Hypernuclei with a Microscopic Lambda-Nucleon Force

with

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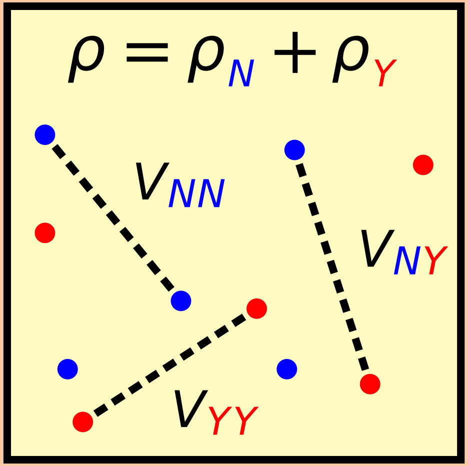
- BHF approach of hypernuclear matter
- Neutron star properties
- Hypernuclei

PLB 355, 21 (1995)
PRC 57, 704 (1998)
PRC 61, 055801 (2000)
PRC 62, 064308 (2000)
PRC 64, 044301 (2001)
PRC 73, 058801 (2006)
PRC 76, 034312 (2007)
PRC 78, 028801 (2008)
PRC 78, 054306 (2008)
PTP 123, 569 (2010)
PRC 84, 035801 (2011)

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, . . .)

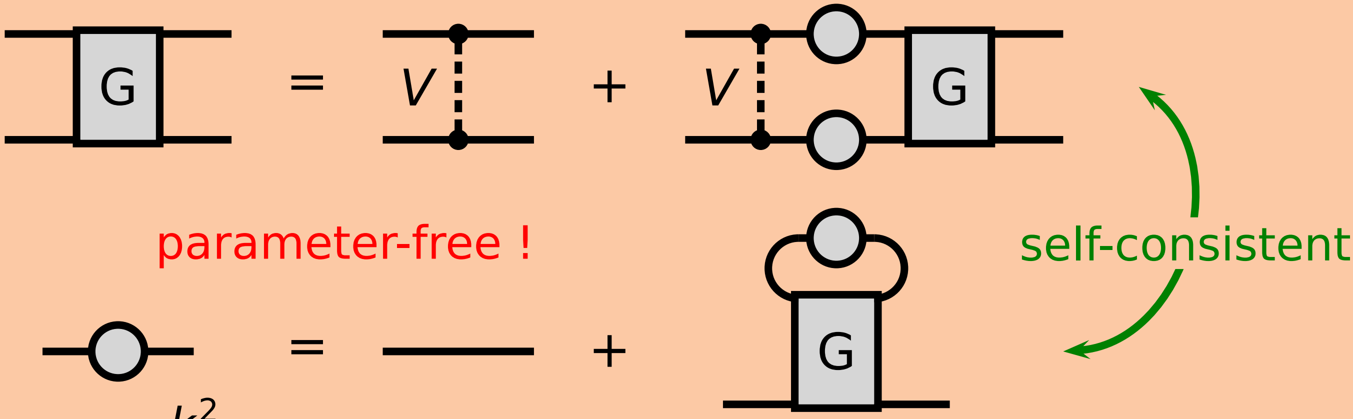
V_{YY} : ? (no scattering data)

In free space weak decay: $Y \rightarrow N + \pi$ etc. ($c\tau \approx 8$ cm)

In dense nucleonic medium the decay is Pauli-blocked !

Brueckner Theory of Nuclear Matter:

- Effective in-medium interaction G from potential V:



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

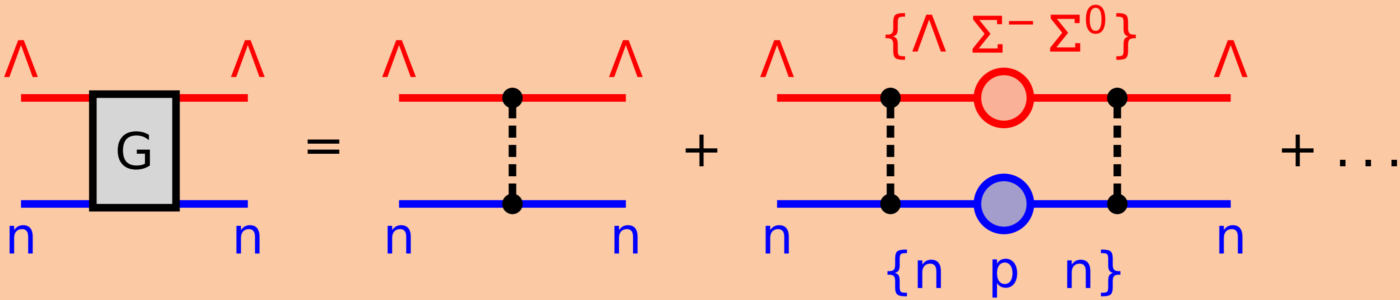
Compute: binding energy, s.p. properties, cross sections, ...

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

Extension to hypernuclear matter ...

Include Hyperons:

- Technical difficulty: coupled channels:



