Hypernuclei with a Microscopic Lambda-Nucleon Force

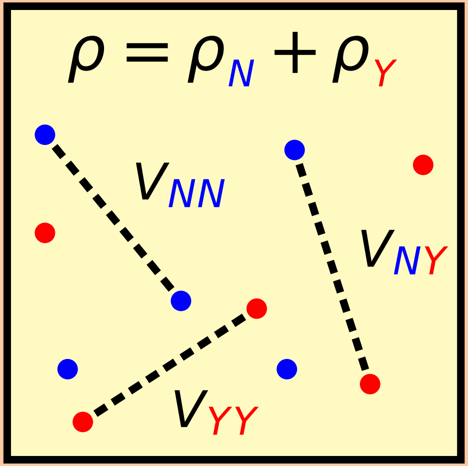
with

M. Baldo & F. Burgio & U. Lombardo & H.-J. S., Catania
K. Hagino & H. Sagawa & Myaing Thi Win, Japan
A. Polls & A. Ramos & I. Vidaña, Barcelona
E.G. Zhao & X.R. Zhou, China
J. Cugnon & A. Lejeune, Liège

- BHF approach of hypernuclear matter
- Hypernuclei
- Neutron star properties

PLB 355, 21 (1995)
PRC 57, 704 (1998)
PRC 62, 064308 (2000)
PRC 64, 044301 (2001)
PRC 76, 034312 (2007)
PRC 78, 054306 (2008)

Hypernuclear Matter:



$N = qqq$: n, p (939 MeV)

$Y = qqs$: Λ^0 (1116 MeV), Σ^{+0-} (1193 MeV)

V_{NN} : Argonne, Bonn, Paris, . . .

V_{NY} : Nijmegen (NSC89, NSC97)

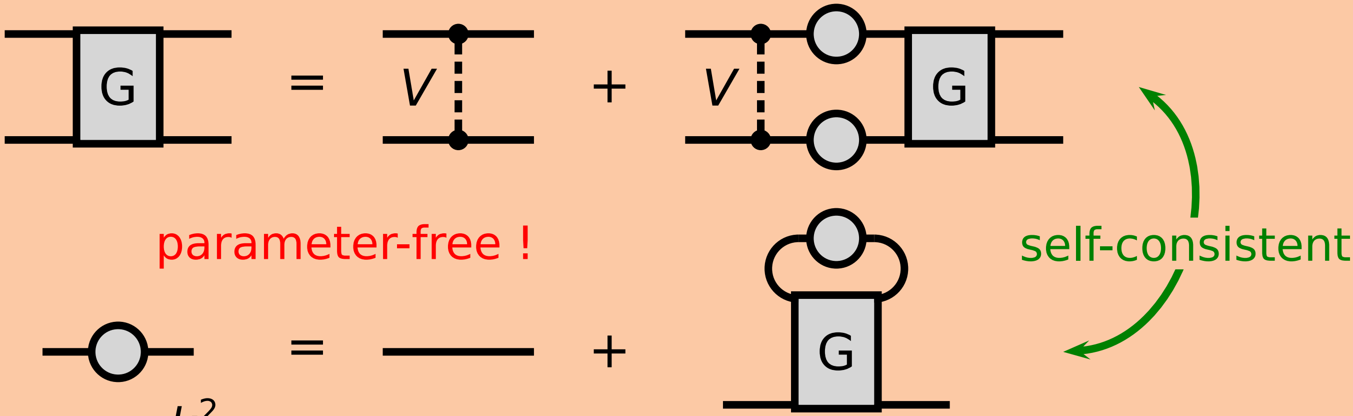
V_{YY} : ? (no scattering data)

In free space weak decay: $Y \rightarrow N + \pi$ etc.

In dense nucleonic medium the decay is Pauli-blocked!

Brueckner Theory of (Hyper)Nuclear Matter:

- Effective in-medium interaction G from potential V:



$$e_k = \frac{k^2}{2m} + U(k)$$

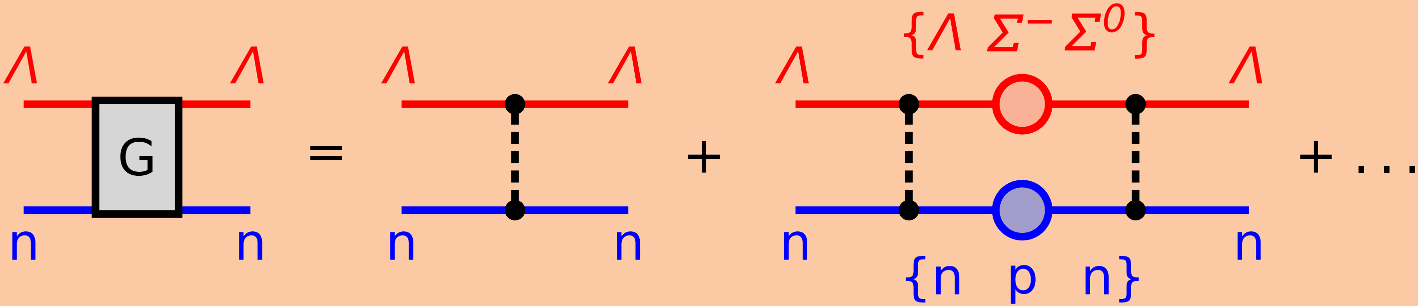
Compute: binding energy, s.p. properties, cross sections, ...

K.A. Brueckner and J.L. Gammel; PR 109, 1023 (1958) for nuclear matter

Extension to hypernuclear matter ...

