}_{\Lambda\Lambda}$Z in weak decay. Furthermore,
- H$\rightarrow\Lambda$n weakly, $\tau\sim 10^{-10}$ sec. If below Λn, it decays weakly, H$\rightarrow$nn, by π exchange, with τ not much longer than 1yr, $\ll \tau$(Universe).
- Thus, a deeply bound uuddss 'sexaquark' fails as a long-lived Dark-Matter candidate [Barnea-Gal-Schaefer, in progress].

ΛNN vs. ΛN content of $V_\Lambda^{\rm opt}$

from Λ hypernuclei

Update: Millener, Dover, Gal PRC 38, 2700 (1988)



Woods-Saxon $V = 30.05$ MeV, $r = 1.165$ fm, $a = 0.6$ fm

B_Λ values in ${}^{7}_{\Lambda}$Li to ${}^{208}_{\Lambda}$Pb from experiment and as calculated from a 3-parameter WS potential, suggesting a Λ-nucleus potential depth $D_\Lambda \approx -30$ MeV.

Data: Table IV Gal-Hungerford-Millener, RMP 88 (2016) 035004.

D_Λ in ΛN-ΣN models

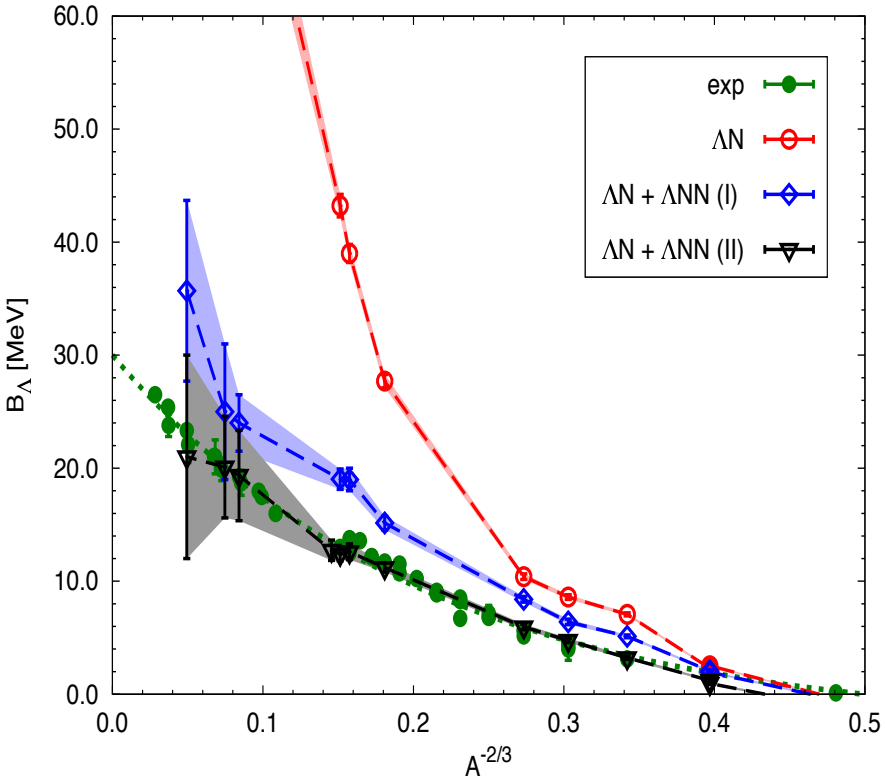
Most 2-body YN models overbind: $|D_\Lambda^{(2)}| > 30$ MeV.

- **NSC and ESC models overbind, with $D_\Lambda^{(2)} \sim -40$ MeV.**
- **χEFT(LO) overbinds, substantial cutoff dependence.**
- **χEFT(NLO): substantial model & cutoff dependence, NLO13(600): -21.6 MeV, NLO19(600): -32.6 MeV.**
- **χEFT(N^{2}LO) overbinds, $D_\Lambda^{(2)} \approx -33$ to -38 MeV.**

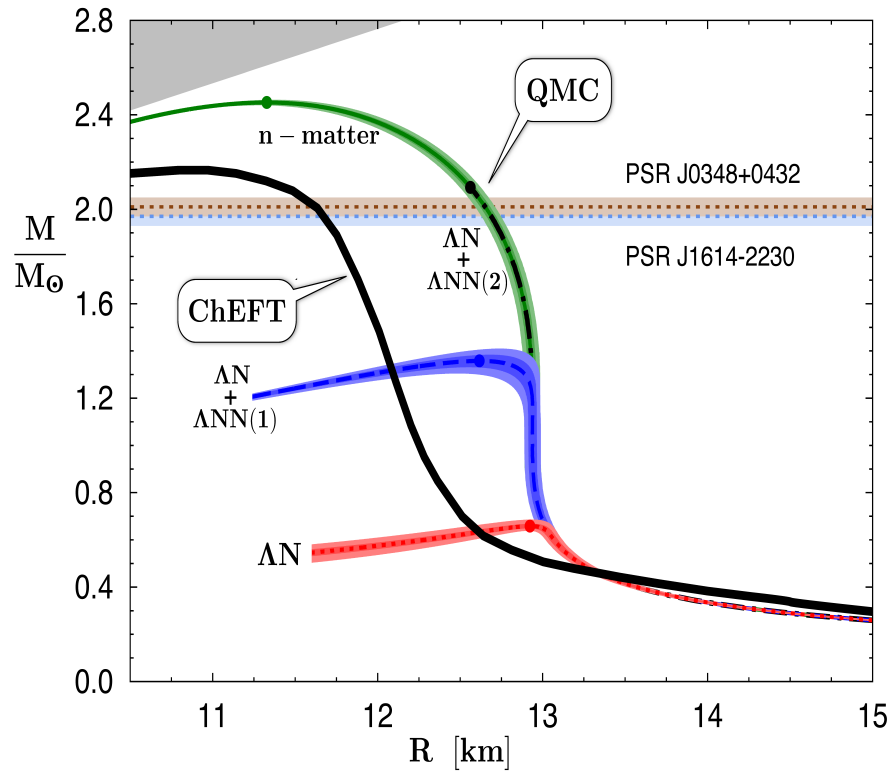
Underbinding would be disastrous for neutron-star matter considerations, implying attractive ΛNN contribution $D_\Lambda^{(3)}$ which will soften the EoS at sufficiently large density.

