ΛNN content of Λ-nucleus potential

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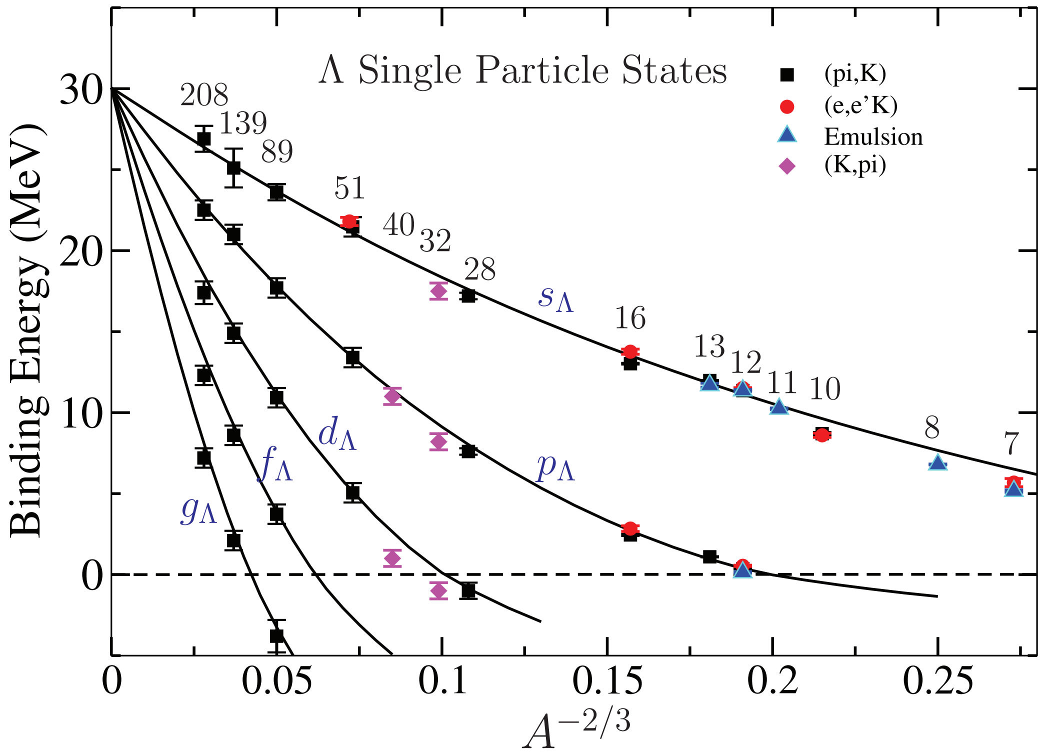
based on arXiv:2204.02264

Abstract: **A minimally constructed Λ-nucleus density-dependent optical potential is used to calculate binding energies of observed $1s_\Lambda$, $1p_\Lambda$ states across the periodic table, leading to ≈14 MeV repulsive ΛNN contribution to the phenomenological Λ-nucleus potential depth $D_\Lambda \approx -30$ MeV, thereby potentially resolving the 'hyperon puzzle'.**