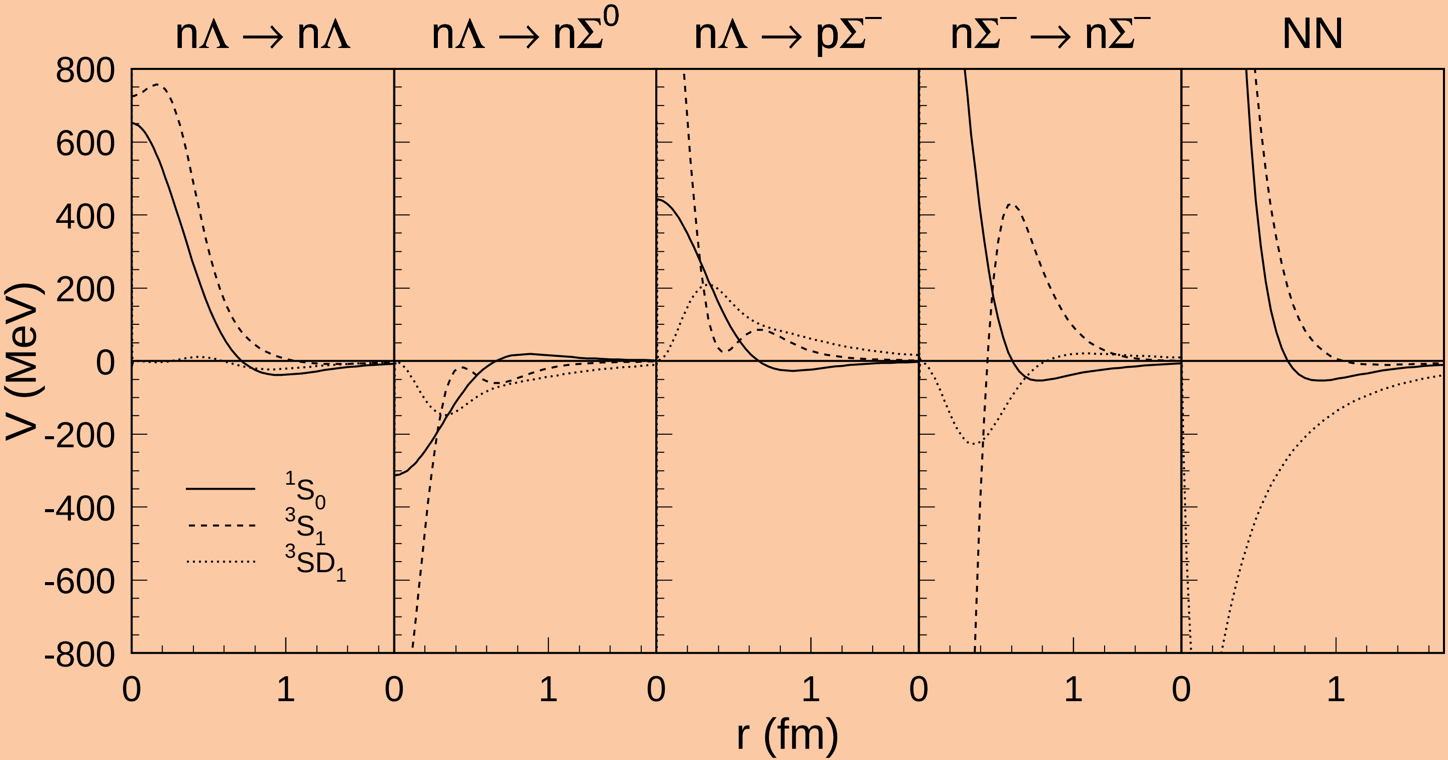
Include Hyperons:

- Technical difficulty: coupled channels:



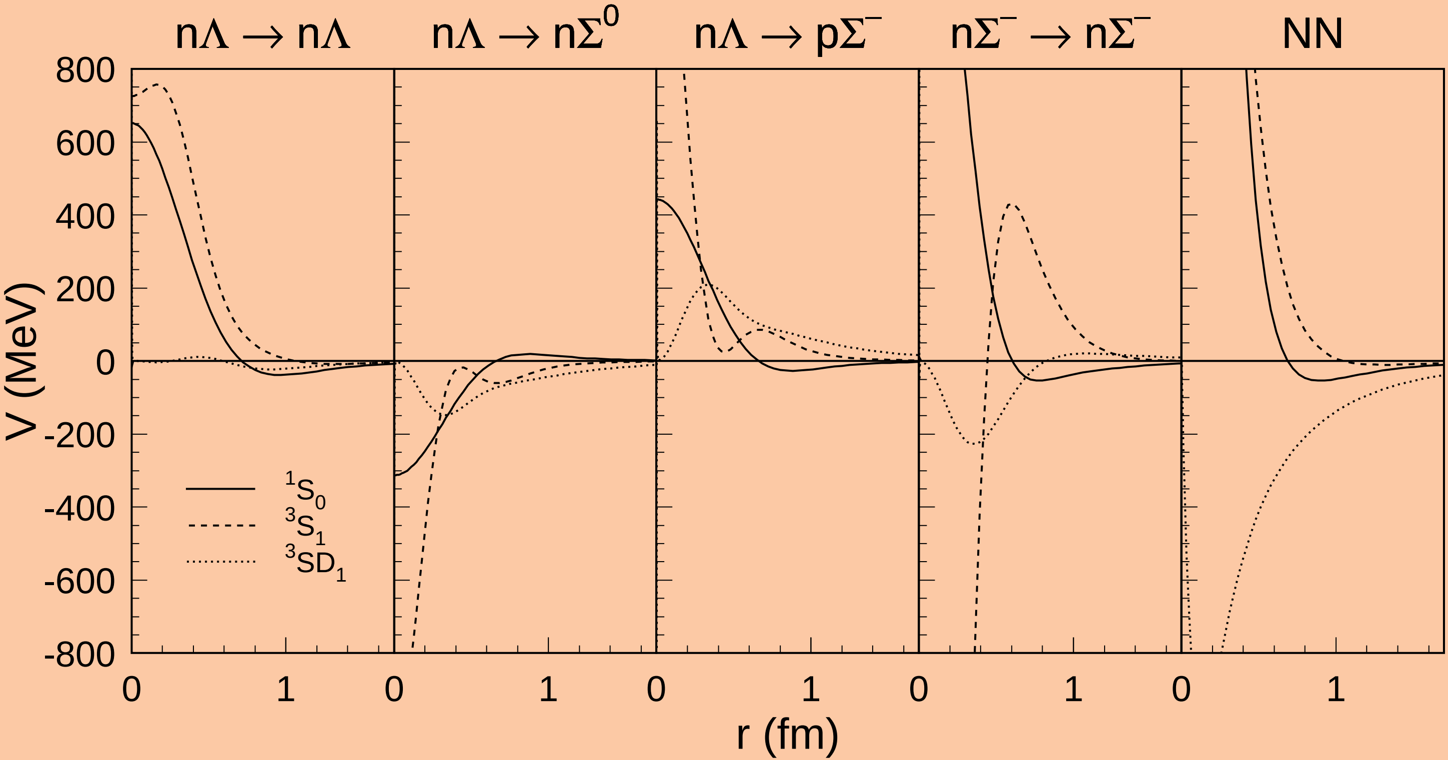
- Applications: neutron stars, hypernuclei, ...

- Hyperon-nucleon potentials (NSC89) vs. Paris NN:



↪ "Soft" cores, Strong coupling $N\Lambda \longleftrightarrow N\Sigma$

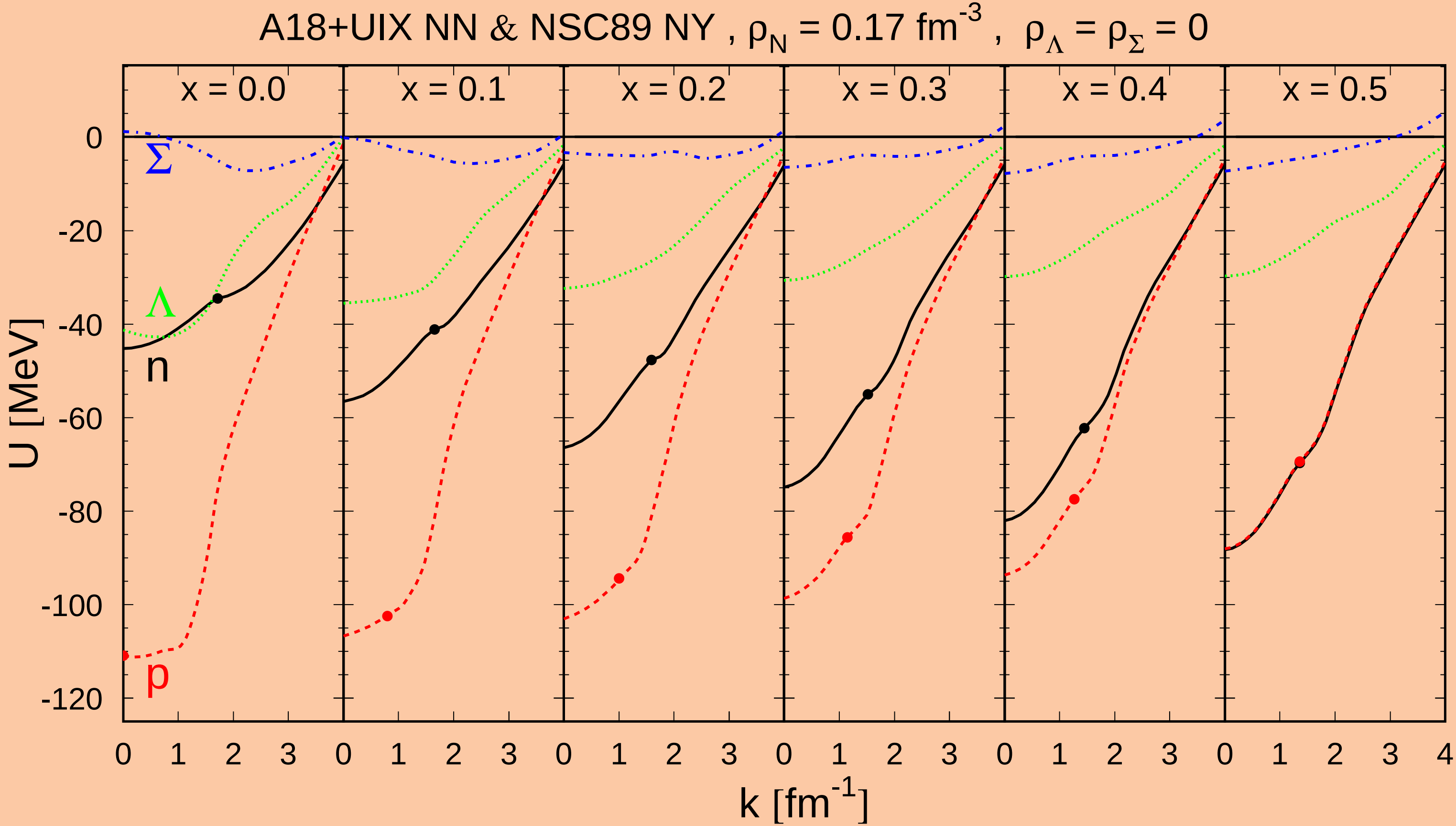
- Hyperon-nucleon potentials (NSC89) vs. Paris NN:



↪ "Soft" cores, Strong coupling $N\Lambda \longleftrightarrow N\Sigma$

Talk of T.Rijken

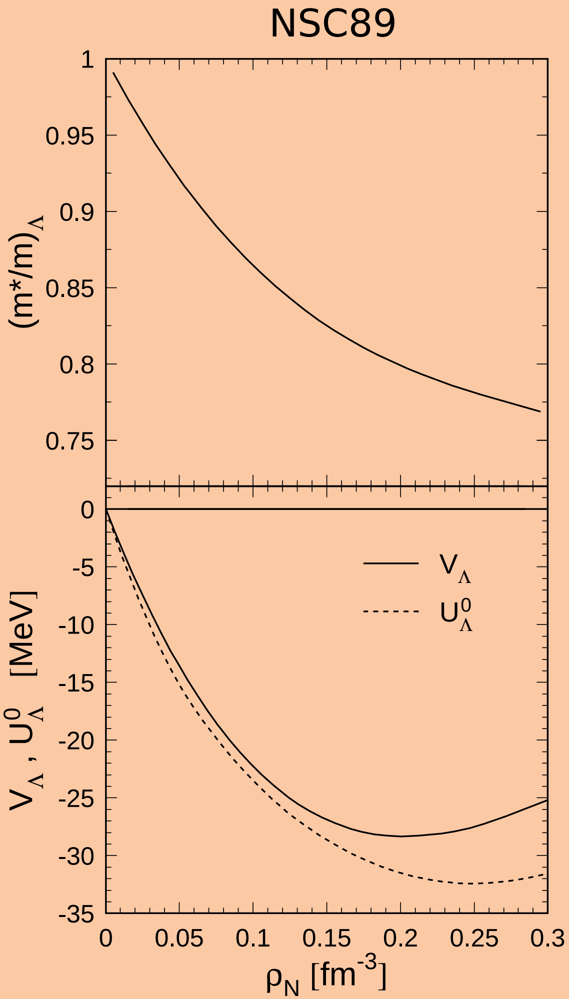
- Single-particle potentials in nuclear matter ($\rho_N = \rho_0$):