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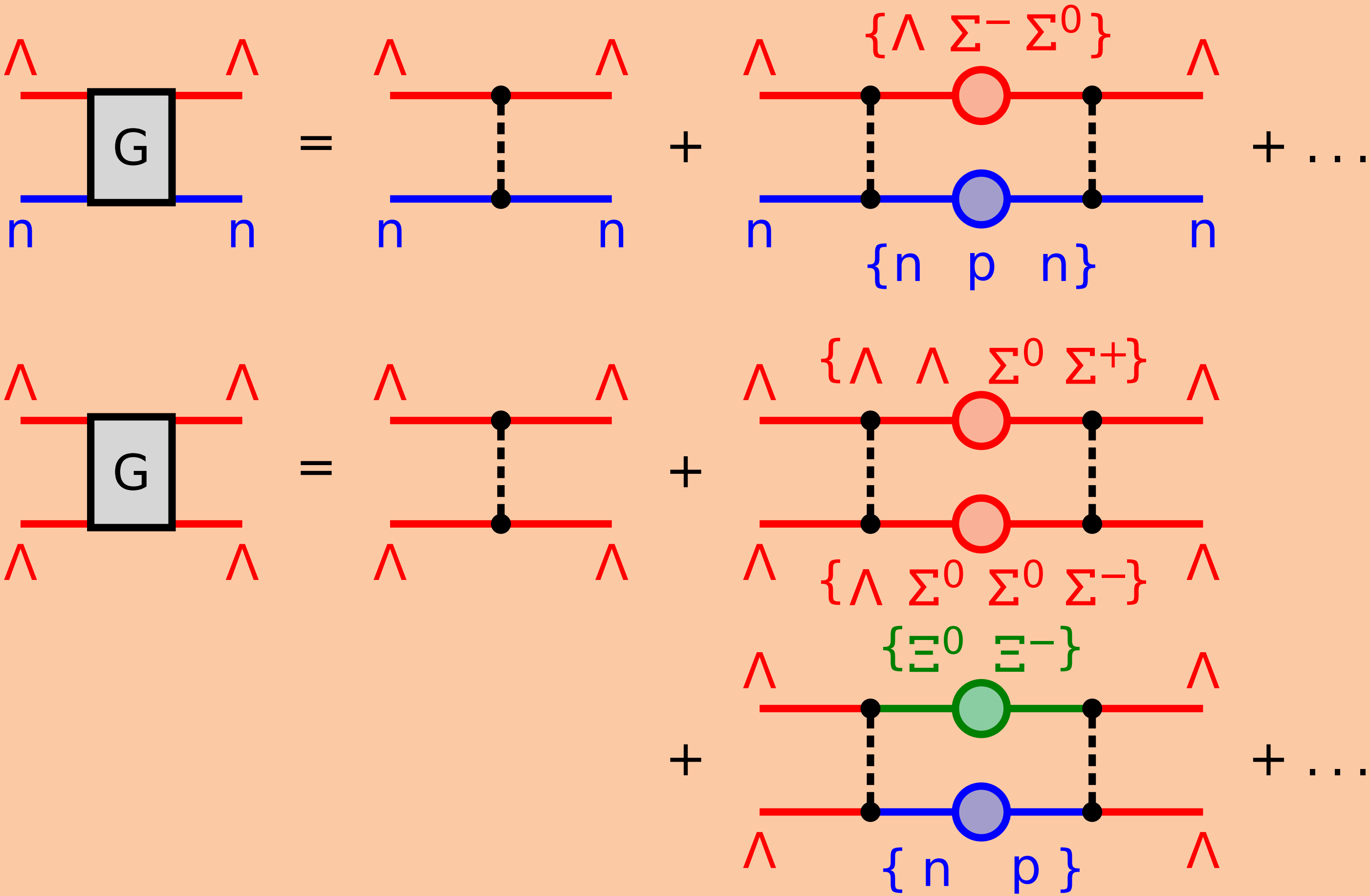
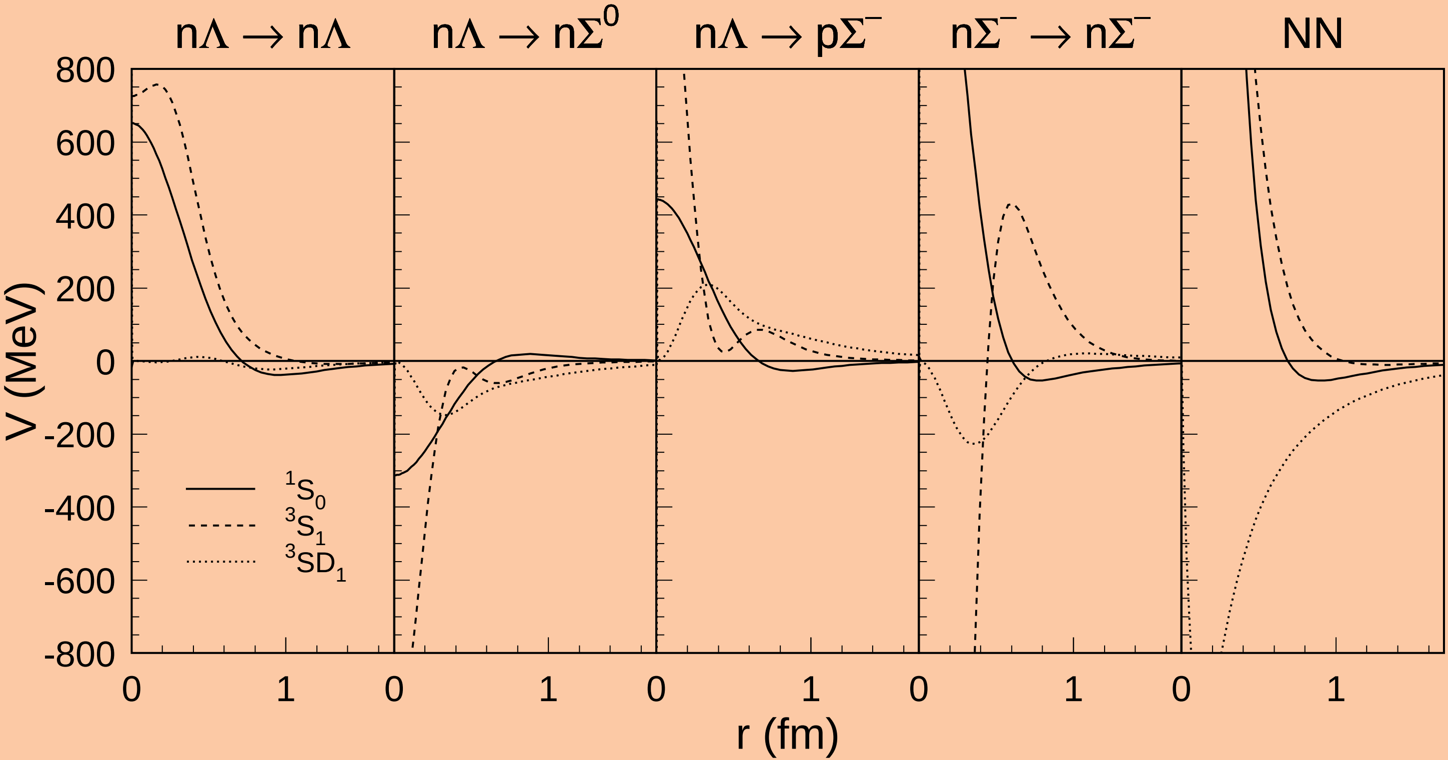
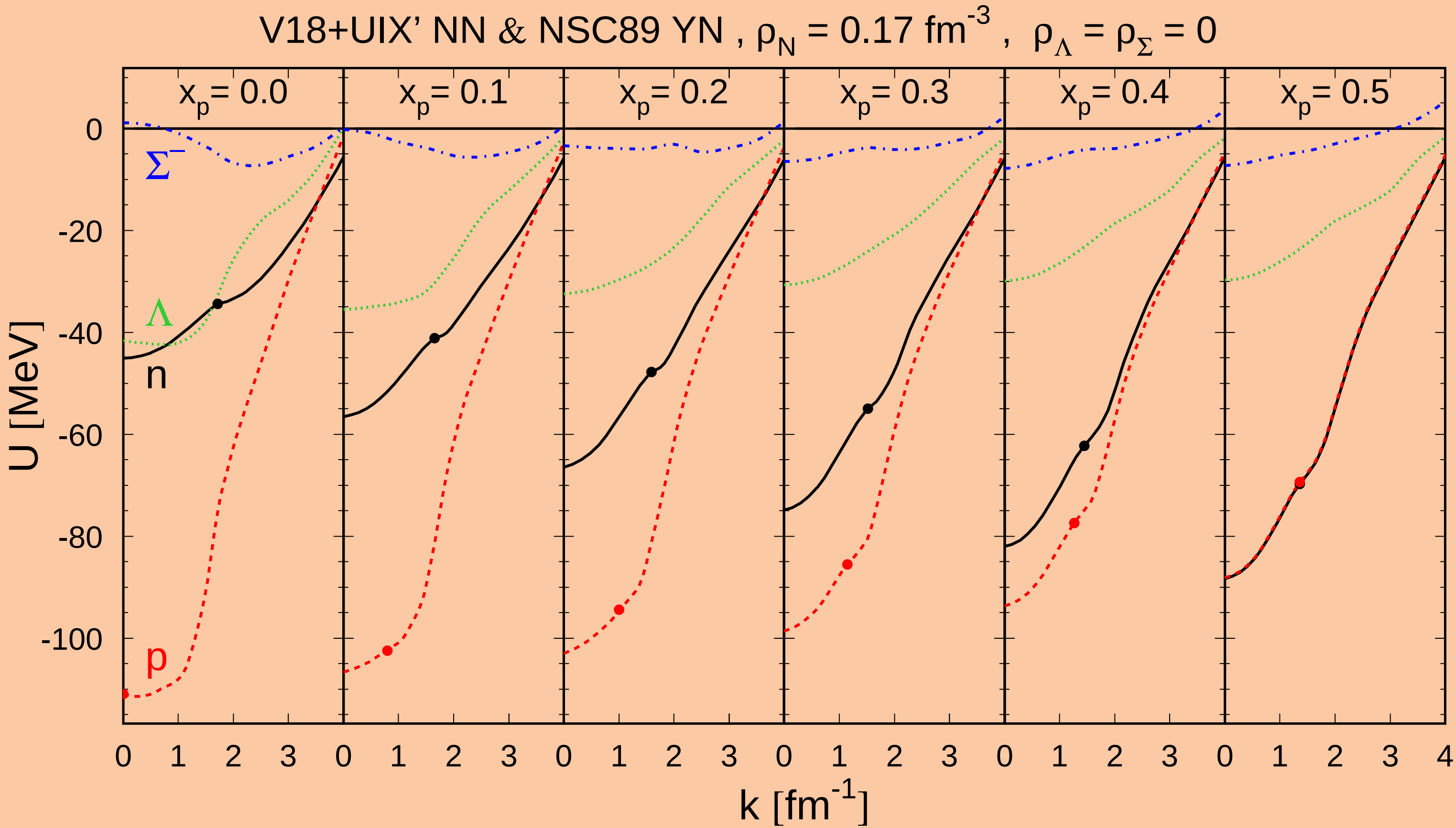