If repulsive, how large $D_\Lambda^{(3)}$ is?

Hyperon puzzle: AFDMC calculations



Lonardoni et al, PRC 89 (2014) 014314



PRL 114 (2015) 092301

- ΛN overbinds; added ΛNN stiffens neutron-star EoS.
- However, problematic ${}^{5}_{\Lambda}$He & unlisted ${}^{17}_{\Lambda}$O B_Λ input.
- Produced nuclear radii are ≈20% too small.

Critique of Skyrme-Hartree-Fock (SHF)

Millener-Dover-Gal, PRC 38 (1988) 2700
Schulze-Hiyama, PRC 90 (2014) 047301

$V_\Lambda(\rho_N) = [\, V_\Lambda^{(2)}(\rho_N) = a_0\rho_N \,] + [\, V_\Lambda^{(3)}(\rho_N) = a_3\rho_N^2 \,]$

is fitted to some $B_\Lambda(A)$ data points [ρ_0=0.17 fm^{-1}]

Ref.	Points	$V_\Lambda^{(2)}(\rho_0)$	$V_\Lambda^{(3)}(\rho_0)$	$V_\Lambda(\rho_0)$ (MeV)
MDG88	3	−57.8	31.4	−26.4
SH14	35	−55.4	20.4	−35.0 †
present (Q)	2	−57.6	30.2	−27.4

$^\dagger \approx -31$ MeV adding $M_{\rm eff}(\Lambda)$ contribution.

- Introduce (WRW) Pauli correlations at $\rho^{4/3}$, affecting higher density powers, e.g., ρ^2.
- WRW: Waas-Rho-Weise, NPA 617 (1997) 449, practised since 2013 in K^- atoms analyses.

WRW density dependence of V_Λ

$$\Lambda N \quad \Rightarrow \quad V_\Lambda^{(2)}(\rho) = -\frac{4\pi}{2\mu_\Lambda}\, b_0^{\rm lab}(\rho)\,\rho$$

$$b_0^{\rm lab}(\rho) = \frac{b_0^{\rm lab}}{1+\frac{3k_F}{2\pi}\, b_0^{\rm lab}} \qquad b_0^{\rm lab} = (1+\frac{A-1}{A}\frac{\mu_\Lambda}{m_N})\, b_0$$

for Pauli correlations, with $\mathbf{k}_F$=$(3\pi^2\rho/2)^{1/3}$.

Short-range correlations negligible at $\rho \leq \rho_0$.

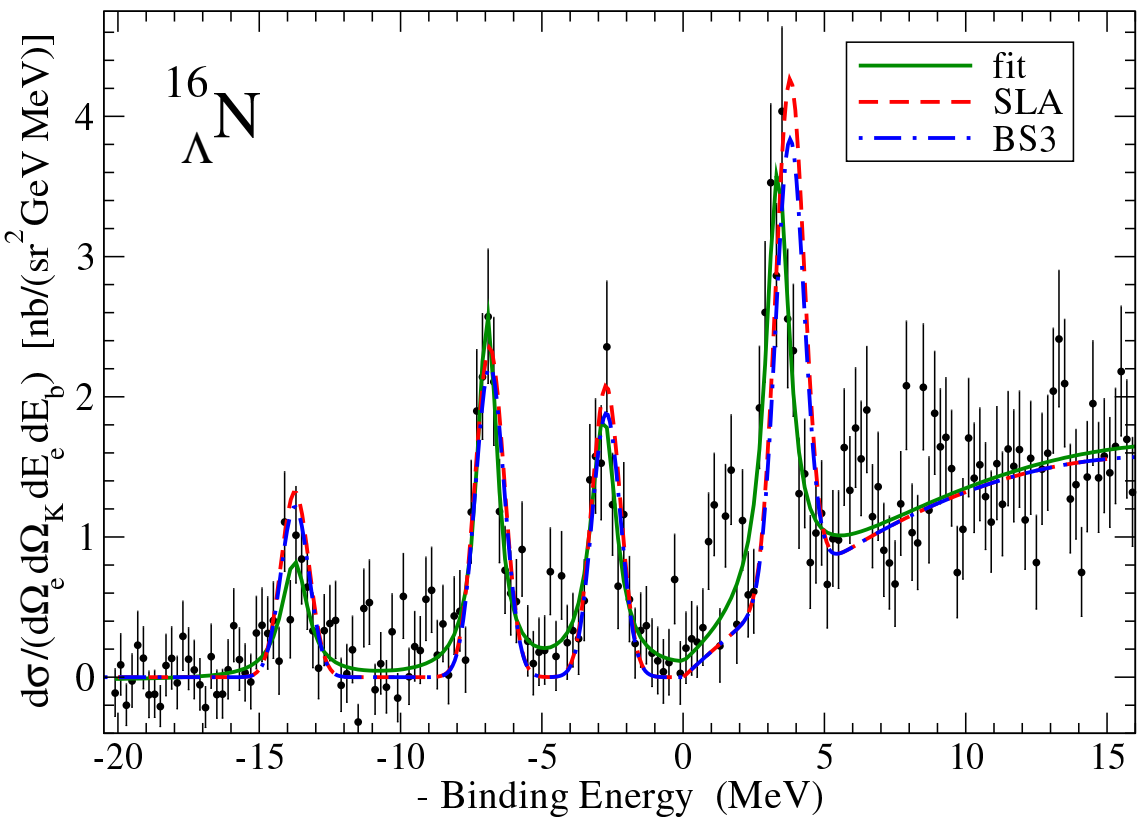
Pauli affects terms beyond $\rho^{4/3}$, e.g., ρ^2.