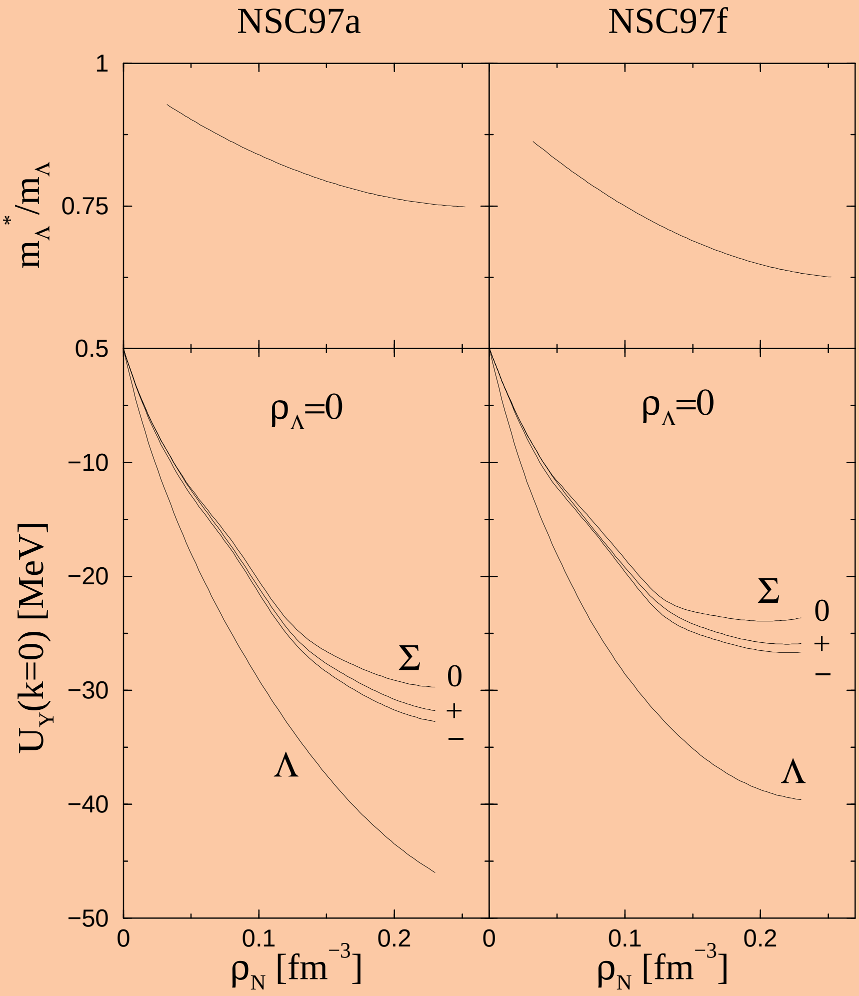


➥ Hyperons weaker bound than nucleons

Only slight dependence on proton fraction

- Lambda effective mass and hyperon well depths:





Hypernuclei: Single, Double, Multi-Lambda:

- Created by (π^+, K^+), (K^-, π^-), $(e, e'K^+)$ reactions (BNL, CERN, JLAB, KEK, LNF, GSI, J-PARC, ...)
- Experimentally known (heavy) Λ hypernuclei:
  - Single-lambda: ${}^{13}_{\Lambda}$C, ${}^{16}_{\Lambda}$O, ${}^{28}_{\Lambda}$Si, ${}^{40}_{\Lambda}$Ca, ${}^{89}_{\Lambda}$Y, ${}^{139}_{\Lambda}$La, ${}^{208}_{\Lambda}$Pb, ...
  - Double-lambda: ${}^{6}_{\Lambda\Lambda}$He, ${}^{10}_{\Lambda\Lambda}$Be, ${}^{13}_{\Lambda\Lambda}$B (4 events !)
  - Multi-lambda: None !
- Observables:
  - Single-particle levels: $e_q^i \quad (q = n, p, \Lambda)$
  - Binding energy: $B_\Lambda = E({}^{A-1}Z) - E({}^{A}_{\Lambda}Z)$
  - Rms radii: $R_q = \sqrt{\langle r^2 \rangle_q}$

Lambda Hypernuclear Chart:

568 O. Hashimoto, H. Tamura / Progress in Particle and Nuclear Physics 57 (2006) 564–653

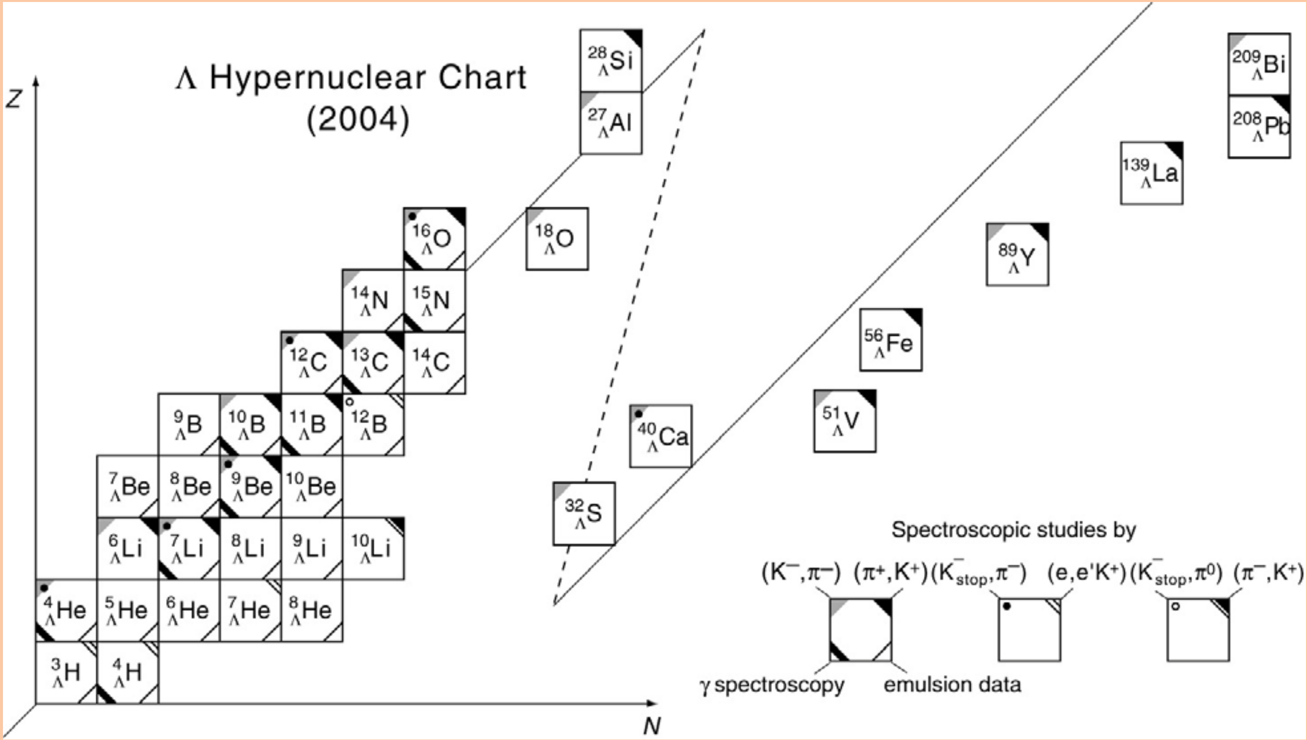
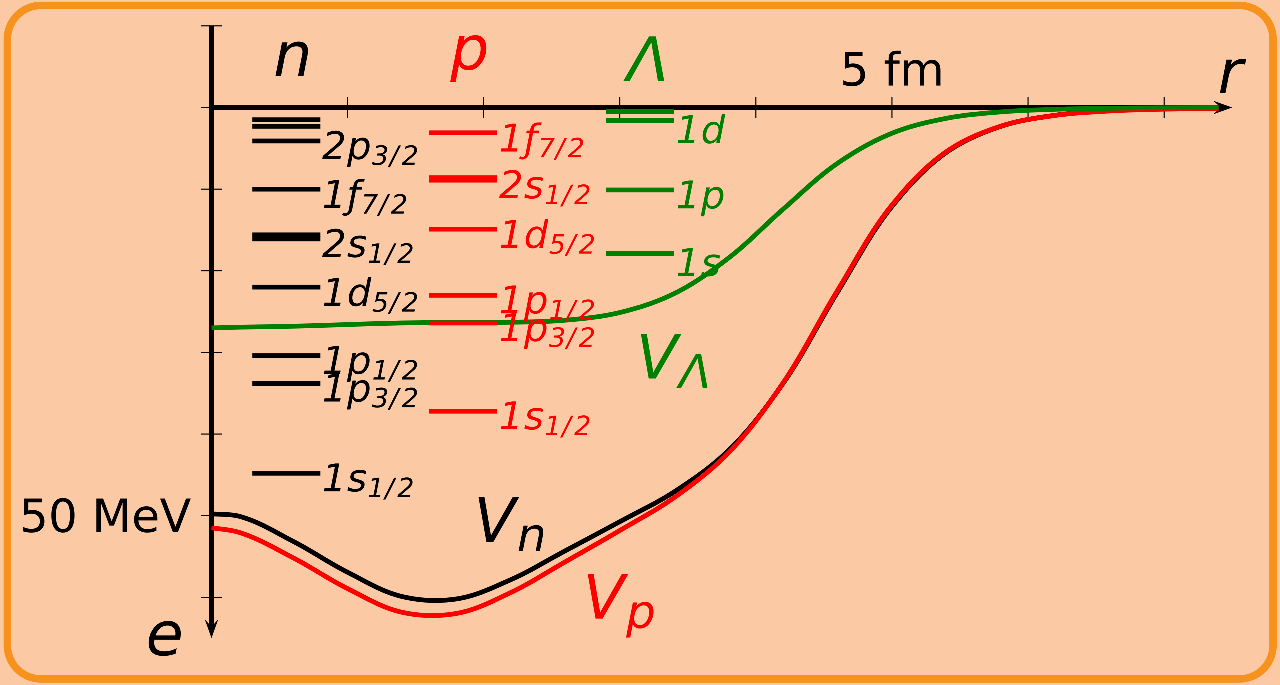


