Hypernuclei and *Strange* Neutron Stars

with

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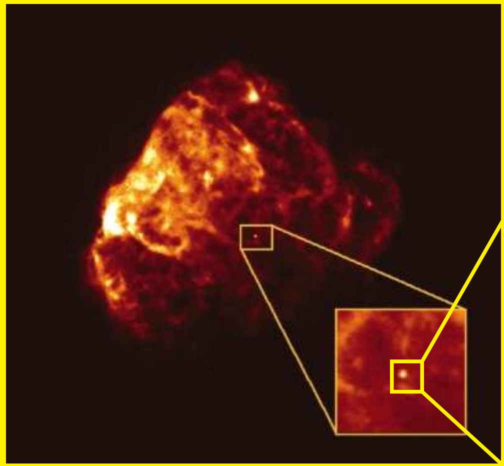
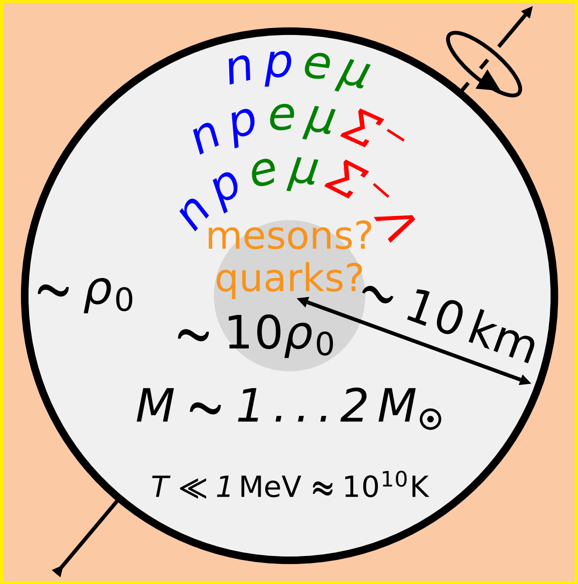
- BHF approach of hypernuclear matter
- Hypernuclei
- Neutron star properties

PRC 57, 704 (1998)
PRC 62, 064308 (2000)
PRC 64, 044301 (2001)
PRC 76, 034312 (2007)
PRC 78, 054306 (2008)
NPA 835, 19 (2010)
PTP 123, 569 (2010)
PRC 84, 035801 (2011)
PRC 88, 024322 (2013)

A Theorist’s View of a Neutron Star:



ROSAT image of *Puppis A*



$n\,p\,e\,\mu$

$n\,p\,e\,\mu\,\Sigma^-$

$n\,p\,e\,\mu\,\Sigma^-\,\Lambda$

mesons?

quarks?

$\sim \rho_0$

$\sim 10\rho_0$

$\sim 10\,\mathrm{km}$

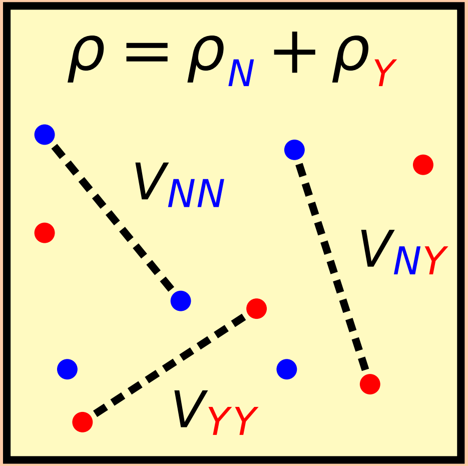
$M \sim 1 \ldots 2\,M_\odot$

$T \ll 1\,\mathrm{MeV} \approx 10^{10}\mathrm{K}$

↪ The only “laboratory” for $\rho_B \sim 10\rho_0$ in the Universe !

Need EOS of nuclear matter including hyperons and quarks

Hypernuclear Matter:



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

$Y = qqs$: Λ^0 (1116 MeV)

Σ^{-0+} (1193 MeV)

qss: Ξ^{-0} (1318 MeV)

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

V_{NY} : Nijmegen (NSC89, NSC97, . . .)

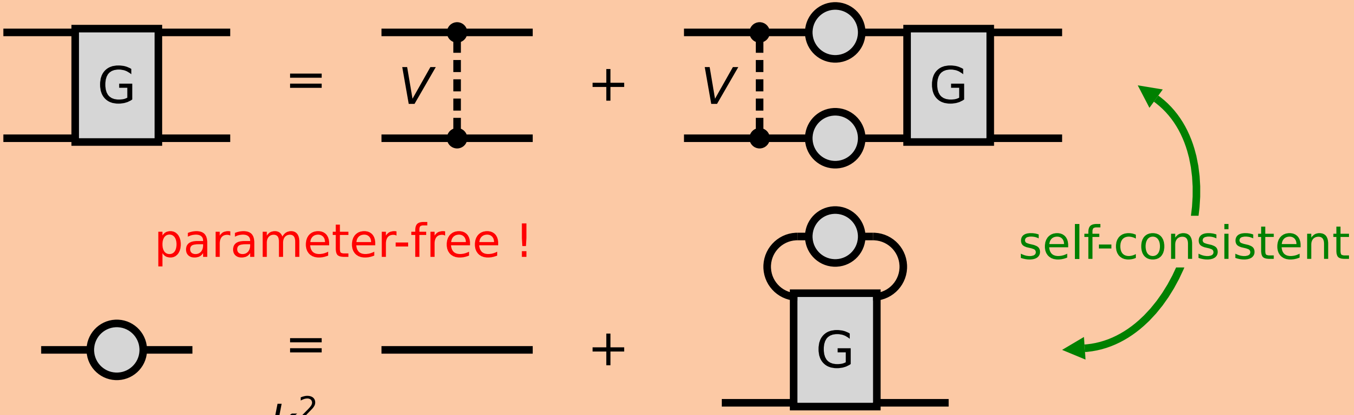
V_{YY} : ? (no scattering data)

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

In dense nucleonic medium the decay is Pauli-blocked !

Brueckner Theory of (Hyper)Nuclear Matter:

- Effective in-medium interaction G from potential V:



parameter-free !

self-consistent

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

Results: binding energy $\epsilon(\rho_n,\rho_p,\rho_\Lambda,\rho_\Sigma) = \sum_i \sum_{k<k_F^{(i)}} \left[e_k^{(i)} - \frac{U_i(k)}{2} \right]$

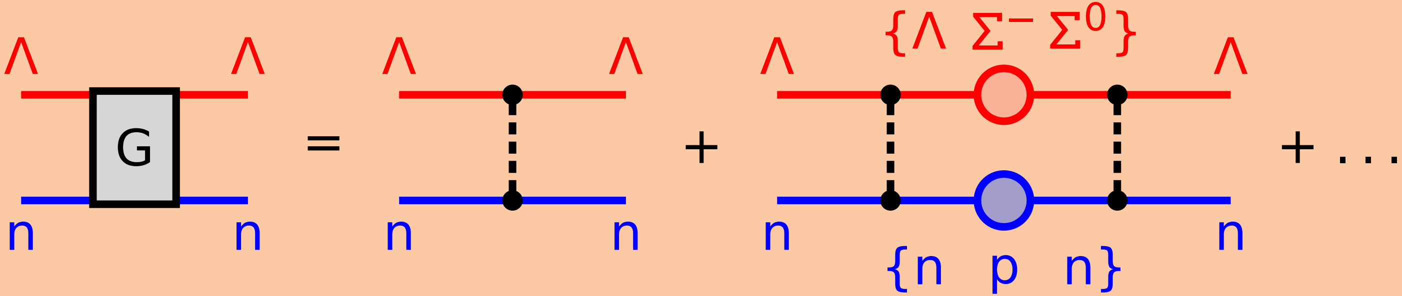
s.p. properties, cross sections, ...