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

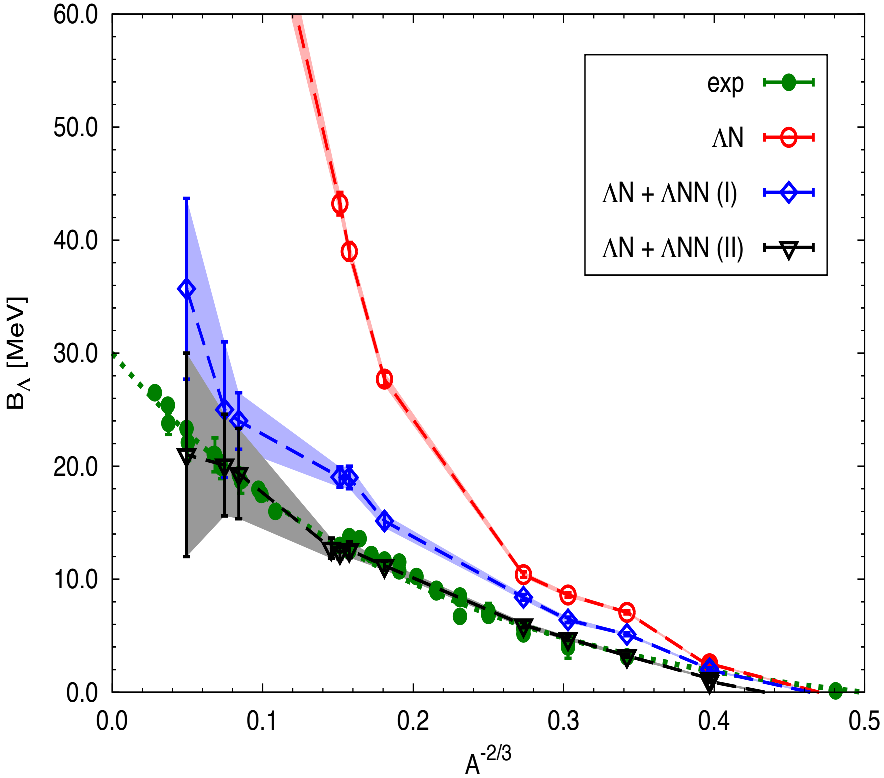
Most 2-body YN models overbind: $|D_\Lambda^{(2)}| > 30$ MeV.

- **NSC and ESC models overbind, with $D_\Lambda^{(2)} \sim -40$ MeV.**
- **χEFT(LO) models also overbind, with substantial cutoff dependence.**
- **χEFT(NLO) models have substantial model and cutoff dependence; some might underbind.**

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.

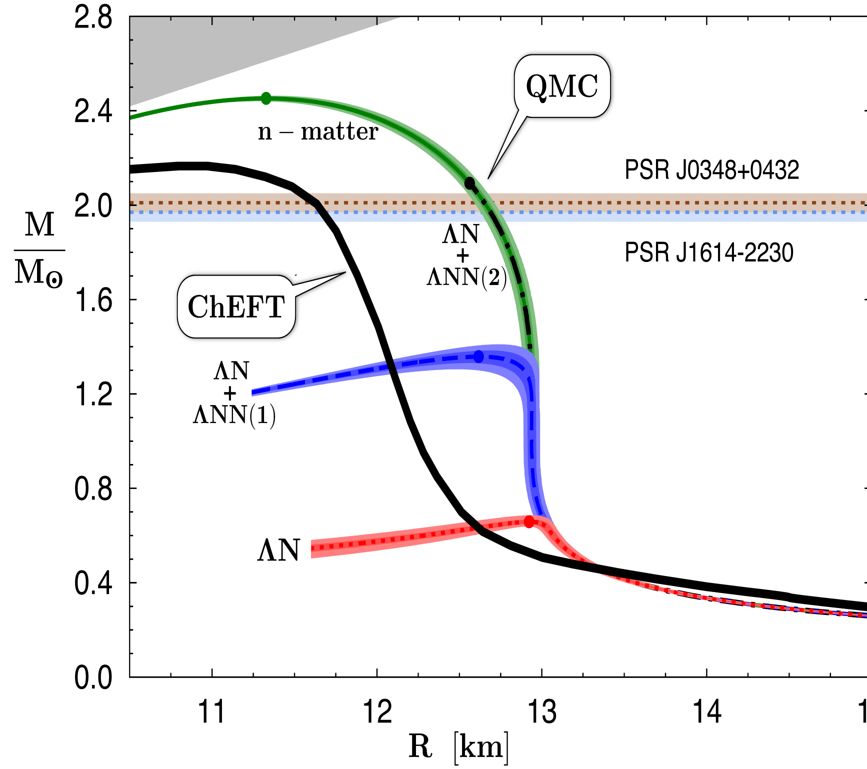
If repulsive, how large $D_\Lambda^{(3)}$ is?