Low density limit: $b_0 = \Lambda$N scattering length.

$$\Lambda NN \quad \Rightarrow \quad V_\Lambda^{(3)}(\rho) = +\frac{4\pi}{2\mu_\Lambda}\,(1+\frac{A-2}{A}\frac{\mu_\Lambda}{2m_N})\, B_0\,\frac{\rho^2}{\rho_0}$$

Applying Pauli to $V_\Lambda^{(3)}(\rho)$ has a minor effect.

Fit b_0 and B_0 to $\mathbf{B}_\Lambda^{1s,1p}(^{16}_{\Lambda}\mathbf{N})$.

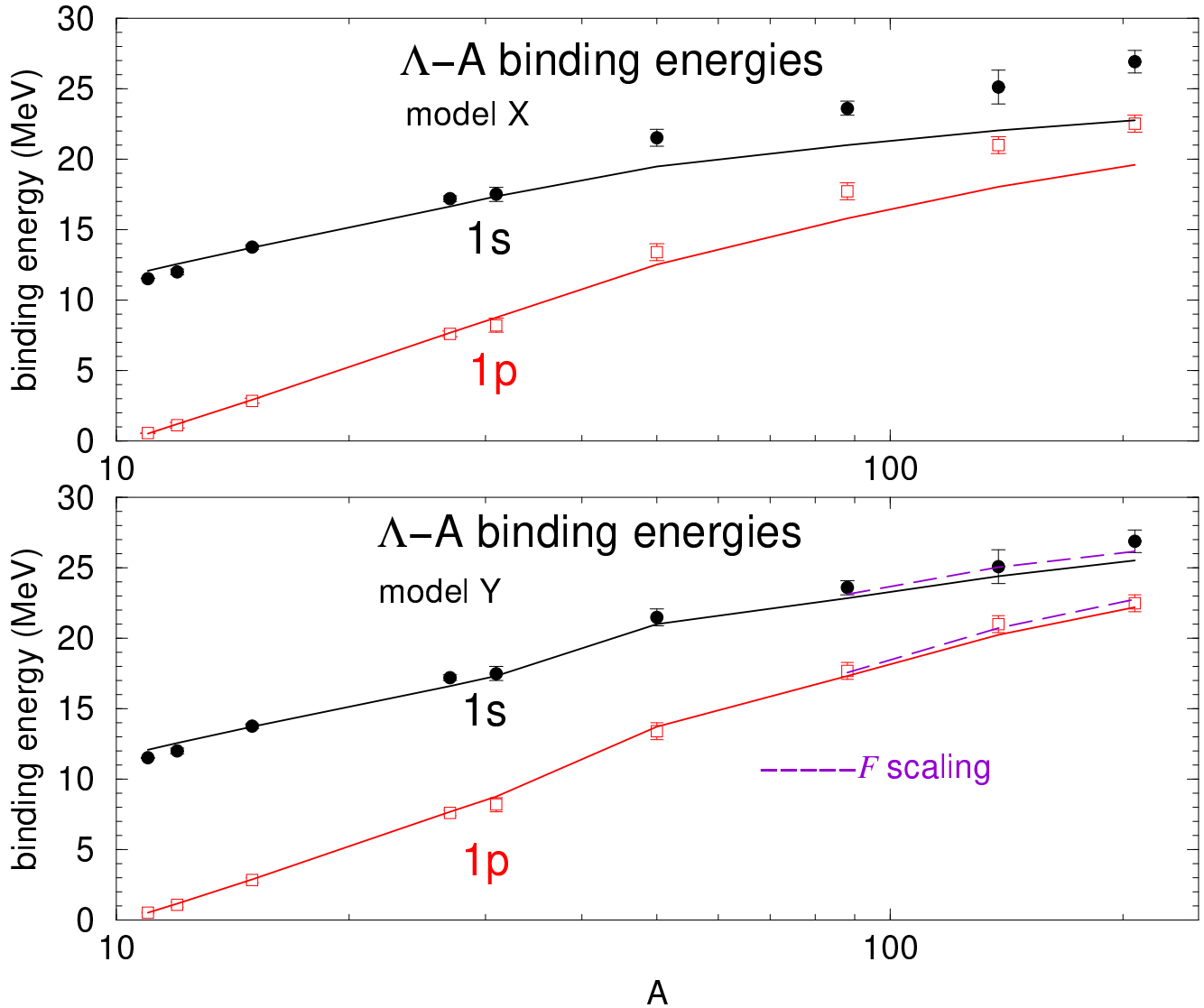


$^{16}_{\Lambda}$N spectrum from JLab Hall A (e,e'K$^+$) experiment

PRL (2009) & PRC 99 (2019) 054309

Why $^{16}_{\Lambda}$N? – (i) very accurate data

(ii) end of p-shell, very simple s.p. structure



Fit b_0 & B_0 to $B_\Lambda^{1s,1p}({}^{16}_{\Lambda}N)$, then calculate all other $B_\Lambda^{1s,1p}(A)$.

Note: neutron excess in Model Y is decoupled

from sym. nucl. core: $\rho^2 = (\rho_{\rm sym} + \rho_{\rm exc})^2 \to (\rho_{\rm sym}^2 + \rho_{\rm exc}^2)$.