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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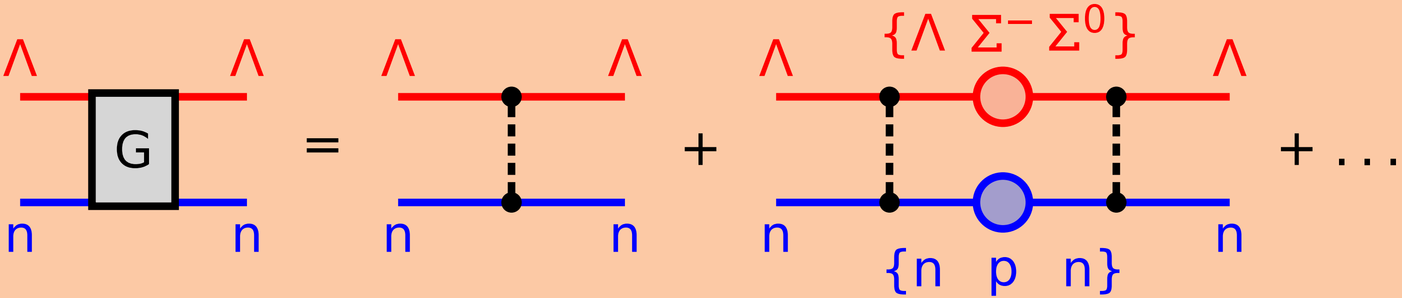
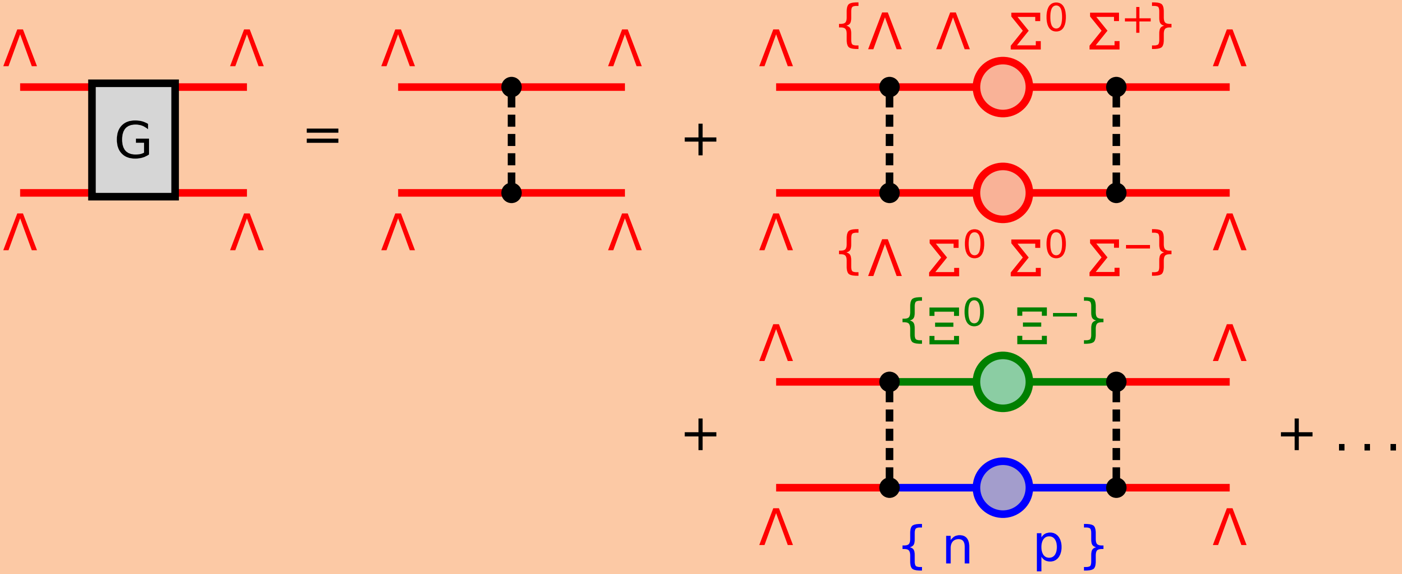
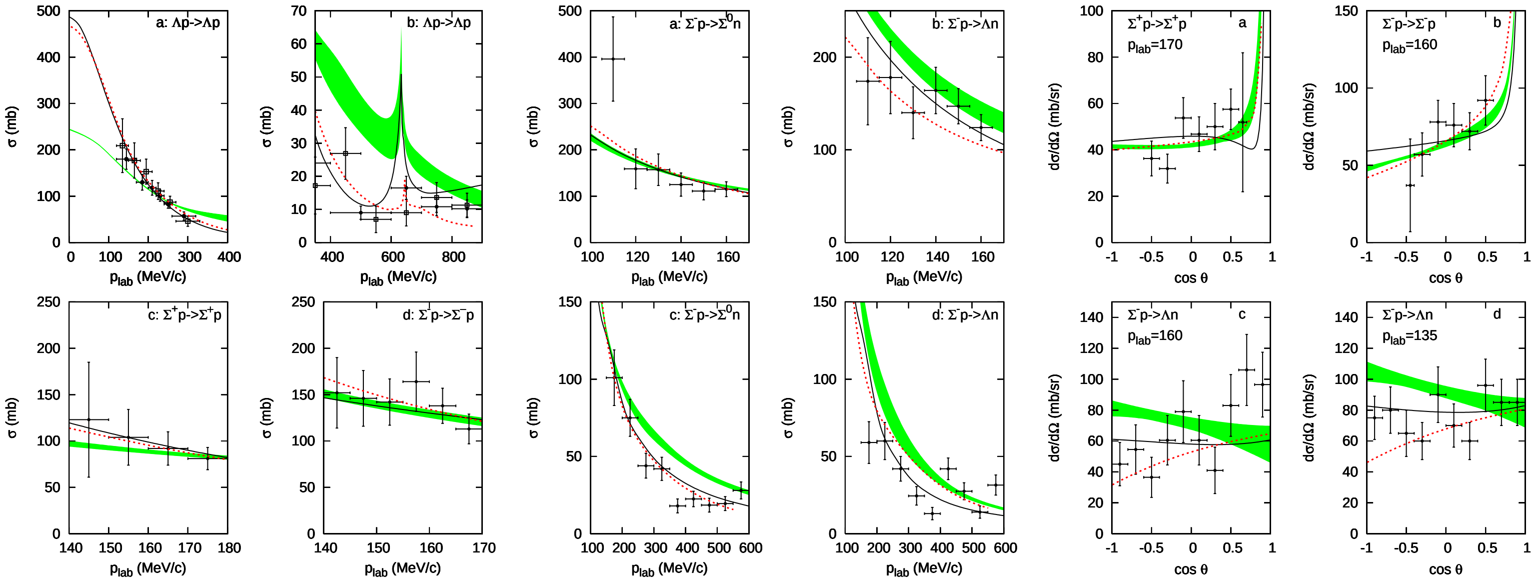




NY Cross Section Data:

Polinder & Haidenbauer & Meissner, NPA 779, 244 (2006)