Hyperon puzzle: QMC calculations



Lonardoni et al, PRC 89 (2014) 014314

ΛNN effect on B_Λ(g.s.)



PRL 114 (2015) 092301

ΛNN effect on neutron stars

- **ΛN overbinds, adding ΛNN stiffens EOS of neutron stars.**
- **However, it uses problematic $^{5}_{\Lambda}$He & unlisted $^{17}_{\Lambda}$O B_Λs.**
- **And produces nuclear radii ≈20% too small.**

Critique of SHF methodology

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

† ≈ −31 MeV adding $M_{\text{eff}}(\Lambda)$ contribution.

- Missing Pauli correlations (WRW97) start as $\rho^{4/3}$, affect higher density powers, e.g., ρ^2.
- Waas-Rho-Weise, NPA 617 (1997) 449 has been practised in K^- atoms (see Obertova's talk).

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 $k_F=(3\pi^2\rho/2)^{1/3}$.

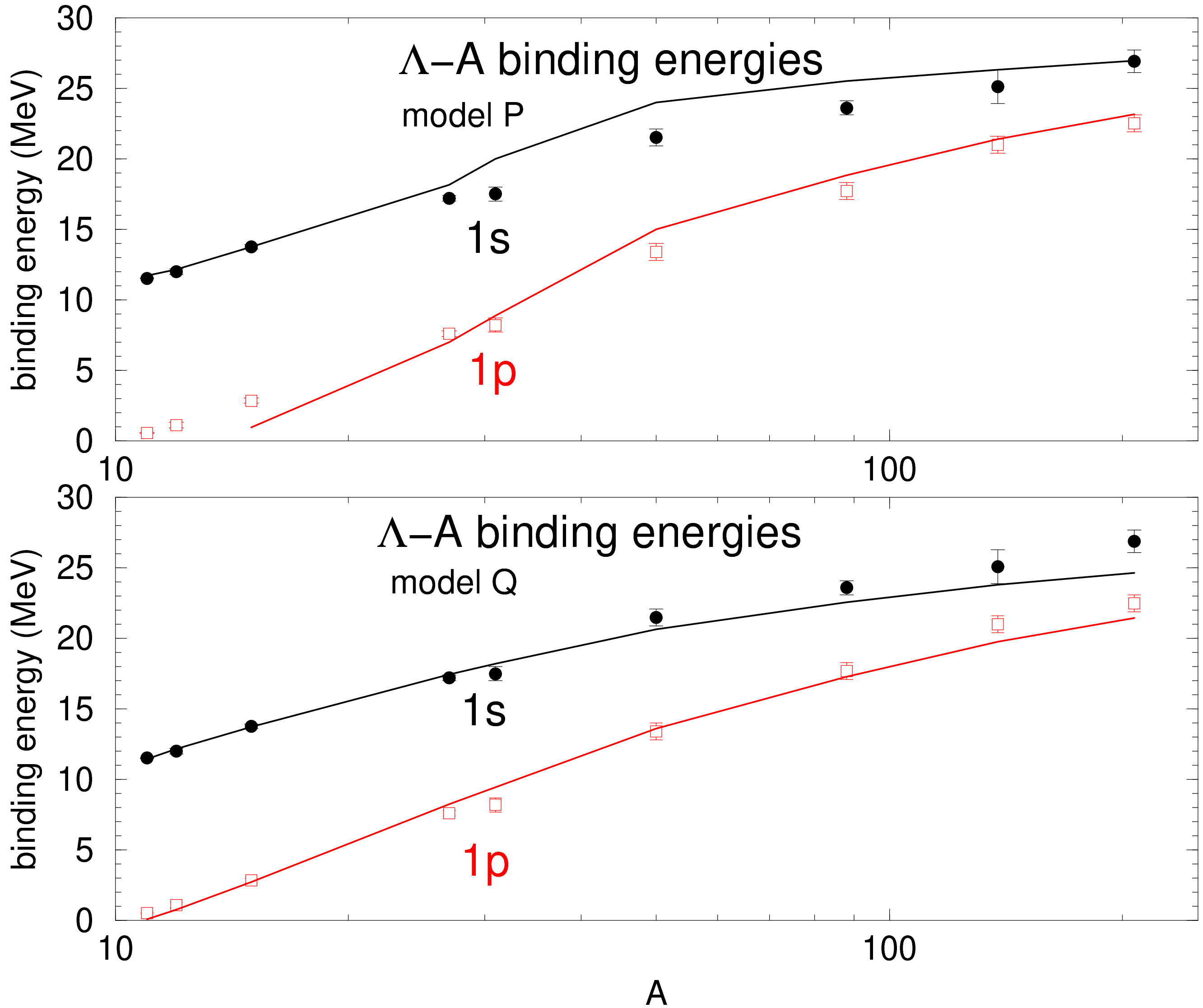
Short-range correlations negligible at $\rho \leq \rho_0$.