ΛN & ΛNN contributions to D_Λ

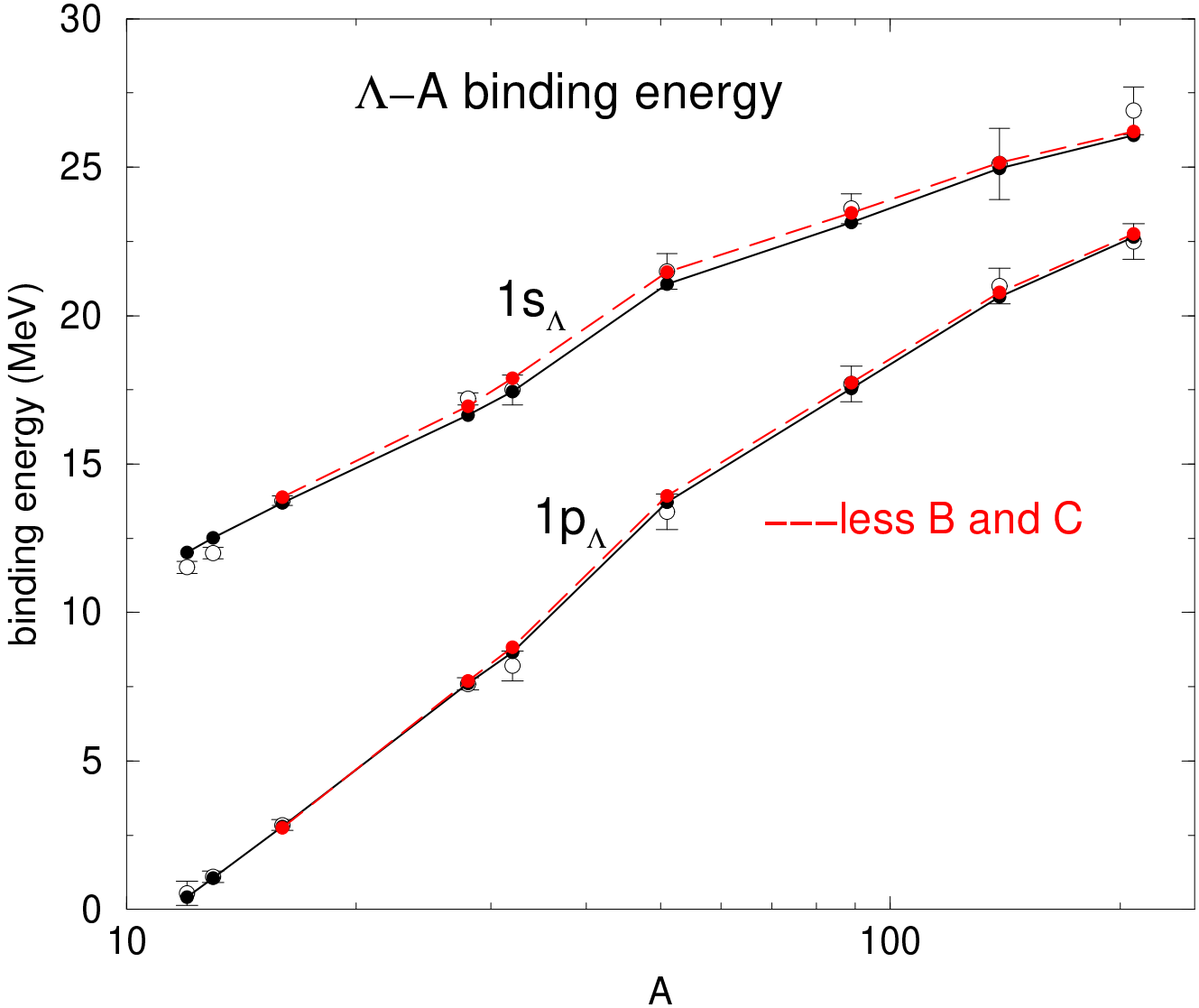
Model	Pauli	$D_\Lambda^{(2)}$	$D_\Lambda^{(3)}$	D_Λ (MeV)
P	No	−34.1	–	−34.1
P'	Yes	−31.3	–	−31.3
MDG88	No	−57.8	31.4	−26.4
Q	No	−57.6	30.2	−27.4
X,Y	Yes	−39.9	13.9	−26.0

- **Final depth values, including uncertainties:**
  $D_\Lambda^{(2)}$=−40.4±0.6 MeV, $D_\Lambda^{(3)}$=13.9±1.4 MeV
  D_Λ=−26.5±1.5 MeV.
- **AFDMC depths: scale ρ_0=0.17 fm^{-3} by r_N^{-3}.**
  $D_\Lambda^{(2)}$=−78.9±1.2 MeV, $D_\Lambda^{(3)}$=53.0±5.3 MeV
  D_Λ=−26.5±1.5 MeV.