Fig. 1. Λ hypernuclear chart. The experimentally identified Λ hypernuclei and the experimental methods used to study them (reaction spectroscopies of (K^-, π^-), (π^+, K^+), $(e, e'K^+)$, etc., γ spectroscopy, and the emulsion method) are shown.

- Typical example: $^{40}_{\Lambda}$Ca :



- Theoretical model:
  - Skyrme-Hartree-Fock (SHF) [Vautherin & Brink, PRC 5, 626 (1972)]
  - Standard *NN* force: SIII, SGII, SkI4, SLy4, . . .
  - Effective microscopic *ΛN* force from BHF results . . .

- SHF Schrödinger equation:

$$\left[-\nabla\cdot\frac{1}{2m_q^*(r)}\nabla + V_q(r) - i\nabla W_q(r)\cdot(\nabla\times\boldsymbol{\sigma})\right]\phi_q^i(r) \;=\; -e_q^i\phi_q^i(r)$$

  - SHF mean fields:

$$V_N \;=\; V_N^{\text{SHF}} + \frac{\partial\epsilon_{N\Lambda}}{\partial\rho_N} \quad , \quad V_\Lambda = \frac{\partial\epsilon_{N\Lambda}}{\partial\rho_\Lambda} \quad , \quad W_\Lambda = 0$$

  - Effective mass $m_\Lambda^*(\rho_N,\rho_\Lambda)$ and
    Energy density due to $N\Lambda$ interaction: no free parameters

$$\epsilon_{N\Lambda}(\rho_N,\rho_\Lambda) = (\rho_N+\rho_\Lambda)\frac{B}{A}(\rho_N,\rho_\Lambda) - \rho_N\frac{B}{A}(\rho_N,0) - \rho_\Lambda\frac{B}{A}(0,\rho_\Lambda)$$

  - Coupled equations for eigenvalues e_q^i

- SHF Schrödinger equation:

$$\left[-\nabla\cdot\frac{1}{2m_q^*(r)}\nabla+V_q(r)-i\nabla W_q(r)\cdot(\nabla\times\boldsymbol{\sigma})\right]\phi_q^i(r) = -e_q^i\phi_q^i(r)$$

  - SHF mean fields:

$$V_N = V_N^{\mathrm{SHF}}+\frac{\partial\epsilon_{N\Lambda}}{\partial\rho_N} \quad , \quad V_\Lambda=\frac{\partial\epsilon_{N\Lambda}}{\partial\rho_\Lambda} \quad , \quad W_\Lambda=0$$

  - Effective mass $m_\Lambda^*(\rho_N,\rho_\Lambda)$ and from BHF
    Energy density due to $N\Lambda$ interaction: no free parameters

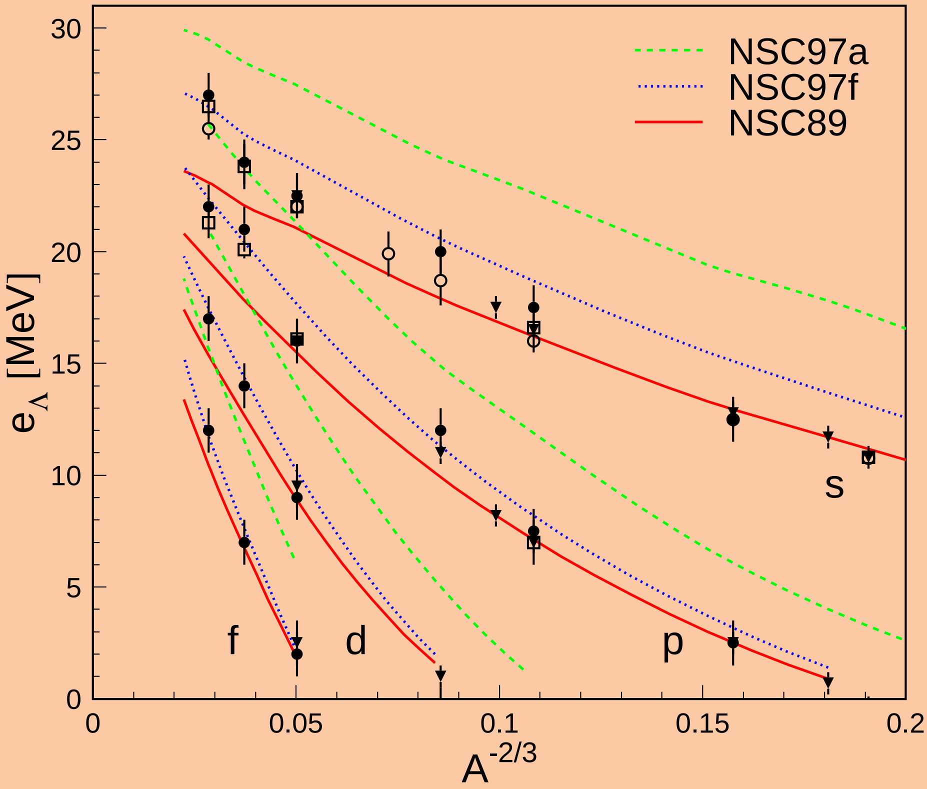
$$\epsilon_{N\Lambda}(\rho_N,\rho_\Lambda)=$$

$$(\rho_N+\rho_\Lambda)\frac{B}{A}(\rho_N,\rho_\Lambda)-\rho_N\frac{B}{A}(\rho_N,0)-\rho_\Lambda\frac{B}{A}(0,\rho_\Lambda)$$