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

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

$$\Lambda N N \quad \Rightarrow \quad V_\Lambda^{(3)}(\rho) = +\frac{4\pi}{2\mu_\Lambda}\, B_0^{\rm lab}\, \frac{\rho^2}{\rho_0}$$

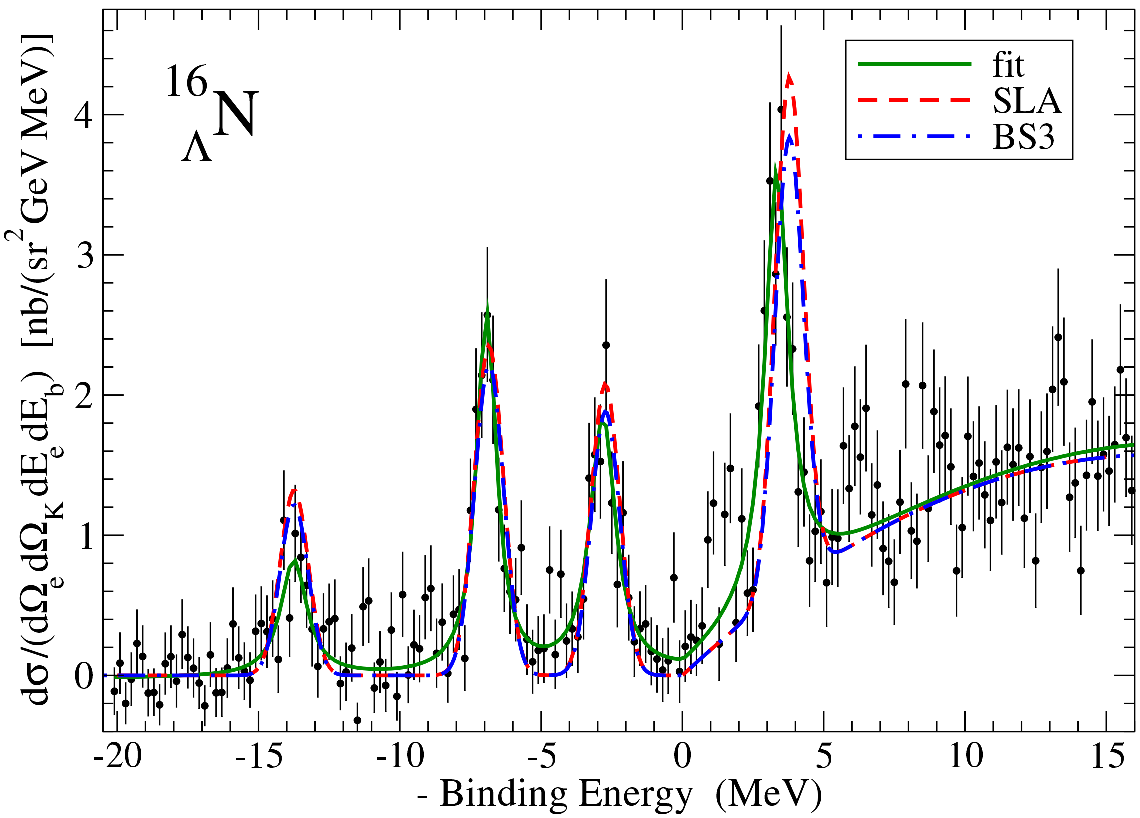
Applying Pauli to $V_\Lambda^{(3)}(\rho)$ has a minor effect.