ΛNN vs. ΛN content of $V_\Lambda^{\rm opt}$

Least Squares Fit to Λ Hypernuclei

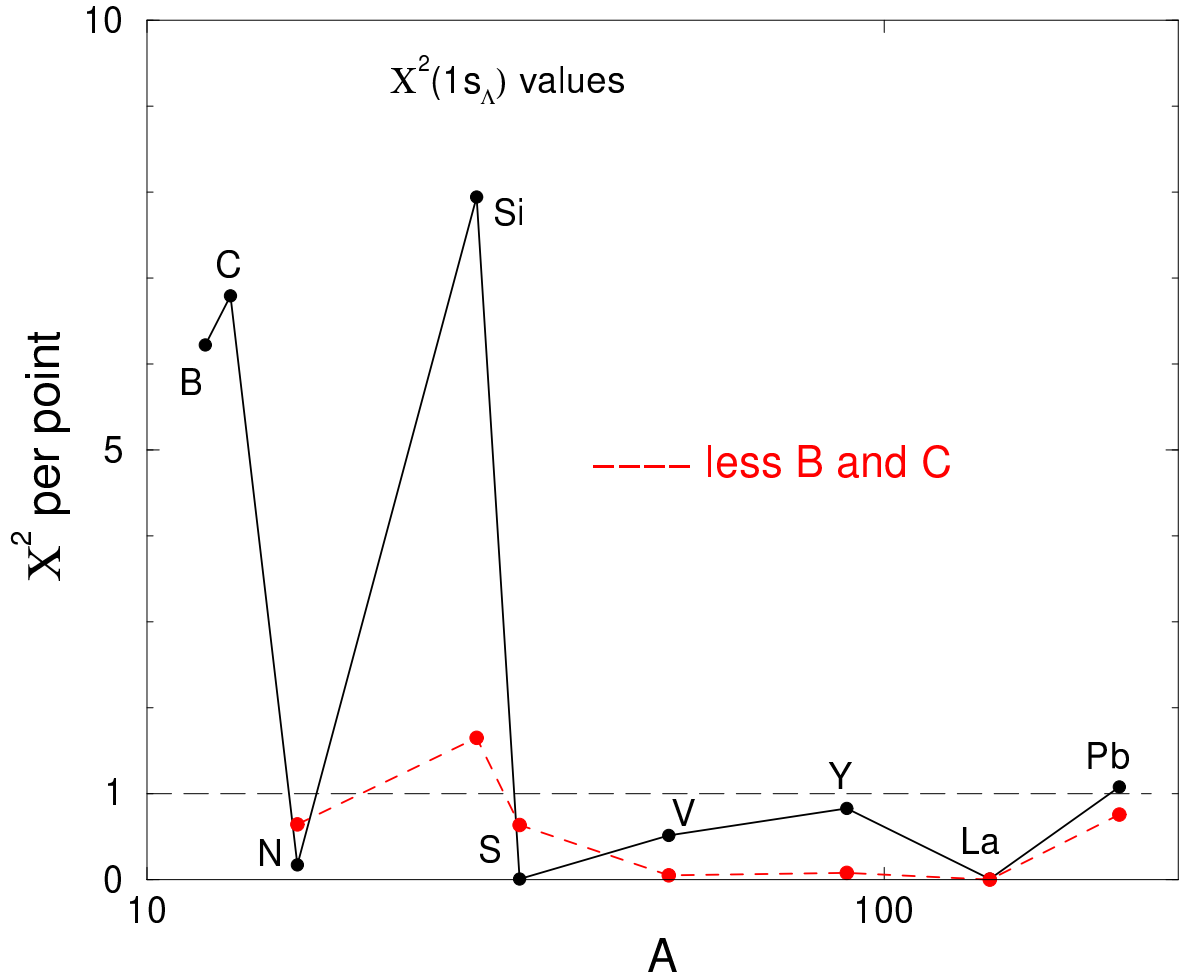
UPDATE: Friedman-Gal, arXiv:2306.06973



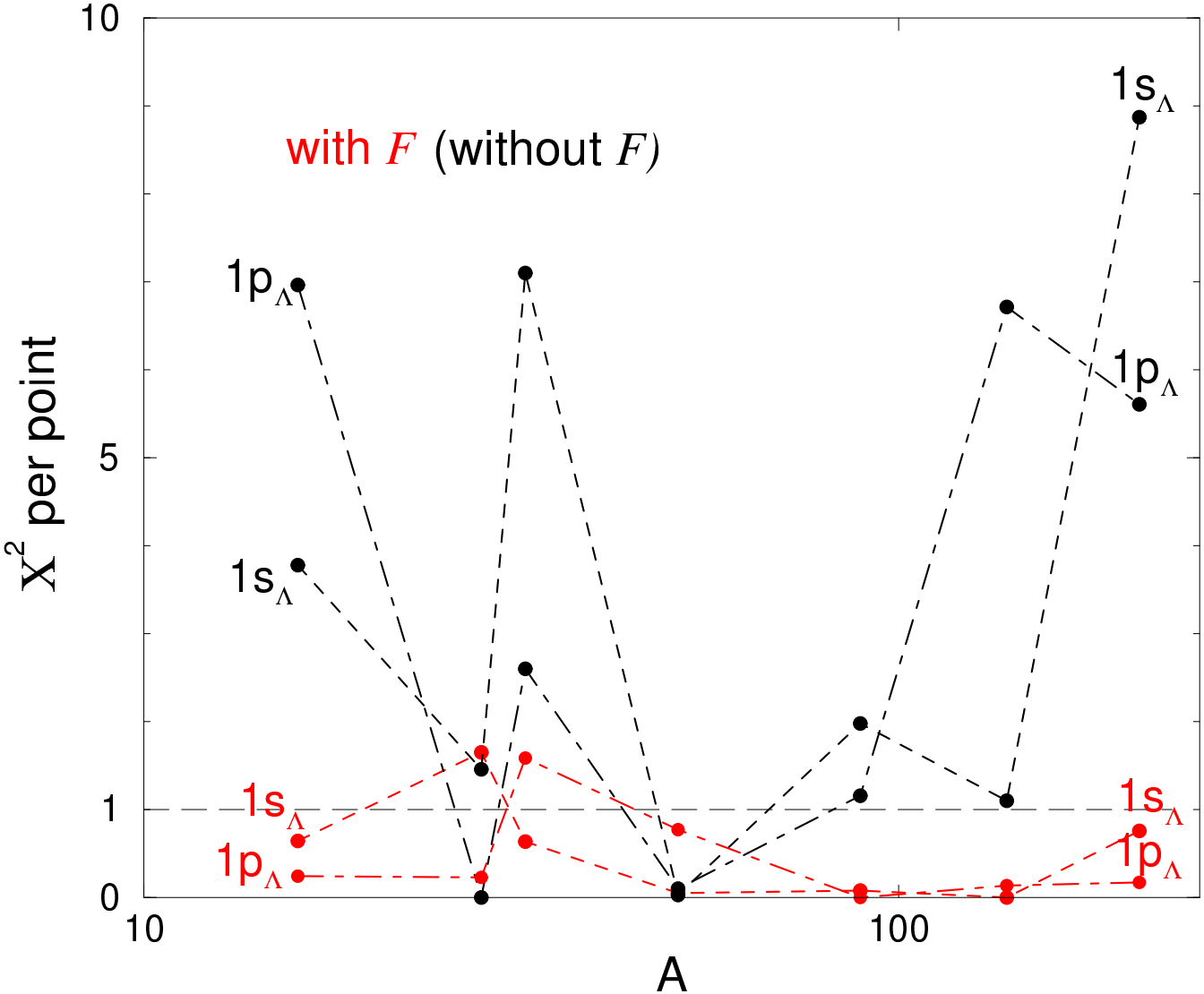
Two-parameter (ΛN & ΛNN) least-squares fit to $\mathrm{B}_\Lambda^{1s,1p}(\mathrm{A})$.