- Hyperon-nucleon potentials (NSC89) vs. Paris NN:



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

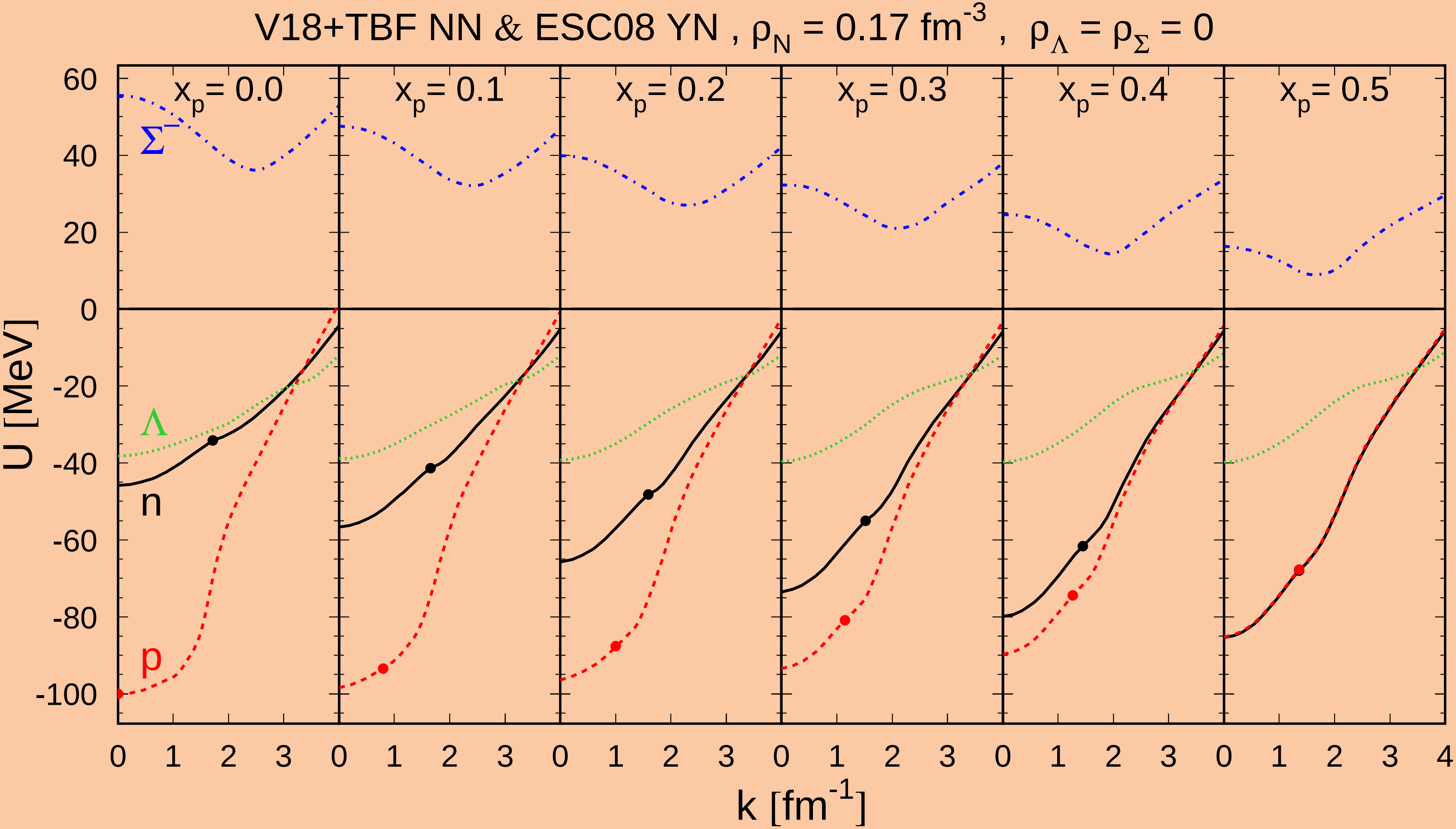
- Single-particle potentials in nuclear matter ($\rho_N = \rho_0$):