$B_\Lambda^{1s,1p}(A)$ in Models P,Q fitted to $^{16}_{\Lambda}N$. **No Pauli**

Model P: $b_0 \neq 0$, $B_0 = 0$ Model Q: $b_0 \neq 0$, $B_0 \neq 0$

Model Q results close to SHF results

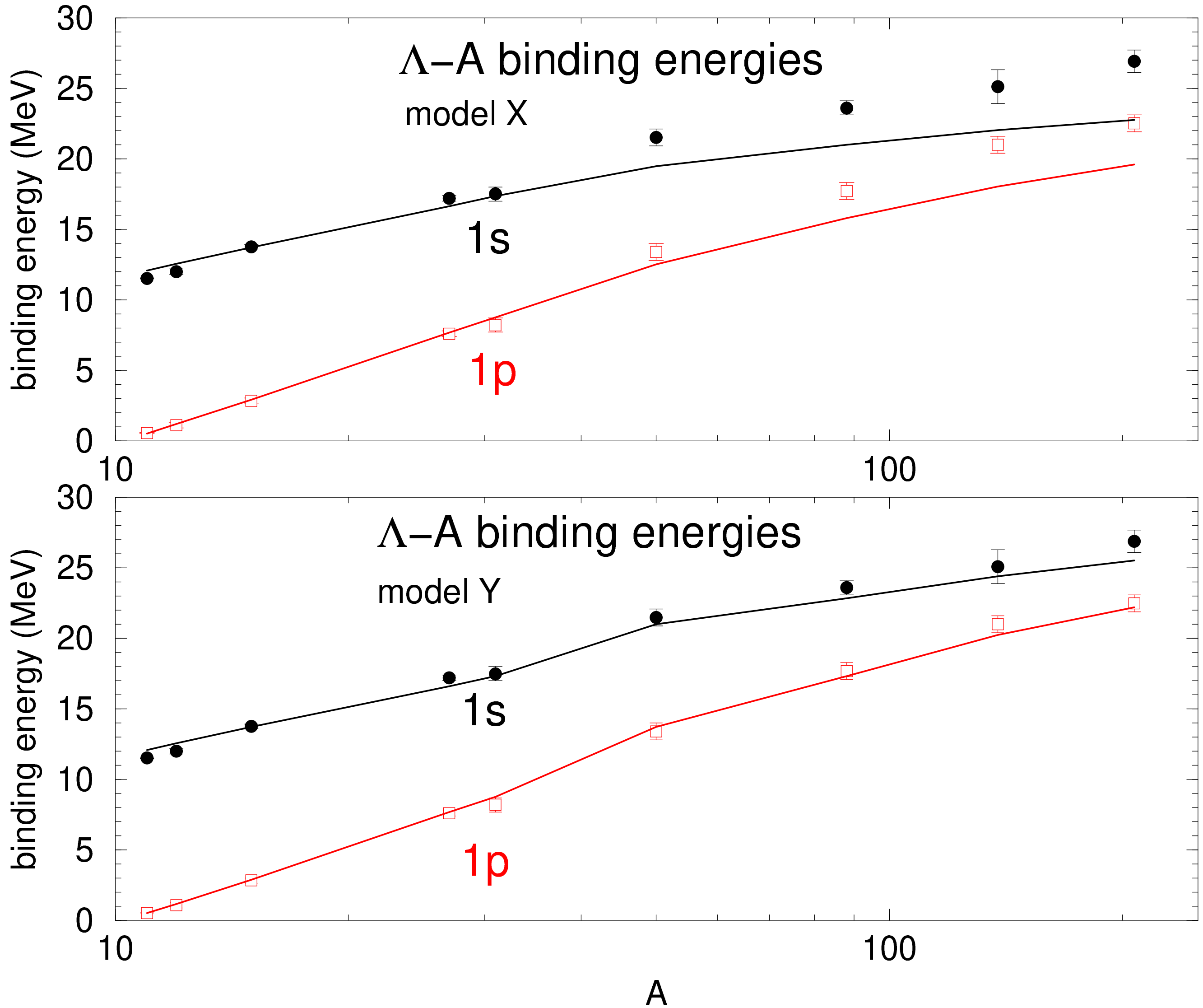


$^{16}_{\Lambda}$N spectrum from JLab Hall A (e,e'K^{+}) experiment

PRL (2009) & PRC 99 (2019) 054309

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

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



$B_{\Lambda}^{1s,1p}(A)$ **in Models X,Y fitted to** $^{16}_{\Lambda}N$**.** **Yes Pauli**

$b_0 \neq 0$**,** $B_0 \neq 0$ **in both Models X,Y**

Neutron excess decoupled from rest in Model Y

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:** $D_\Lambda^{(2)}=-40.4\pm0.6$ MeV, $D_\Lambda^{(3)}=13.9\pm1.4$ MeV $D_\Lambda=-26.5\pm1.5$ MeV.
- **AFDMC depths: scale $\rho_0=0.17$ fm^{-3} by r_N^{-3}.** $D_\Lambda^{(2)}=-78.9\pm1.2$ MeV, $D_\Lambda^{(3)}=53.0\pm5.3$ MeV $D_\Lambda=-26.5\pm1.5$ MeV.

Summary & Outlook

- **DD optical potential methodology applied to Λ-nucleus single-particle spectra across the periodic table.**