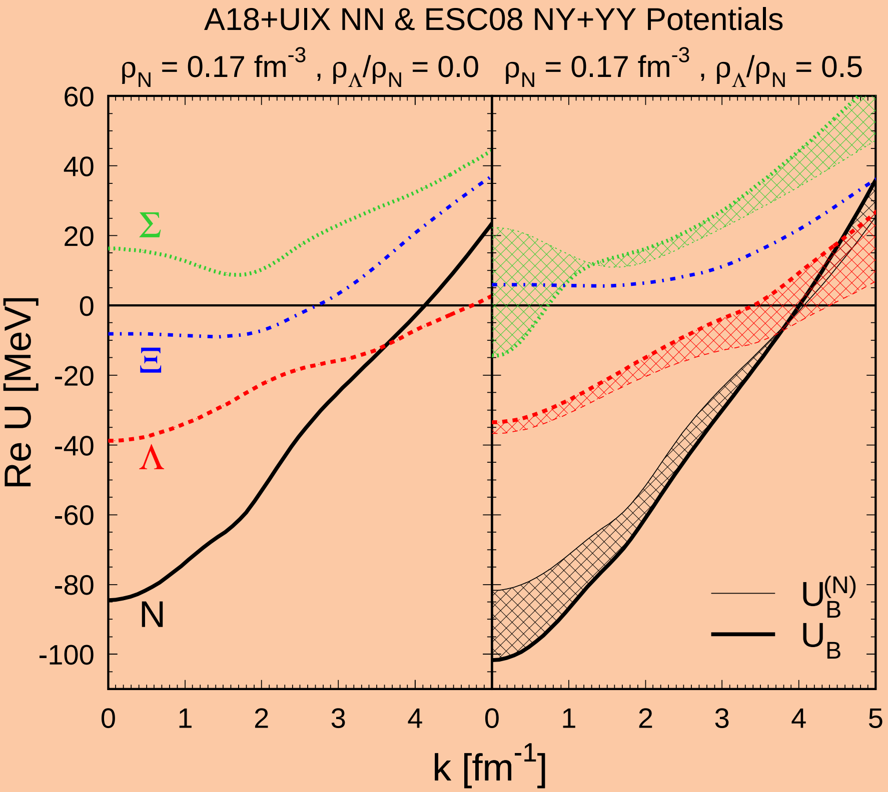
— NSC97f — Jülich04 — EFT LO

Data from the 1960’s !

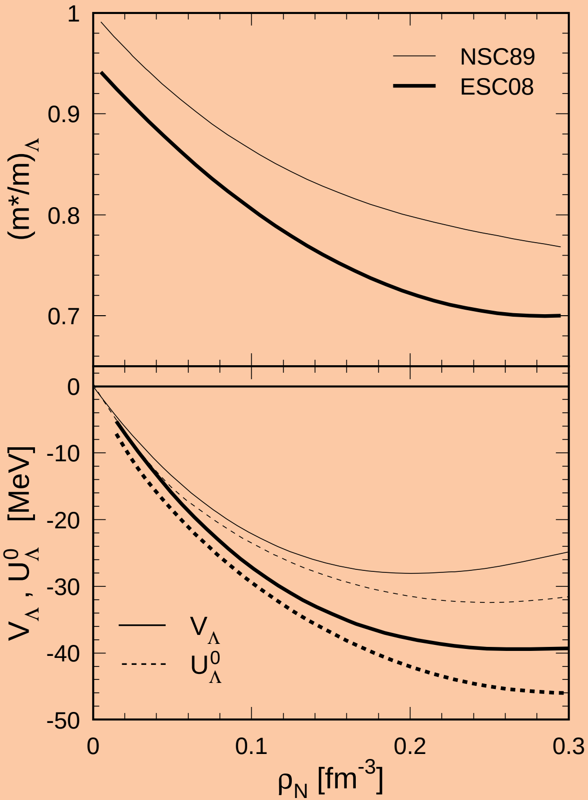
➡ Need more and better data

Example BHF Results:

s.p. potentials



Λ eff. mass & mean field



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:

PTEP **2012**, 02B012 H. Tamura

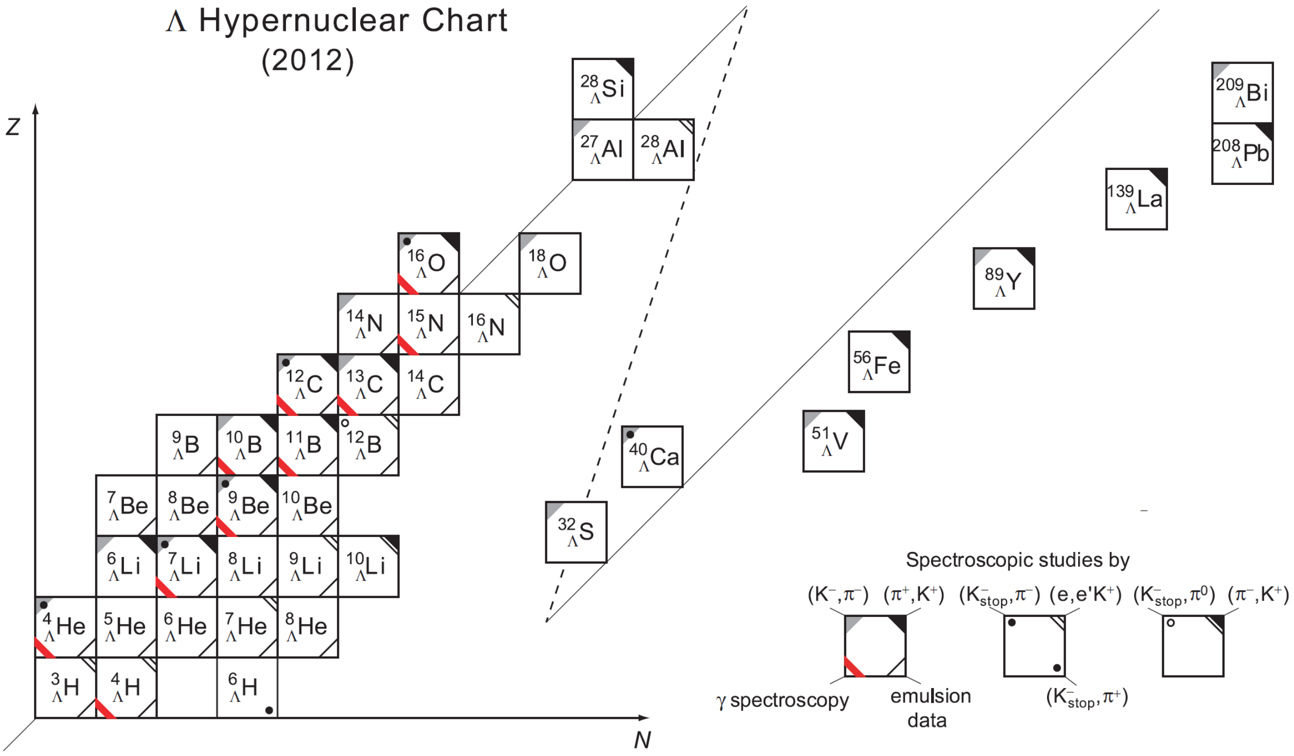
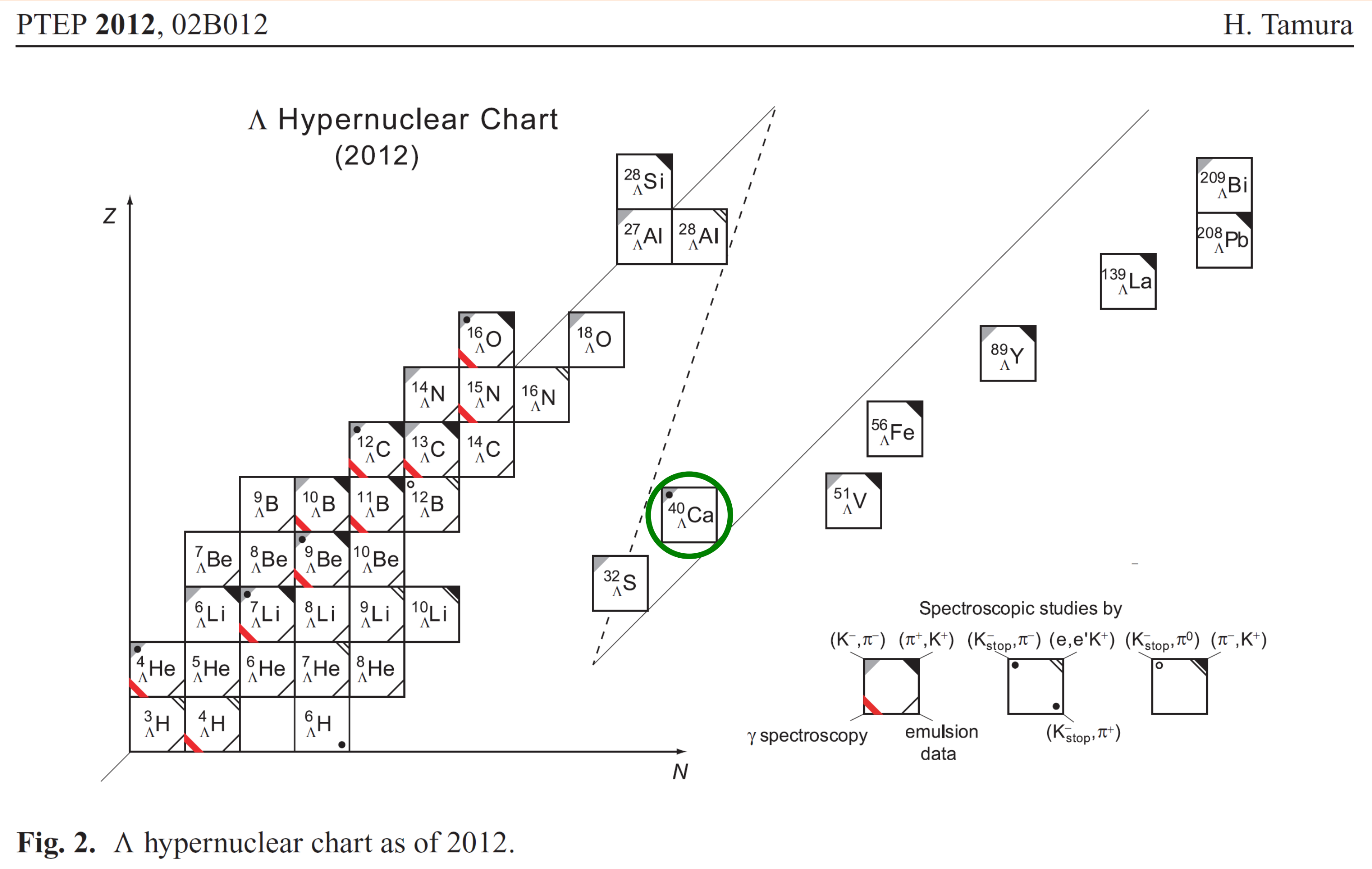