↪ Hyperons are weaker bound than nucleons

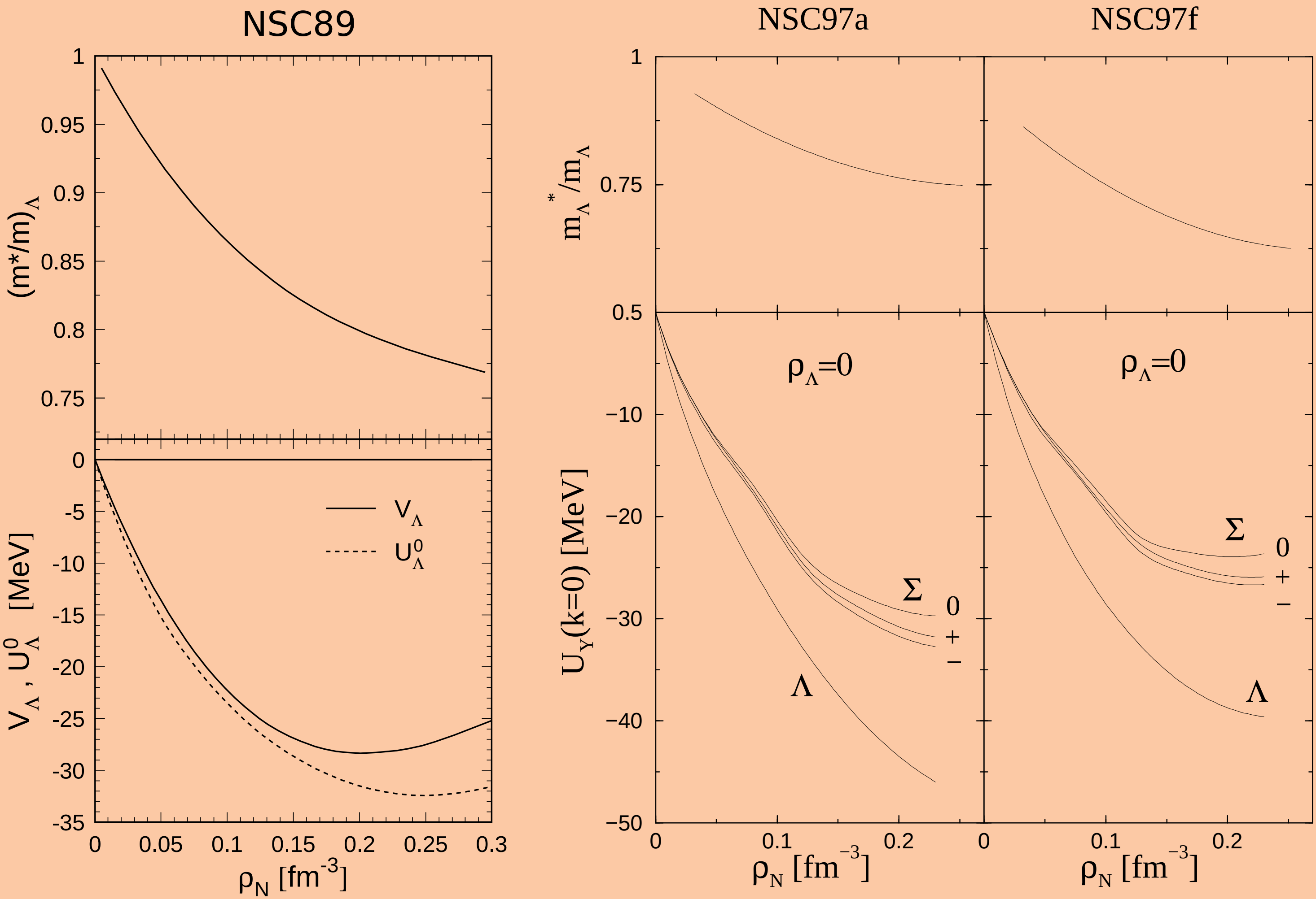
Only slight dependence on proton fraction $x_p = \rho_p/\rho_N$

- Results with ESC08b NY potential:

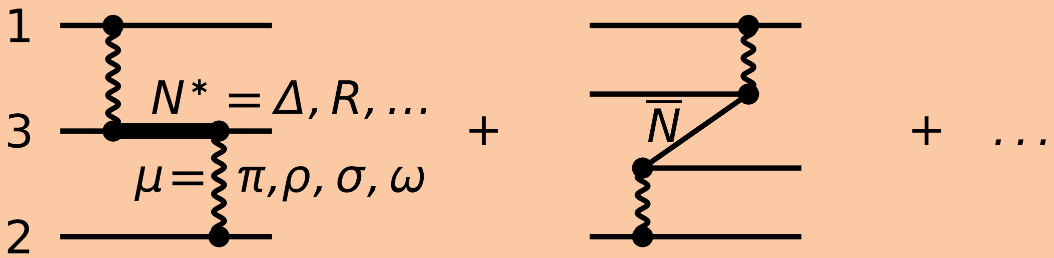


↪ $\Sigma^- N$ interaction is repulsive

• Lambda effective mass and hyperon well depths:



Three-Nucleon Forces:



- Only small effect required [$\delta(B/A) \approx 1$ MeV at ρ_0]
- Model dependent, no final theory yet
- Use and compare microscopic and phenomenological TBF...
  - Microscopic TBF of P. Grangé et al., PRC 40, 1040 (1989):
    Exchange of $\pi, \rho, \sigma, \omega$ via $\Delta(1232)$, $R(1440)$, $N\bar{N}$
    Parameters compatible with two-nucleon potential (Paris,V_{18},...)
  - Urbana IX phenomenological TBF:
    Only 2π-TBF + phenomenological repulsion
    Fit saturation point

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, ${}^{10,11,12}_{\Lambda\Lambda}$Be, ${}^{13}_{\Lambda\Lambda}$B (8 events !)
  - Multi-lambda: None !
- Observables:
  - Single-particle levels: $e^i_q \quad (q = n, p, \Lambda)$
  - 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

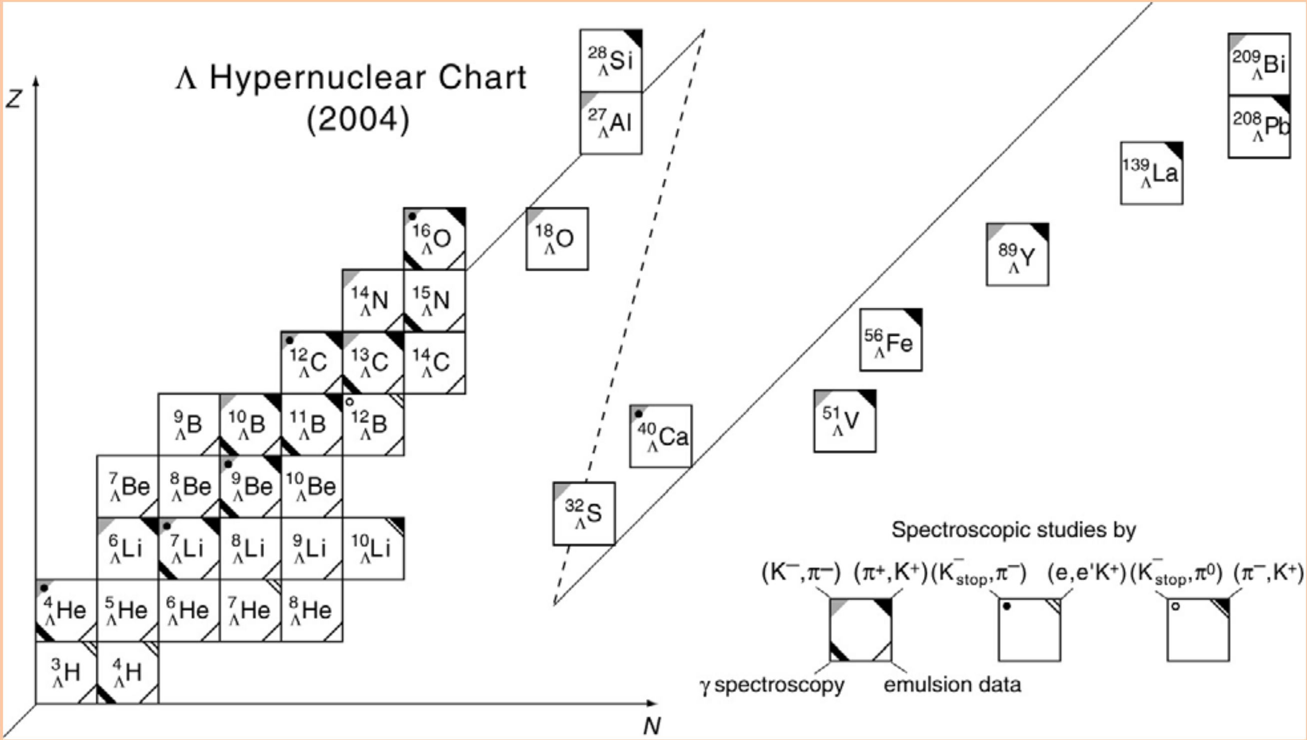
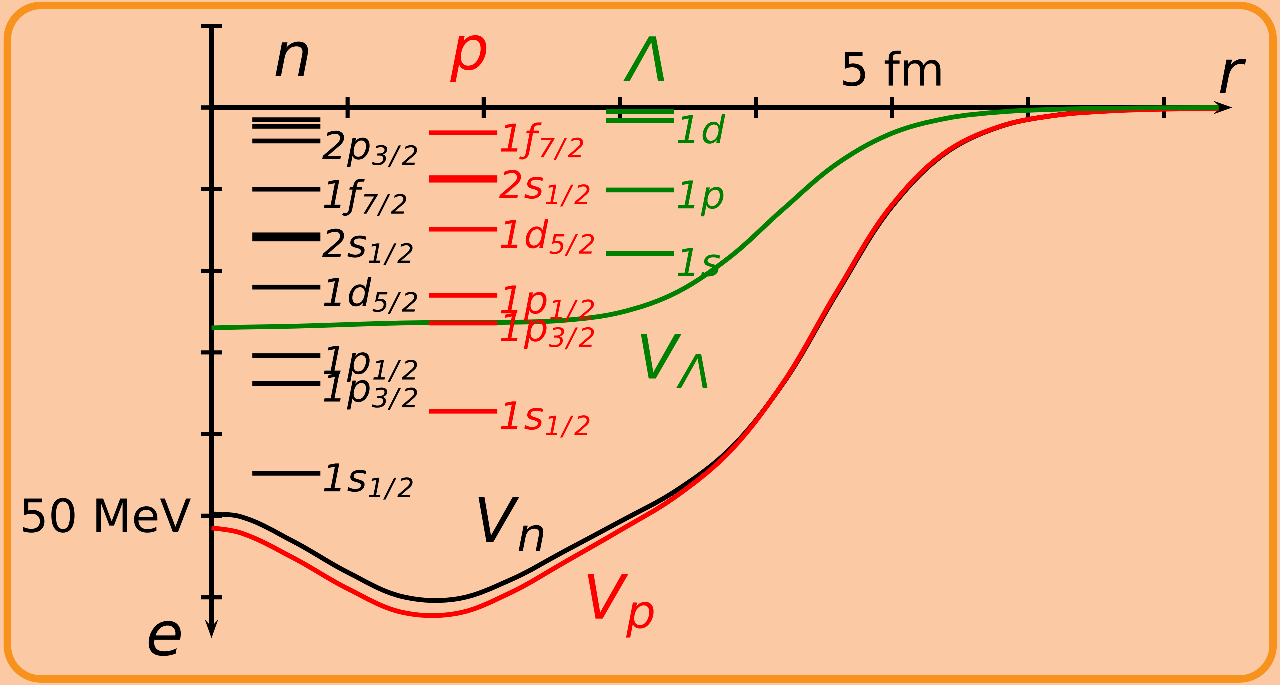