- **Pauli corrected ΛN term, plus ΛNN term.**
- **Isospin dependence in ΛNN term: neutron-excess density decoupled from SNM density.**
- **Final depth values, including uncertainties:** $D_\Lambda^{(2)}=-40.4\pm0.6$ **MeV,** $D_\Lambda^{(3)}=13.9\pm1.4$ **MeV** $D_\Lambda=-26.5\pm1.5$ **MeV.**
- **Implications to dense neutron-star matter in the following talk.**

Back-up transparencies

Over/Under binding in s-shell

(MeV)	$B_\Lambda({}^3_\Lambda\mathbf{H})$	$B_\Lambda({}^4_\Lambda\mathbf{H}_{\mathrm{g.s.}})$	$E_x({}^4_\Lambda\mathbf{H}_{\mathrm{exc.}})$	$B_\Lambda({}^5_\Lambda\mathbf{He})$
Exp.	**0.13(5)**	**2.16(8)**	**1.09(2)**	**3.12(2)**
Dalitz(1972)	**0.10**	**2.24**	**0.36**	**≥5.16**
χ**EFT**$^{\mathrm{LO}}_{600}$	**0.11(1)**	**2.31(3)**	**0.95(15)**	**5.82(2)†**
χ**EFT**$^{\mathrm{LO}}_{700}$	–	**2.13(3)**	**1.39(15)**	**4.43(2)†**
AFDMC(I)	–	**1.97(11)**	–	**5.1(1)**
AFDMC(II)	**−1.2(2)**	**1.07(8)**	–	**3.22(14)**

† R. Wirth, R. Roth, PLB 779 (2018) 336.