Fig. 2. Λ hypernuclear chart as of 2012.

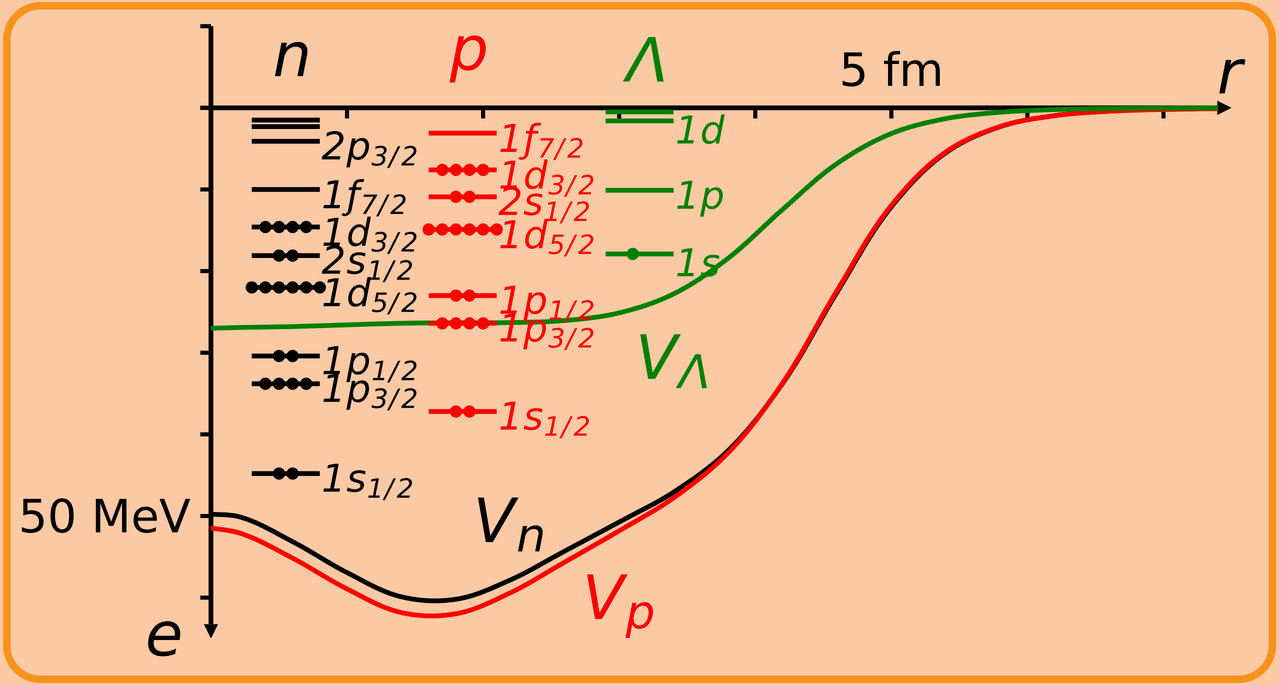
Lambda Hypernuclear Chart:



PTEP **2012**, 02B012 H. Tamura

Fig. 2. Λ hypernuclear chart as of 2012.

Hypernuclei: 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 *N*Λ force from BHF results . . .