Fig. 1. Λ hypernuclear chart. The experimentally identified Λ hypernuclei and the experimental methods used to study them (reaction spectroscopies of (K^-, π^-), (π^+, K^+), $(e, e'K^+)$, etc., γ spectroscopy, and the emulsion method) are shown.

- 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:

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

  - Effective mass $m_\Lambda^*(\rho_N, \rho_\Lambda)$ and 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

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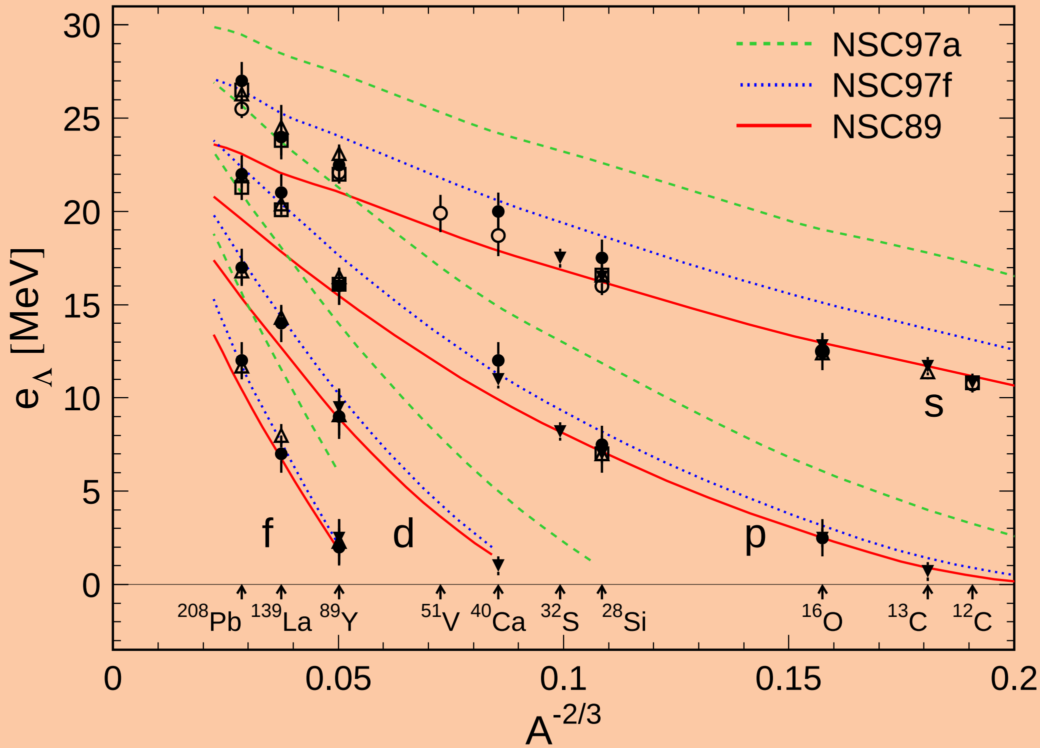
  - Coupled equations for eigenvalues e_q^i

Results: Single-Λ Hypernuclei:

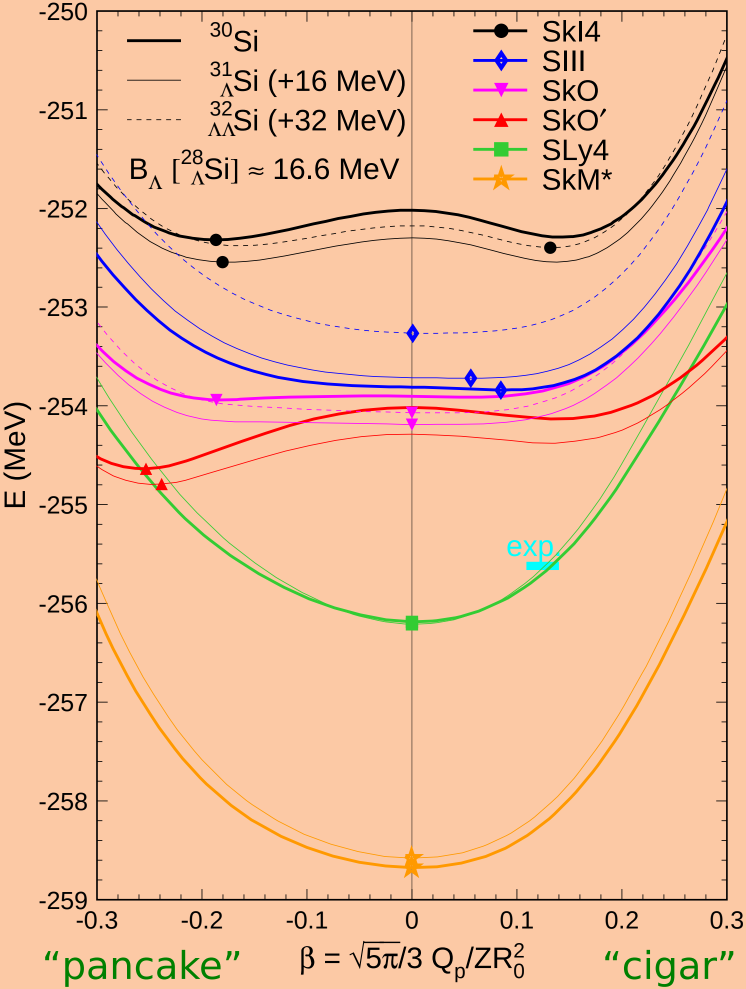
- Lambda single-particle levels:



↪ Fair agreement with NSC89 and NSC97f potentials

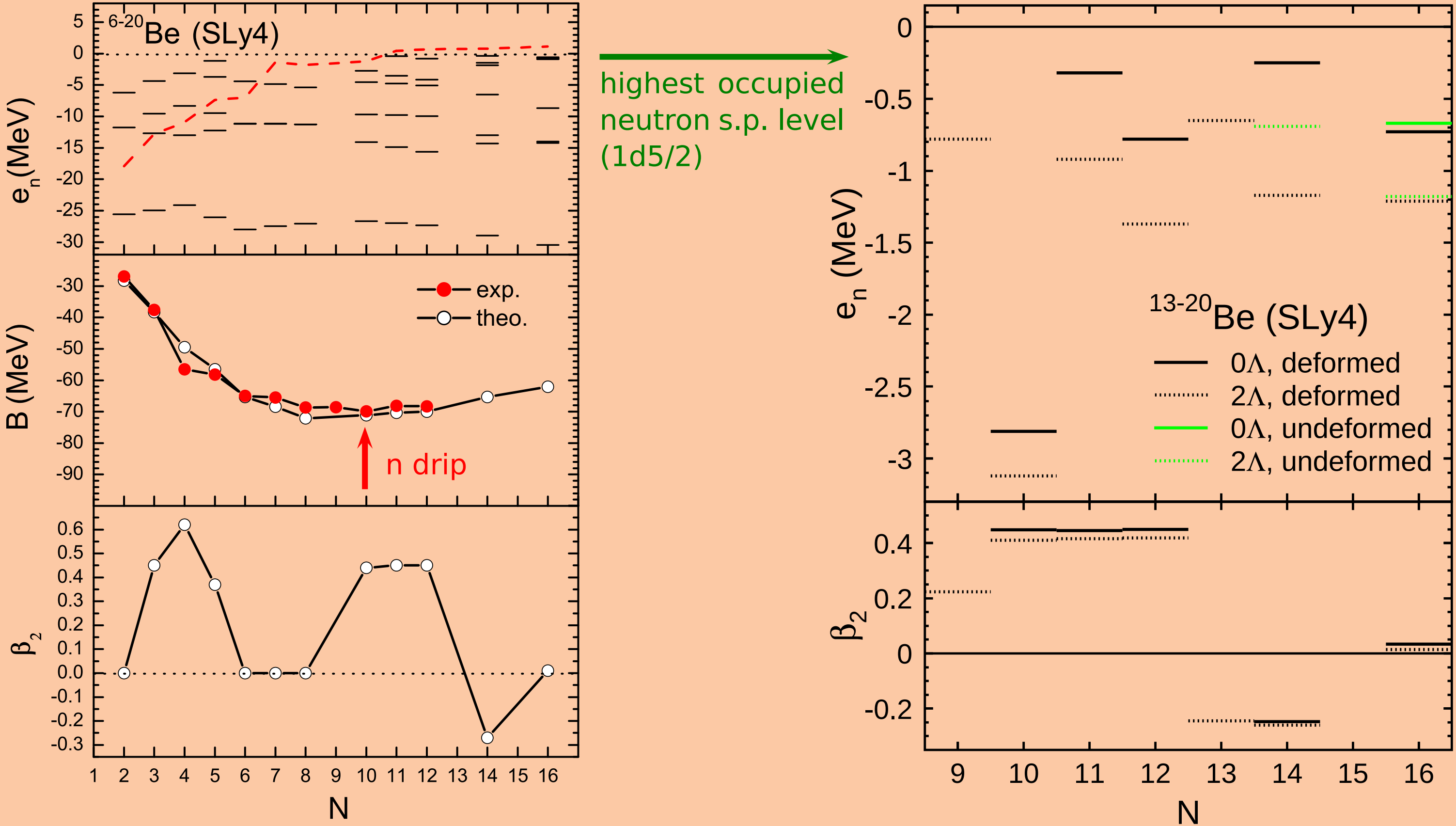
No indication of strong hyperon TBF

● Deformed (hyper)nuclei, e.g., ^{30}Si:



- 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:



↪ Λ's stabilize isotopes near the neutron dripline

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

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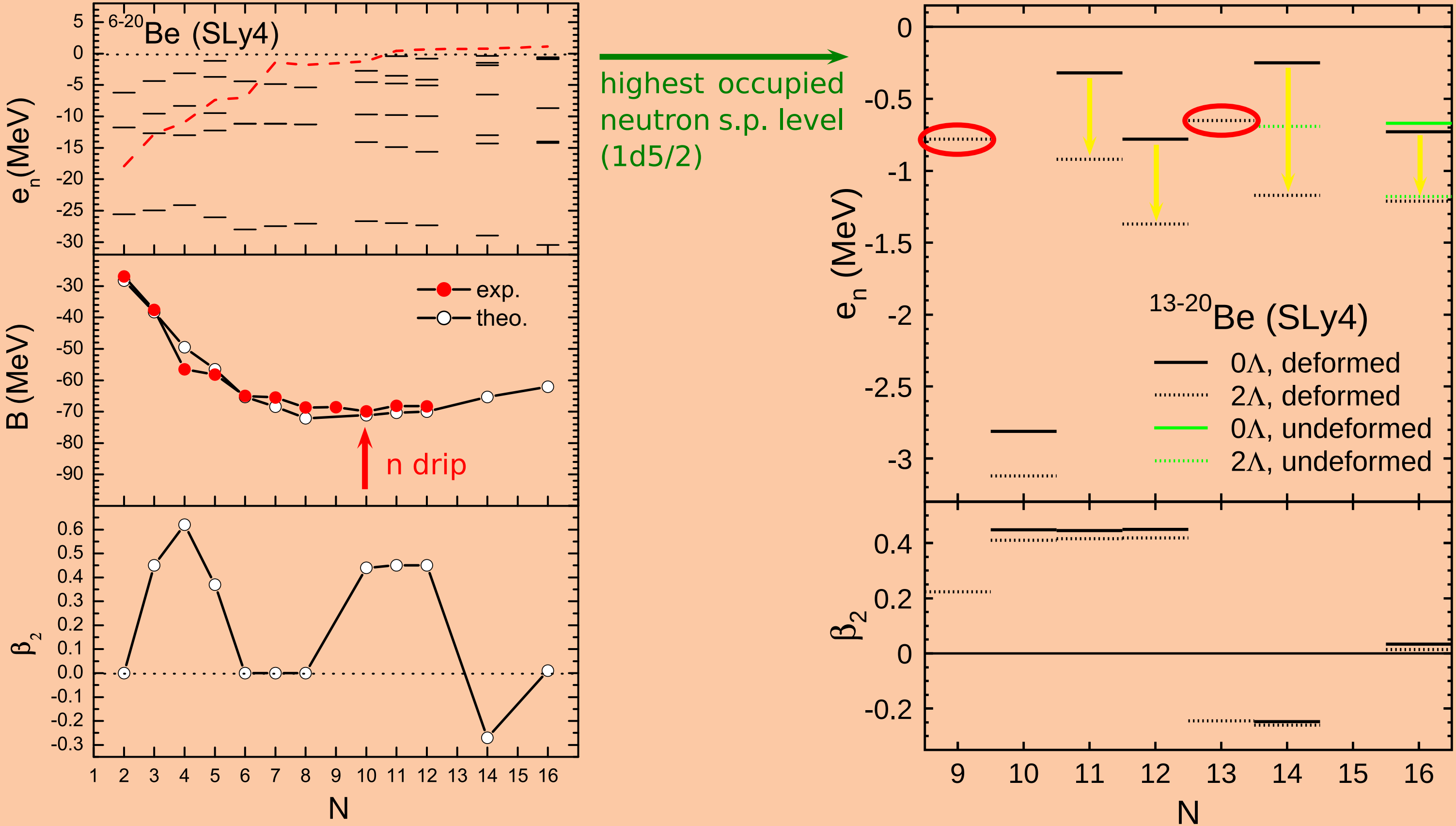