Solid: 18 data points, dashed: less ${}^{12}_{\Lambda}\mathrm{B}$ & ${}^{13}_{\Lambda}\mathrm{C}$.

Decoupled neutron excess: $\rho^2 = (\rho_{\rm sym} + \rho_{\rm exc})^2 \to (\rho_{\rm sym}^2 + \rho_{\rm exc}^2)$.



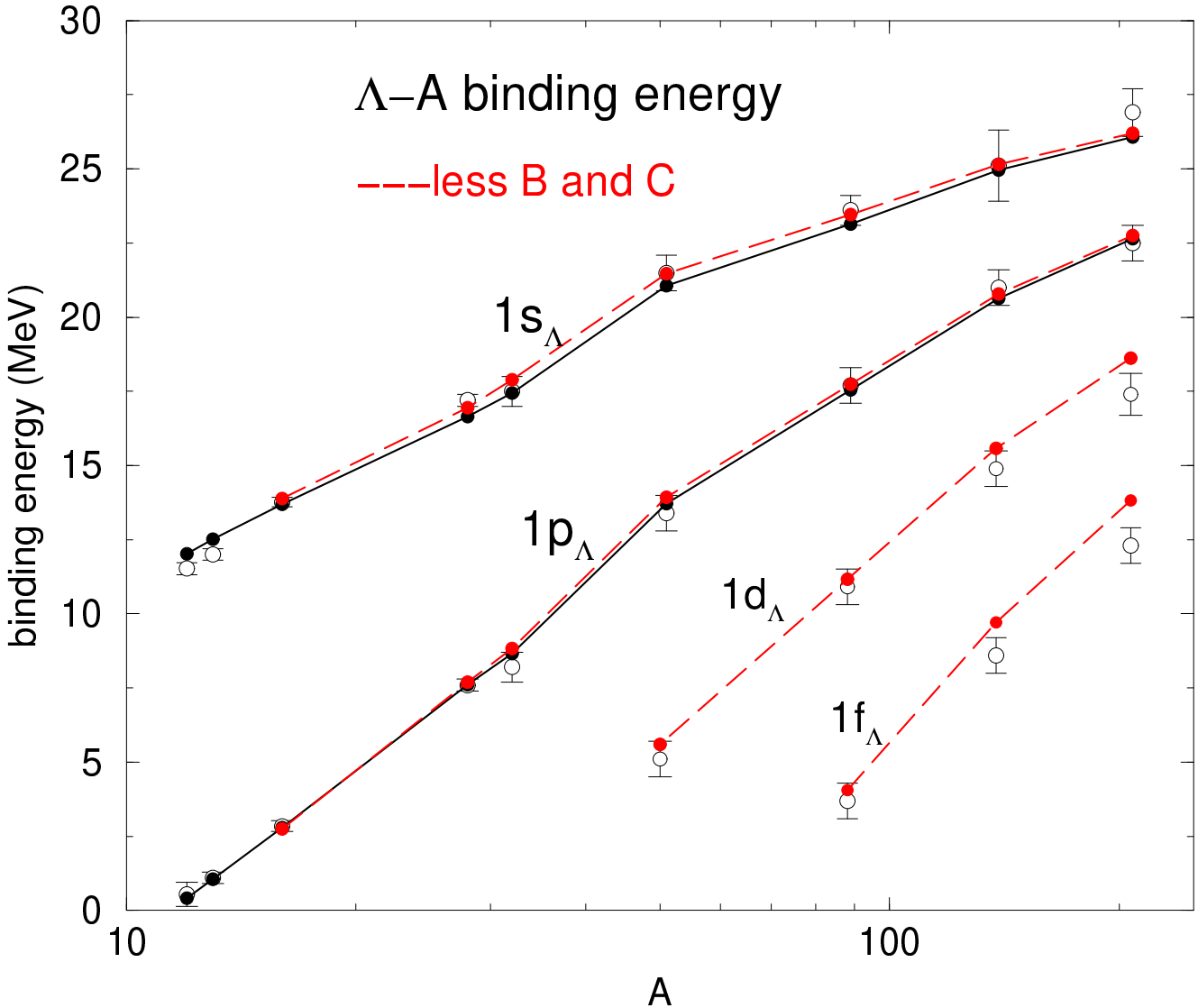
$1s_\Lambda$ best-fit χ^2: all data and also less ${}^{12}_{\Lambda}$B & ${}^{13}_{\Lambda}$C where new noncentral ΛNN terms arise, unconstrained in mid p-shell Λ hypernuclei by γ ray data, etc..