Extended SHF+BHF Model for Hypernuclei:

- Total energy of the hypernucleus:

$$E = \int \mathrm{d}^3 r\, \epsilon(r)$$

Energy density functional:

$$\epsilon = \epsilon_N[\tau_n, \tau_p, \rho_n, \rho_p, \boldsymbol{J}_n, \boldsymbol{J}_p] + \epsilon_\Lambda[\tau_\Lambda, \rho_\Lambda, \rho_N]$$

Local densities:

$$\rho_q = \sum_{i=1}^{N_q} |\phi_q^i|^2\,, \quad \tau_q = \sum_{i=1}^{N_q} |\nabla\phi_q^i|^2\,, \quad \boldsymbol{J}_q = \sum_{i=1}^{N_q} \phi_q^{i\,*} (\nabla\phi_q^i \times \boldsymbol{\sigma})/i$$

i: occupied states, N_q: number of particles $q = n, p, \Lambda$

- 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

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

$$(\rho_N+\rho_\Lambda)\frac{B}{A}(\rho_N,\rho_\Lambda)-\rho_N\frac{B}{A}(\rho_N,0)-\frac{3}{5}\frac{(3\pi^2)^{2/3}}{2m_\Lambda}\rho_\Lambda^{5/3}$$

  - Coupled equations for eigenvalues e_q^i

- SHF Schrödinger equation:

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

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

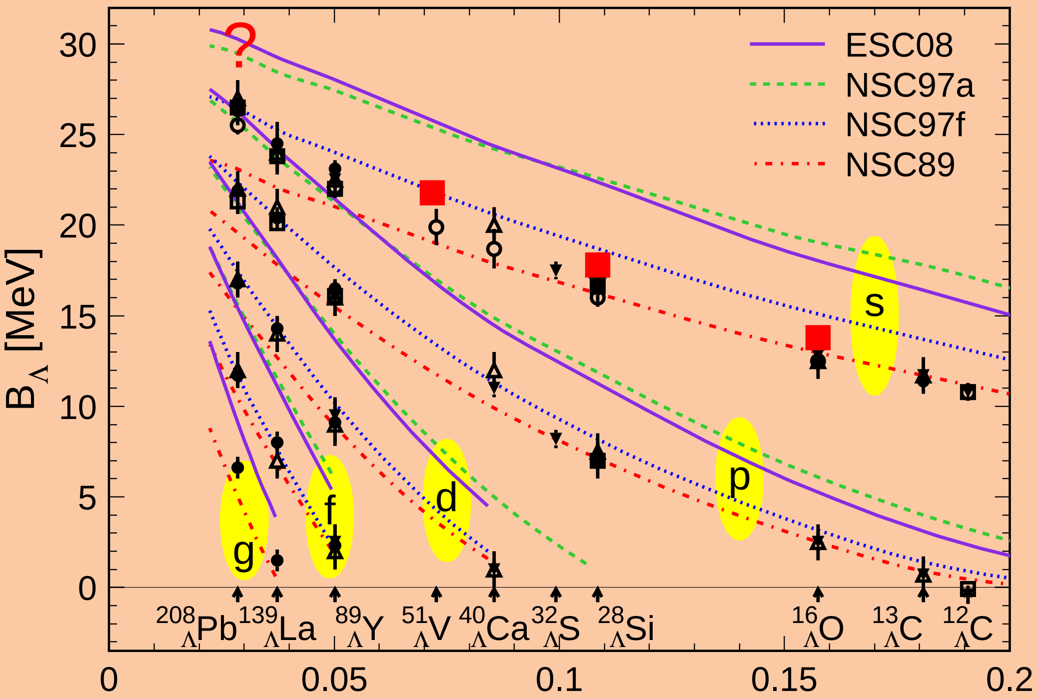
$$\epsilon_{N\Lambda}(\rho_N,\rho_\Lambda)=$$

$$(\rho_N+\rho_\Lambda)\boxed{\frac{B}{A}(\rho_N,\rho_\Lambda)}-\rho_N\frac{B}{A}(\rho_N,0)-\frac{3}{5}\frac{(3\pi^2)^{2/3}}{2m_\Lambda}\rho_\Lambda^{5/3}$$

  - Coupled equations for eigenvalues e_q^i

Results: Single-Λ Hypernuclei:

- Lambda single-particle levels:



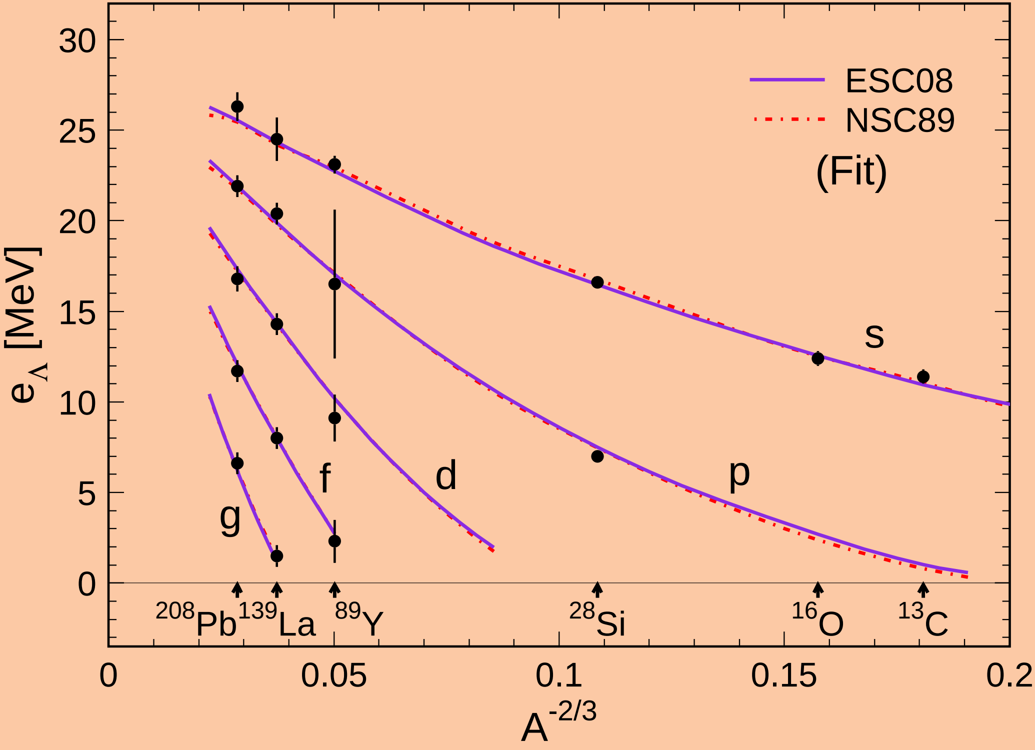
→ Best agreement with NSC89 and NSC97f potentials

No indication of strong hyperon TBF

Fit of empirical hyperon TBF:

$$\epsilon_{N\Lambda}(\rho_N,\rho_\Lambda) = \epsilon^{\mathrm{BHF}}_{N\Lambda}(\rho_N,\rho_\Lambda) + \tilde{\epsilon}_1 \rho_N\rho_N\rho_\Lambda + \tilde{\epsilon}_2 \rho_N\rho_\Lambda\rho_\Lambda + \tilde{\epsilon}_3 \rho_\Lambda\rho_\Lambda\rho_\Lambda$$

Parameters $\tilde{\epsilon}_1, \tilde{\epsilon}_2, \tilde{\epsilon}_3$



Predictions for “JLAB” Nuclei:

- B_Λ (MeV) :

		Exp.	NSC89	ESC08
${}^{7}_{\Lambda}\mathrm{He}$	s	5.6	5.2	8.4
${}^{9}_{\Lambda}\mathrm{Li}$	s	8.4	7.3	10.1
${}^{12}_{\Lambda}\mathrm{B}$	s	11.5	9.9	14.5
${}^{16}_{\Lambda}\mathrm{N}$	s	13.8	12.1	17.1
	p	2.8	1.5	4.3
${}^{28}_{\Lambda}\mathrm{Al}$	s	17.9?	15.7	21.8
	p	7.4?	6.5	10.6

JLAB Key Experiment:

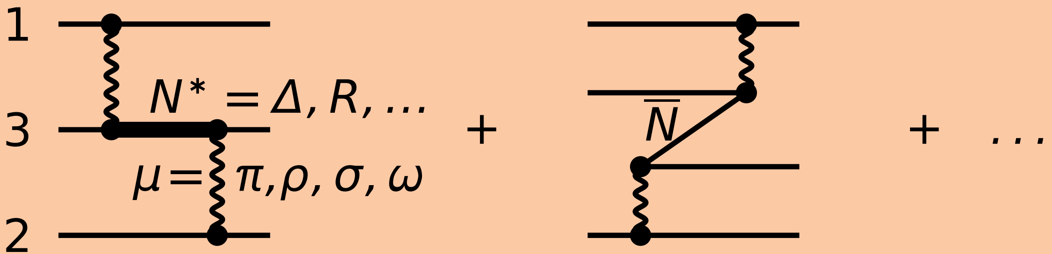
By exclusion, focus on heavy hypernuclei: $^{208}_{\Lambda}$Pb ?