  - Coupled equations for eigenvalues e_q^i

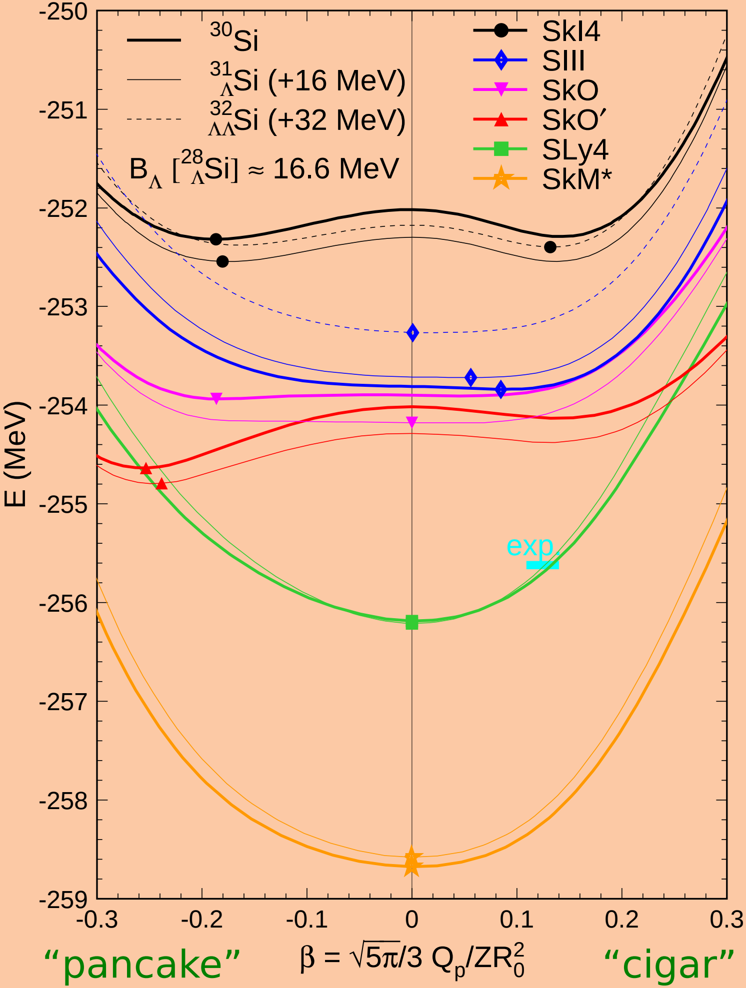
Results: Single-Λ Hypernuclei:

- Lambda single-particle levels:



➥ Fair agreement with NSC89 and NSC97f potentials

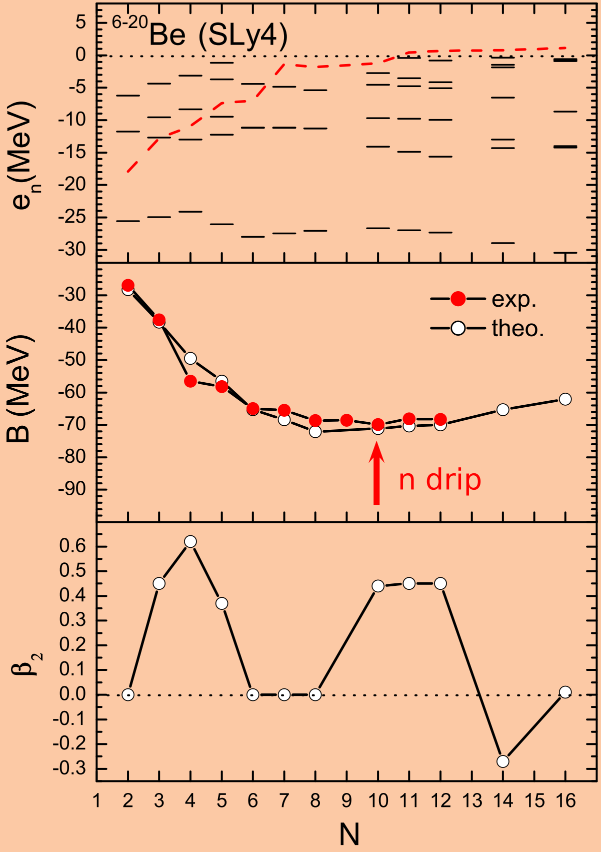
• Deformed (hyper)nuclei:



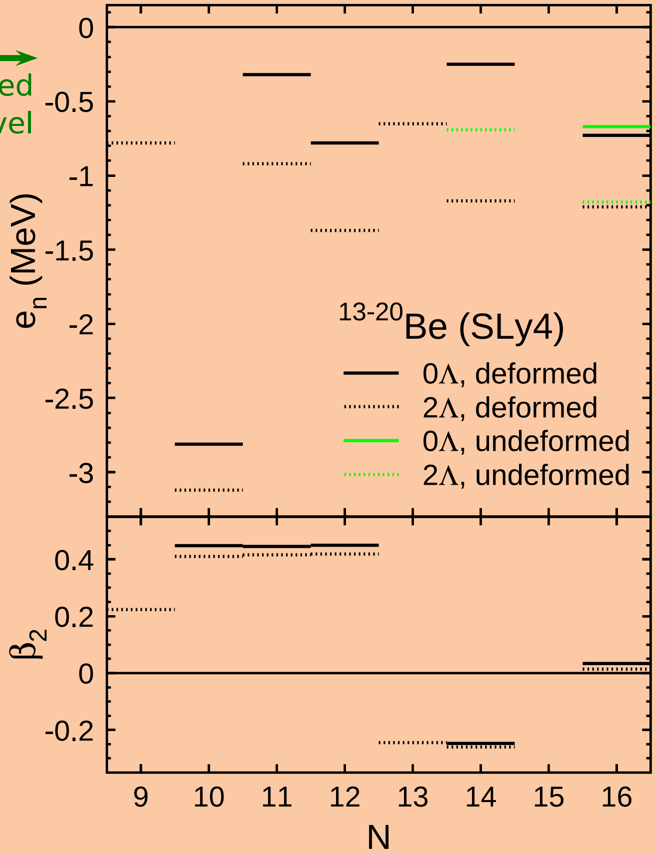
↪ Strong dependence on the NN Skyrme force, not predictive

↪ The Λ’s might ’pull’ together a nucleus with a weak deformation minimum

- Neutron-rich (halo) hypernuclei, e.g., Be isotopes:



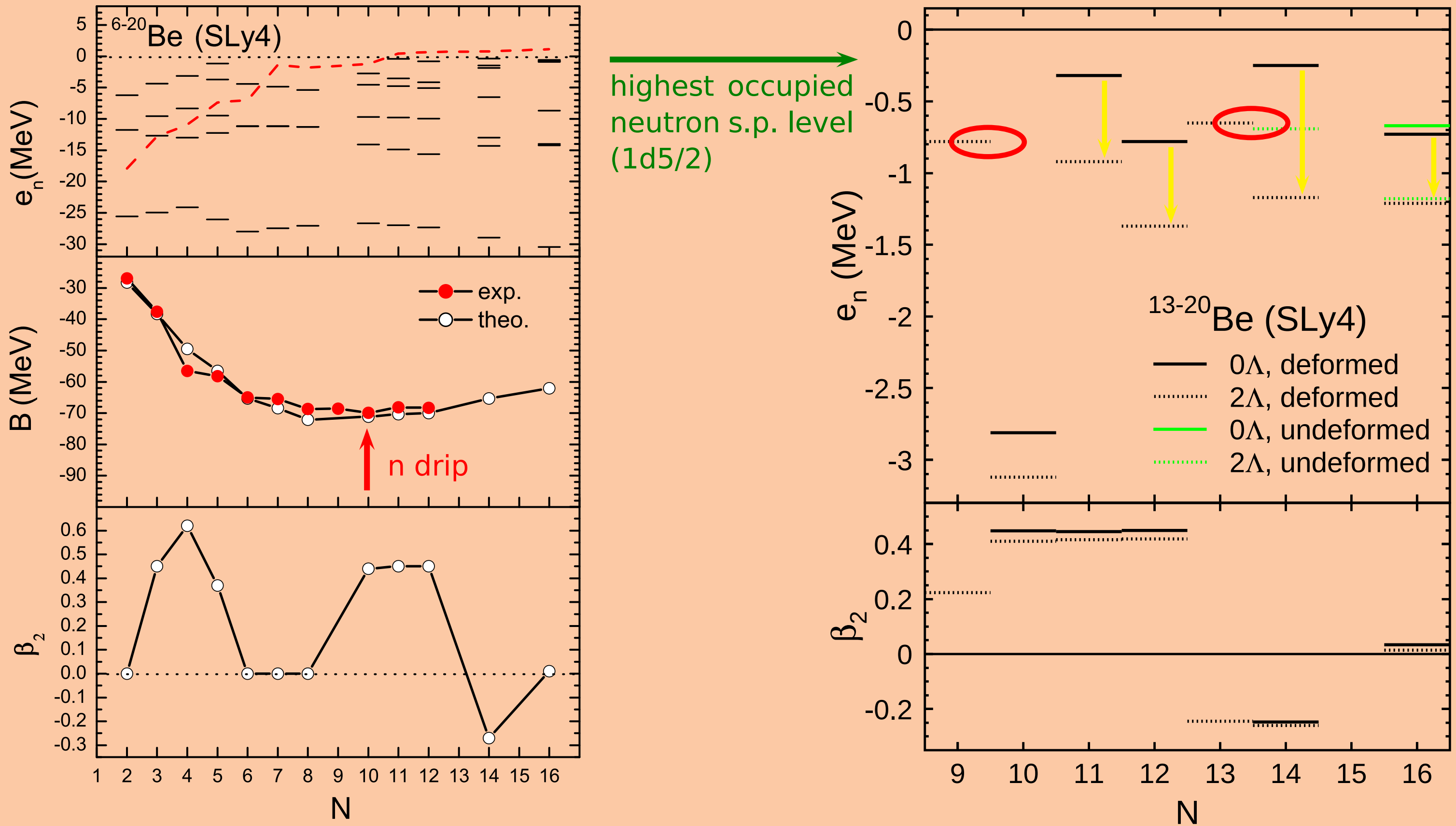
highest occupied neutron s.p. level (1d5/2)



Λ's stabilize isotopes near the neutron dripline

(SHF+BCS, better approach required for halo states)

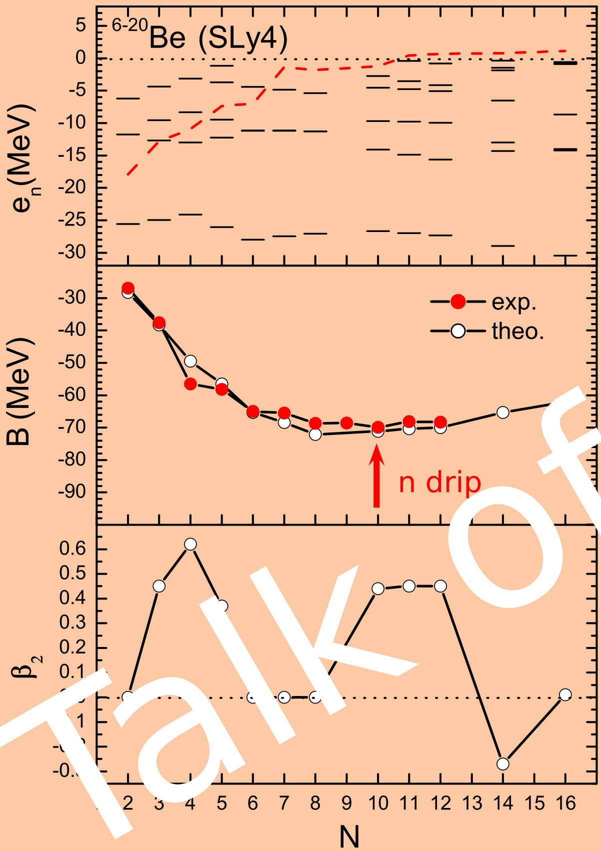
• Neutron-rich (halo) hypernuclei, e.g., Be isotopes:



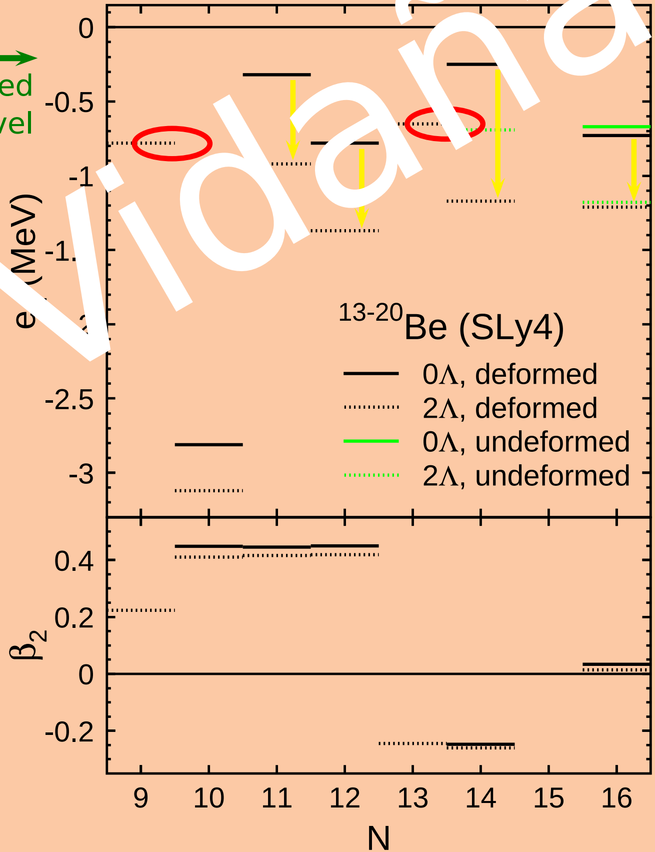
↪ Λ's stabilize isotopes near the neutron dripline