Λ's stabilize isotopes near the neutron dripline

(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: 3+5 events:
  - 3 (1960's): ${}^{6}_{\Lambda\Lambda}$He, ${}^{10}_{\Lambda\Lambda}$Be, ${}^{13}_{\Lambda\Lambda}$B : $\Delta B_{\Lambda\Lambda} \approx 5$ MeV
  - 5 (1991...): ${}^{6}_{\Lambda\Lambda}$He, ${}^{10,11,12}_{\Lambda\Lambda}$Be, ${}^{13}_{\Lambda\Lambda}$B : $\Delta B_{\Lambda\Lambda} \approx -1.5\ldots4$ MeV !?

- Theoretical:

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

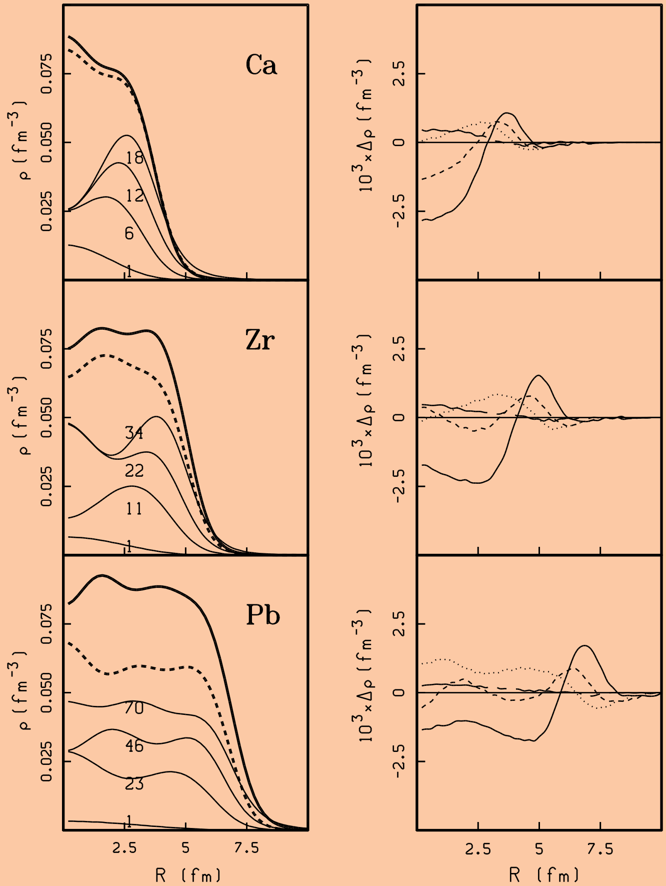
- Results with Nijmegen potentials:

	$\Delta B_{\Lambda\Lambda}$ [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

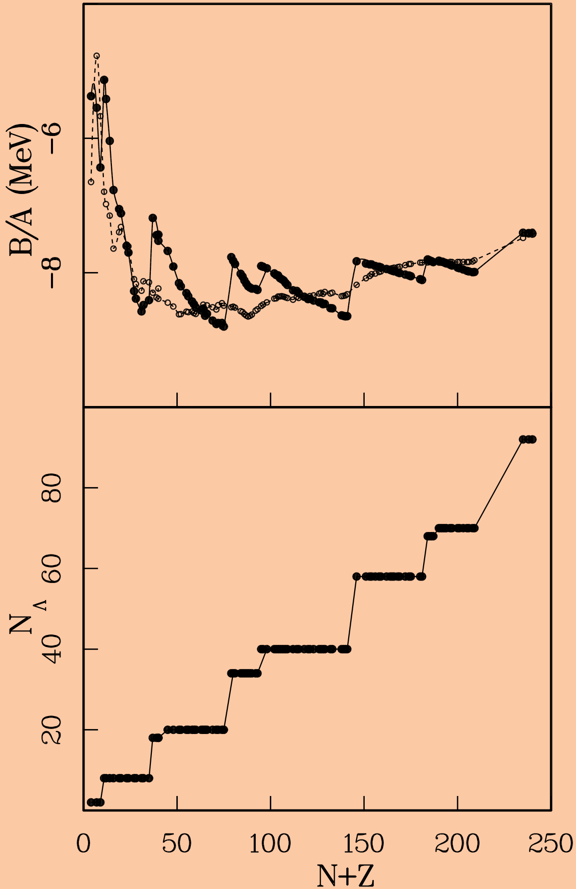
No YY components: core rearrangement effect

→ 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 (ESC08 ...)
  - Spin-orbit force
  - Hyperonic TBF
  - Constrained ΛN Skyrme force
  - HFB for dripline (hyper)nuclei

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  - 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

↪ ESC08 preferred; NSC97,ESC04 excluded; need data !