- Light ones are done in FAIR, J-PARC, LNF, MAMI, ...
- Closest to bulk matter, many s.p. states
- Good to fine-tune in-medium *NY* interaction

Neutron Stars

J0617 in IC 443

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

«Recipe» for Neutron Star Structure Calculation:

Brueckner results: $\boldsymbol{\epsilon(\rho, x_e, x_p, x_\Lambda, x_\Sigma, \ldots)}$; $x_i = \frac{\rho_i}{\rho}$

Chemical potentials: $\mu_i = \frac{\partial \epsilon}{\partial \rho_i}$

Beta-equilibrium: $\mu_i = b_i \mu_n - q_i \mu_e$

Charge neutrality: $\sum_i x_i q_i = 0$

Composition: $x_i(\rho)$

Equation of state: $p(\rho) = \rho^2 \frac{d(\epsilon/\rho)}{d\rho}(\rho, x_i(\rho))$

TOV equations:

$$\frac{dp}{dr} = -\frac{Gm}{r^2} \frac{(\epsilon + p)(1 + 4\pi r^3 p/m)}{1 - 2Gm/r}$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

Structure of the star: $\rho(r)$, $\boldsymbol{M(R)}$ etc.

«Recipe» for Neutron Star Structure Calculation:

Brueckner results: $\boldsymbol{\epsilon(\rho, x_e, x_p, x_\Lambda, x_\Sigma, \dots)}$; $x_i = \frac{\rho_i}{\rho}$

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Charge neutrality: $\sum_i x_i q_i = 0$

$$\mu_e = \mu_\mu = \mu_n - \mu_p$$
$$\mu_{\Sigma^-} = 2\mu_n - \mu_p$$
$$\mu_{\Sigma^0} = \mu_\Lambda = \mu_n$$
$$\mu_{\Sigma^+} = \mu_p$$

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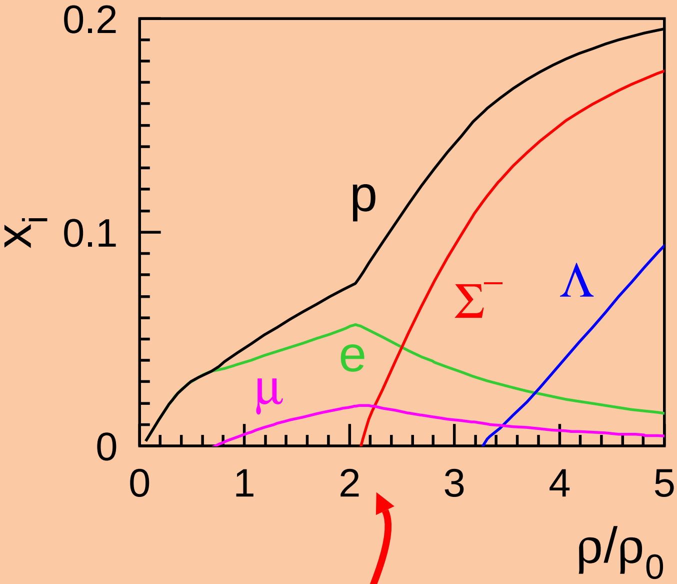
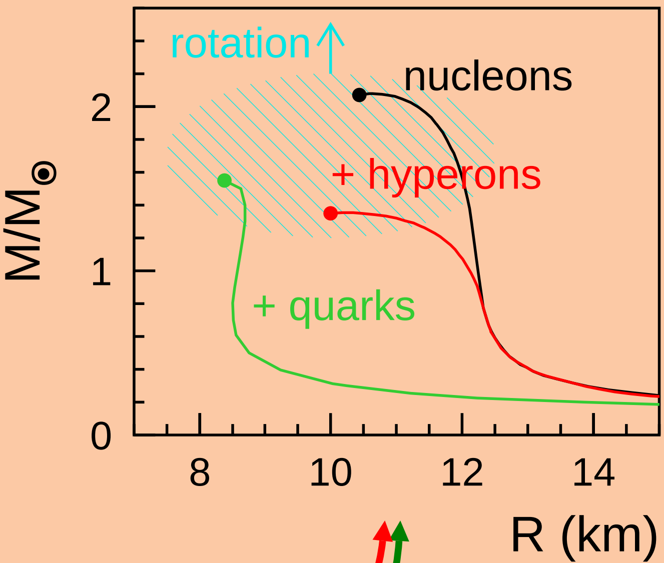
Structure of the star: $\rho(r)$, $\boldsymbol{M(R)}$ etc.

- Generic implications for EOS and stellar structure:

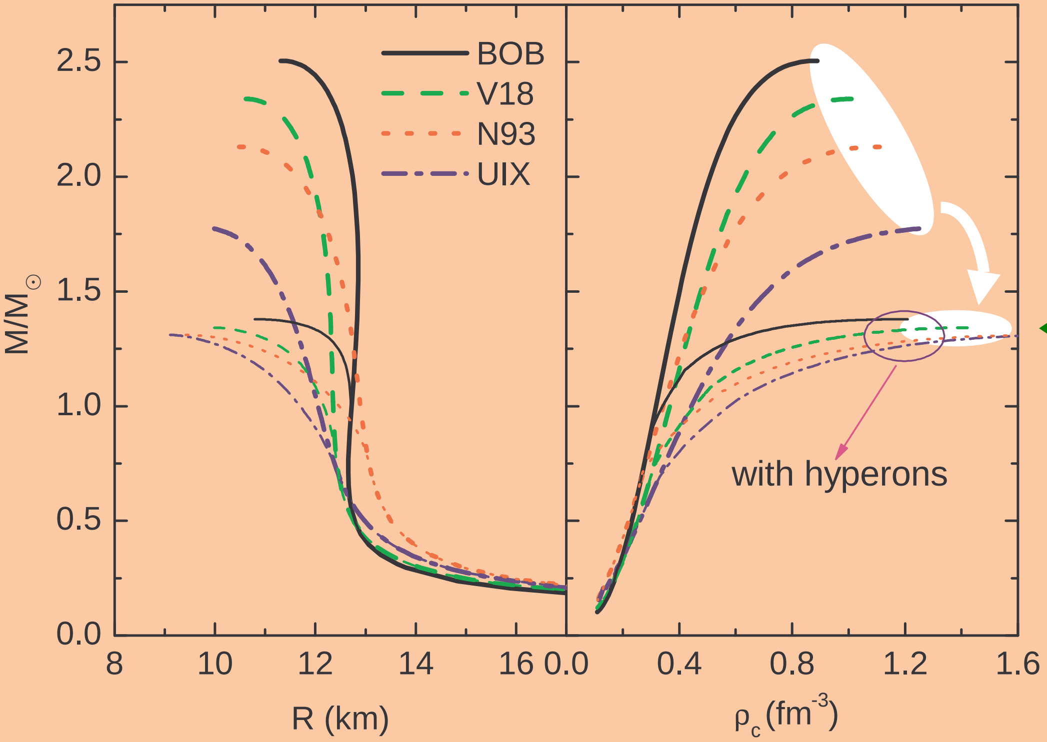




- Hyperon onset occurs at $\rho \sim 2 \ldots 3\, \rho_0$
- Softer EOS
- NS structure including hyperons