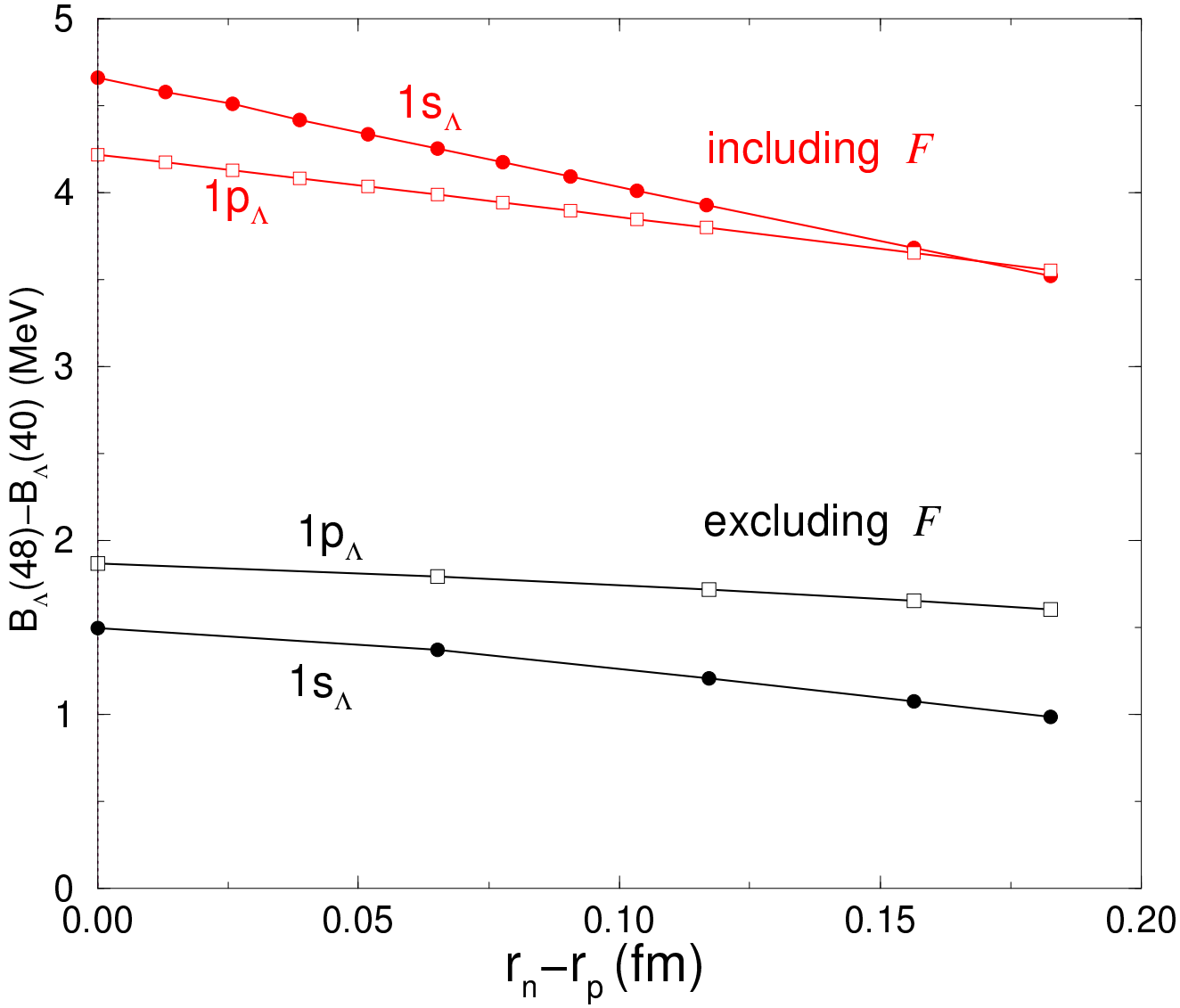
$1s_\Lambda$ & $1p_\Lambda$ best-fit χ^2 excluding ${}^{12}_{\Lambda}$B & ${}^{13}_{\Lambda}$C.

'with F': $\rho^2 = (\rho_{\rm sym} + \rho_{\rm exc})^2 \to (\rho_{\rm sym}^2 + \rho_{\rm exc}^2)$.

'without F': **full** $\rho^2 = (\rho_{\rm sym} + \rho_{\rm exc})^2$.



B_Λ(1d,1f) (two lower lines) calculated by fitting to B_Λ(1s,1p) (two upper lines).



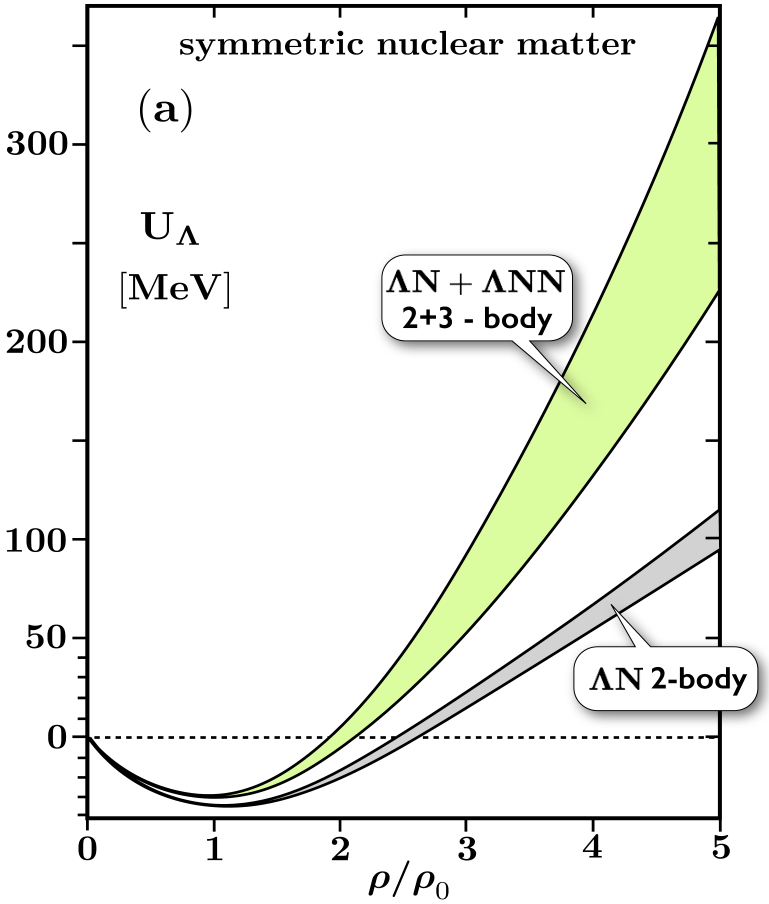
$B_\Lambda({}^{48}_{\Lambda}K)$-$B_\Lambda({}^{40}_{\Lambda}K)$ for $1s_\Lambda$ and $1p_\Lambda$ states,