(SHF+BCS, better approach required for halo states)

• Neutron-rich (halo) hypernuclei, e.g., Be isotopes:



highest occupied neutron s.p. level (1d5/2)



↪ Λ's stabilize isotopes near the neutron dripline

(SHF+BCS, better approach required for halo states)

Results: Double-Λ Hypernuclei:

- Important observable: Bond energy:

$$\Delta B_{\Lambda\Lambda} = 2E({}^{A-1}_{\Lambda}Z) - E({}^{A-2}Z) - E({}^{A}_{\Lambda\Lambda}Z)$$

- Experimental: 4 events:
  - 3 (1960's): ${}^{6}_{\Lambda\Lambda}$He, ${}^{10}_{\Lambda\Lambda}$Be, ${}^{13}_{\Lambda\Lambda}$B : $\Delta B_{\Lambda\Lambda} \approx -5$ MeV
  - 1 (2001): ${}^{6}_{\Lambda\Lambda}$He : $\Delta B_{\Lambda\Lambda} \approx -1$ MeV !?

- Theoretical:

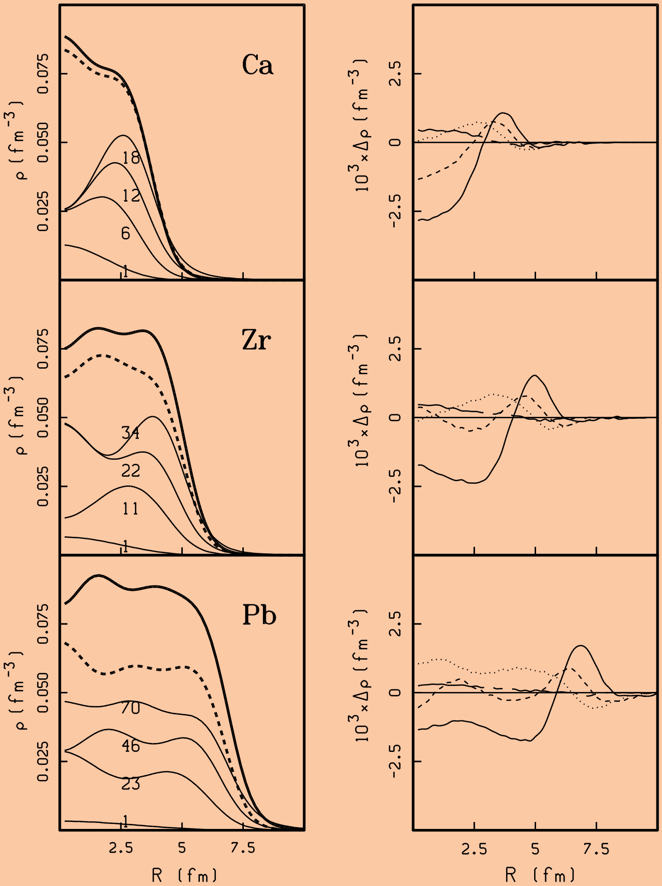
$$\Delta B_{\Lambda\Lambda} \approx U_{\Lambda}^{(\Lambda)}(\bar{\rho}_\Lambda) - U_{\Lambda}^{(\Lambda)}(2\bar{\rho}_\Lambda) \approx -U_{\Lambda}^{(\Lambda)}(\bar{\rho}_\Lambda)\ , \quad \bar{\rho}_\Lambda \approx \rho_0/A$$

- Results with Nijmegen potentials:

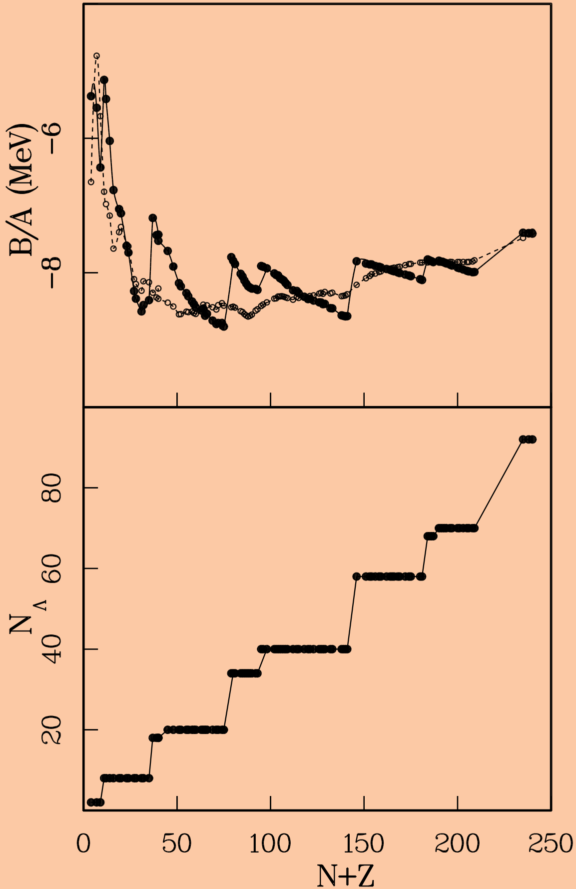
	$\Delta B_{\Lambda\Lambda}$ [MeV]		
	NSC89	NSC97a	NSC97f
$^{10}_{\Lambda\Lambda}$Be	−0.34	+0.37	−0.35
$^{14}_{\Lambda\Lambda}$C	−0.41	+0.32	−0.47
$^{18}_{\Lambda\Lambda}$O	−0.41	+0.32	−0.41
$^{30}_{\Lambda\Lambda}$Si	−0.33	+0.25	−0.35
$^{42}_{\Lambda\Lambda}$Ca	−0.31	+0.19	−0.32
$^{92}_{\Lambda\Lambda}$Zr	−0.21	+0.09	−0.24
$^{142}_{\Lambda\Lambda}$Ce	−0.14	+0.05	−0.18
$^{210}_{\Lambda\Lambda}$Pb	−0.12	+0.01	−0.15

↪ NSC89,97 potentials predict too small ΛΛ binding

Results: Multi-Λ Hypernuclei:



Density profiles



Λ drip line: Shell effect (no ΛΛ force)

Outlook:

- Future work on Λ hypernuclei:
  - New NY, YY potentials (ESC07 ?)
  - Spin-orbit force
  - Hyperonic TBF
  - Constrained Λ*N* Skyrme force
  - HFB for dripline (hyper)nuclei

Outlook:

- Future work on Λ hypernuclei:
  - New NY, YY potentials (ESC07 ?)
  - Spin-orbit force
  - Hyperonic TBF
  - Constrained ΛN Skyrme force
  - HFB for dripline (hyper)nuclei
- What about $N\Sigma^-$ interaction, Σ^- hypernuclei ? :
  - Older data indicate attraction
  - New experiment repulsion, quantitatively unknown

↪ NSC89 preferred, need data !