  . . . and including quark matter

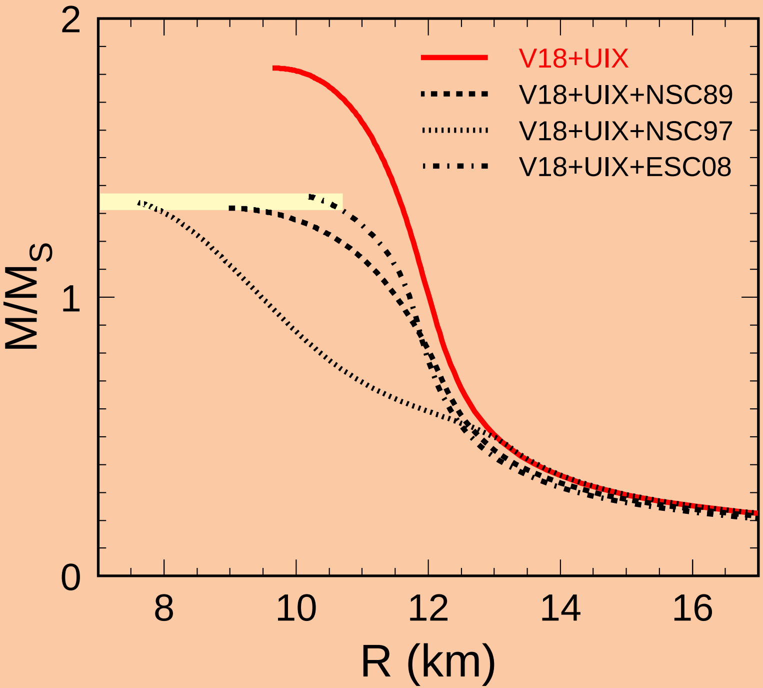
- Mass-radius relations with different nucleonic TBF:



NSC89 *NY* potential
No *YY*
No hyperon TBF

↪ Large variation of M_{max} with nucleonic TBF
Self-regulating softening due to hyperon appearance
(stiffer nucleonic EOS → earlier hyperon onset)

- Using different *NY*,*YY* potentials:

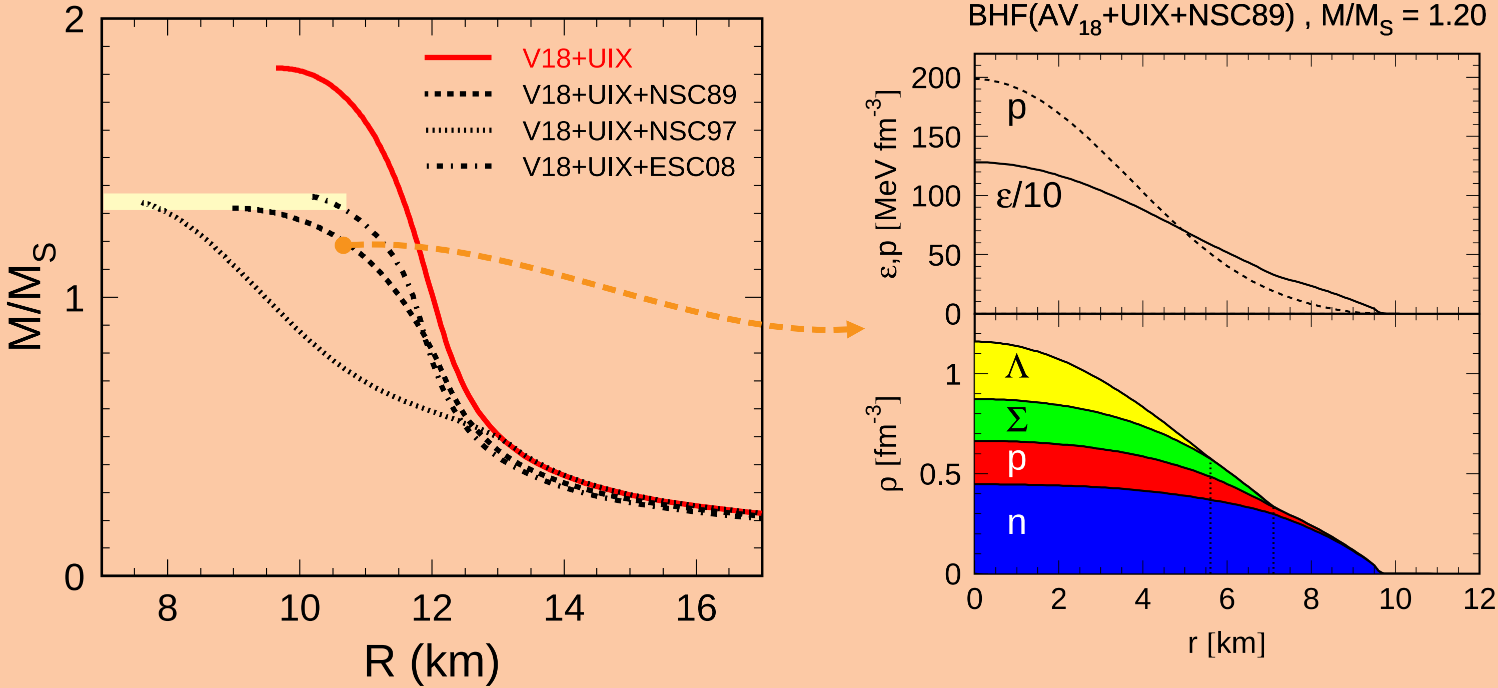


Maximum mass independent of potentials !

Maximum mass too low ($< 1.4\,M_\odot$) !

Proof for “quark” matter inside neutron stars ?

- Using different NY,YY potentials:

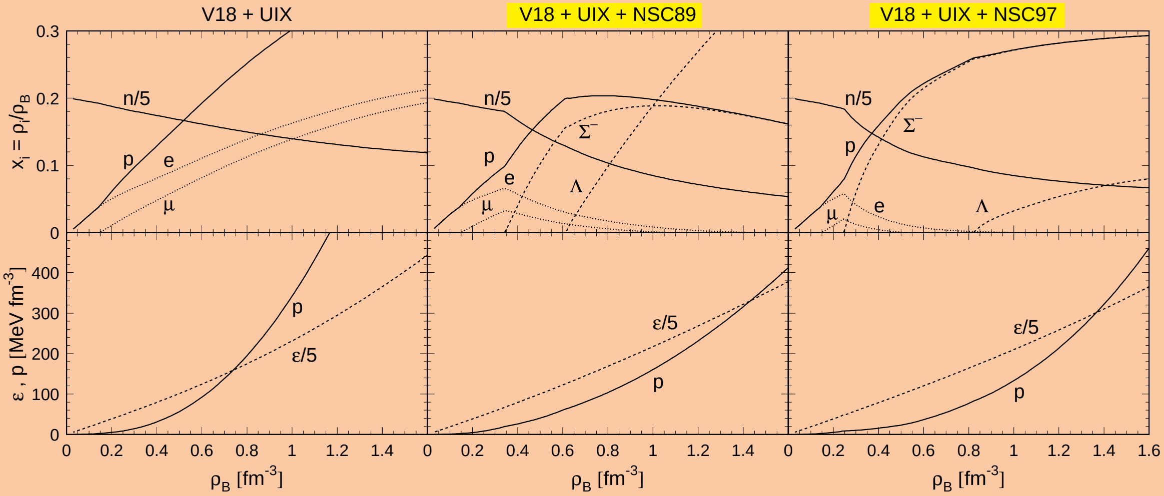


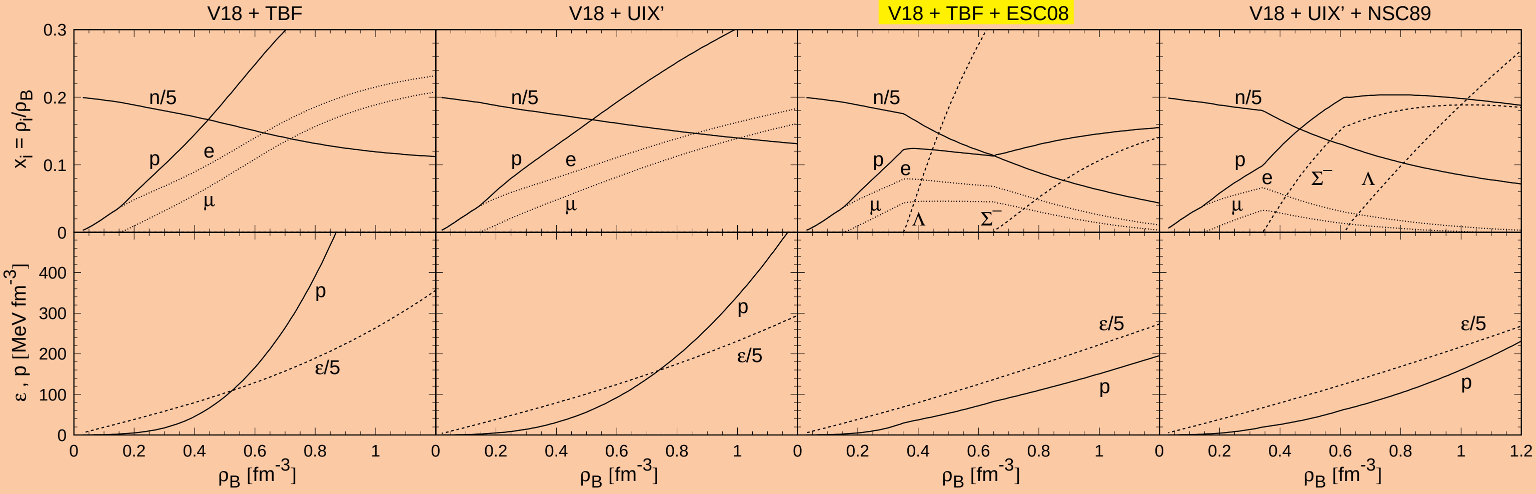
Maximum mass independent of potentials !

Maximum mass too low ($< 1.4\, M_\odot$) !

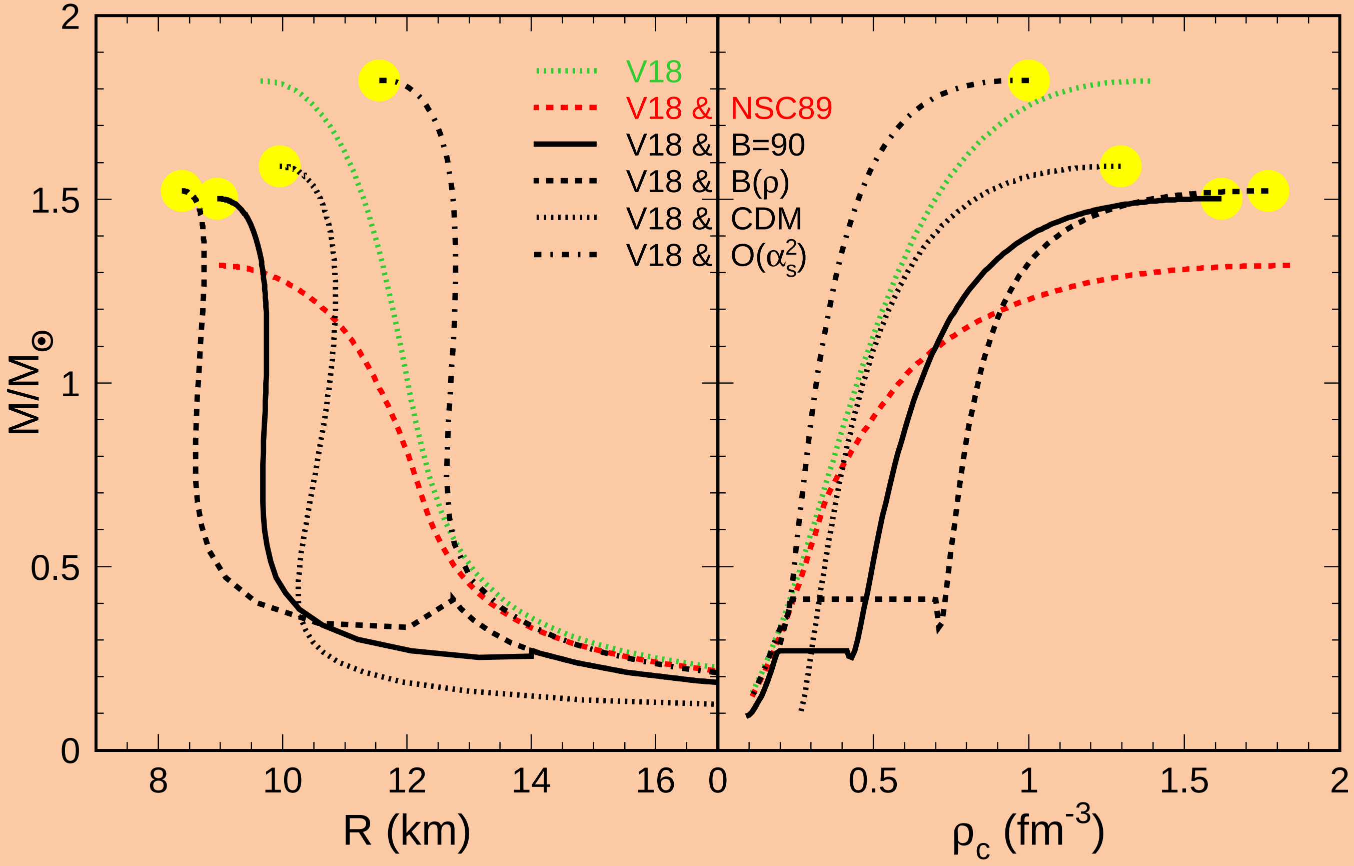
Proof for “quark” matter inside neutron stars ?

- . . . in spite of different compositions:





- Different quark EOS's: bag models, color dielectric model:



NJL, Dyson-Schwinger models: hyperons prevent phase transition

➡ Maximum masses: 1.5...1.9 $M_\odot$, Radii are different !

Summary:

- Consistent theoretical BHF+SHF framework for hypernuclei and neutron star structure
- Nijmegen NY potentials are consistent with hypernuclear structure: Required corrections (TBF etc.) are small
- JLAB key experiment: ${}^{208}_{\Lambda}\mathrm{Pb}$ to fine-tune the NY interaction in bulk matter

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- Hyperons cannot be ignored in neutron stars !
- BHF EOS with hyperons predicts M_{max} not above $\sim 1.4\,M_\odot$
- Need “quark matter” to reach higher masses
- Currently $M_{\mathrm{max}} \approx 1.9\,M_\odot$ for hybrid stars in this approach