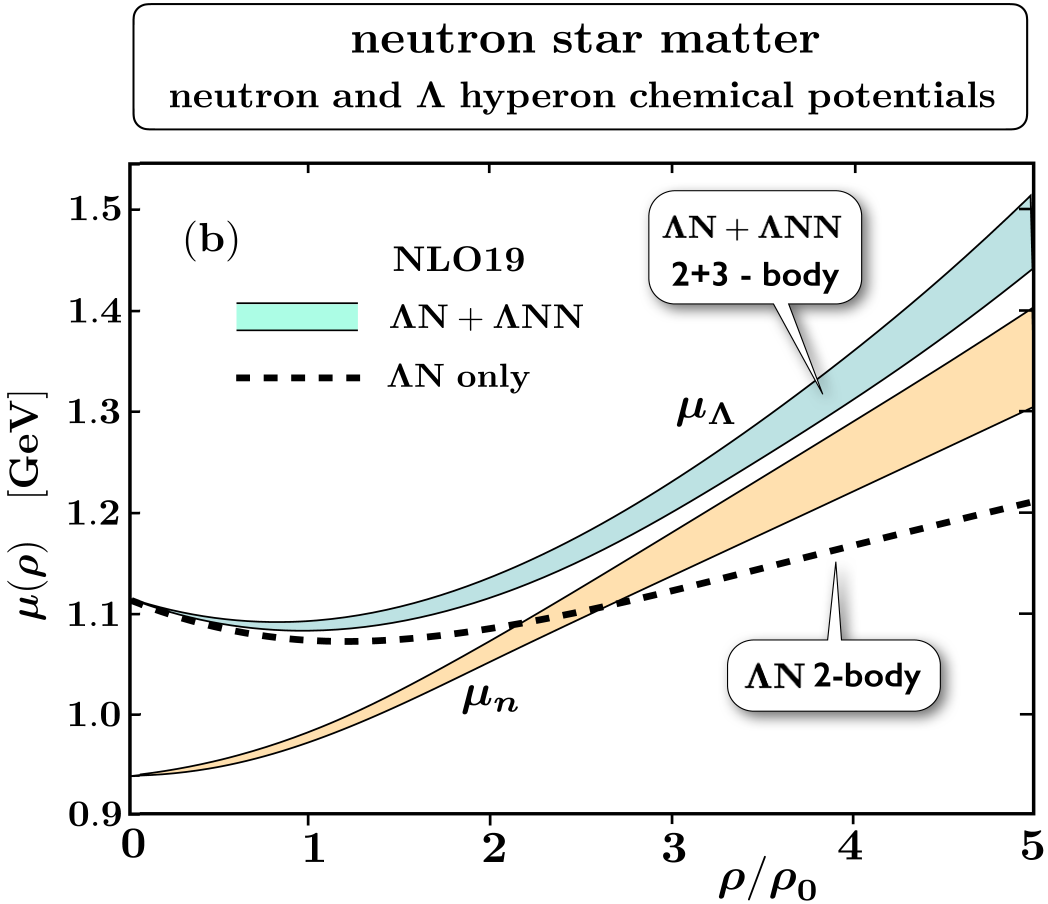
with & without F, as function of r_n-r_p in ${}^{48}_{\Lambda}K$,

ahead of upcoming ${}^{40,48}Ca(e,e'K^+){}^{40,48}_{\Lambda}K$ JLab exp.

ΛNN summary & outlook

- $V_\Lambda^{\rm opt}$ applied to ($1s_\Lambda$, $1p_\Lambda$) single-particle states across the periodic table.
- Pauli corrected ΛN term, plus ΛNN term.
- Decoupling $\rho_{\rm exc}$ from $\rho_{\rm sym}$ in $\Lambda N_1 N_2$ ρ^2 term suggests $\tau_1 \cdot \tau_2$ isospin structure, consistently with $\Lambda \to (\Sigma, \Sigma^*) \to \Lambda$ isovector excitations.
- Depth values $D_\Lambda^{(2)}$ & $D_\Lambda^{(3)}$ fully correlated: $D_\Lambda^{(2)}$=−38.6±0.8 MeV with b_0=1.44±0.10 fm, $D_\Lambda^{(3)}$=11.3±1.4 MeV, D_Λ=−27.3±0.6 MeV.
- $D_\Lambda^{(3)}$ ≈11 MeV excludes in EFT Λ hyperons from dense neutron-star matter, $\mu_\Lambda > \mu_n$, see Gerstung-Kaiser-Weise, EPJA 56 (2020) 175.





W. Weise, EPJ Web Conf. 271 (2022) 06003

Following Gerstung-Kaiser-Weise, EPJA 56 (2020) 175

Thanks for your attention!